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A DECISION-SUPPORT MODEL FOR SELECTION OF A TRENCHLESS CONSTRUCTION METHOD

by

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Dr. Ming Jian Zuo

for Dr. Raymond Sterling

Approved on: 12/19/2002

Dedicated to

my beloved son

the late

ADAR ELIAZAR ALBERT ALLOUCHE

for

the best ten years of my life.

ABSTRACT

The increasing demand for trenchless services over the past fifteen years has resulted in the development of numerous methods for installing and replacing buried pipelines and conduits. Each of these methods has its advantages and limitations, and each is best suited for a particular combination of design requirements, project environment. and subsurface conditions. Previous research and experience has shown that evaluation of various competing construction methods should not be limited to direct costs, but must also account for social and indirect costs, environmental impact as well as the inherent risks associated with underground construction. Accounting for these factors requires a systematic evaluation methodology of the unique characteristics of each method in an unbiased manner. An automated decision-support system can assist the decision-maker in performing this immense task by breaking it into manageable subtasks that can then be automated.

This work describes a framework for a decision-support model for the selection of a construction method for the installation or replacement of buried pipelines and conduits. Review of the literature revealed that a number of well-established decision-making methodologies suffer from some inherent shortcomings when employed in the development of construction method evaluation models. A new algorithm named I.M.P.E.C.T (Innovative Modular Procedure for Evaluation of Construction Technologies) was developed to overcome some of these shortcomings. I.M.P.E.C.T combines well-established concepts in decision-making theory together with innovative algorithms developed during the course of this study to provide a comprehensive decision support environment for the decision-maker.

In contrast to 'black-box' decision support models, when fully implemented, I.M.P.E.C.T will provide the decision-maker with the opportunity to gain an insight into the potential difficulties associated with the project and the quality of the available information. Additionally, the user is required to identify his or her priorities and constraints. Selected aspects of I.M.P.E.C.T were implemented using MS Excel and MATLAB Version 5.3. Initial verification of the model demonsres the ease of automation, the relative simplicity of user input and the striaght forwards, but yet informative, nature of the output. Continuouing research in this area will focues on completing the automation of the framework, further population of the database and a rigorius validation process via the modeling of a series of case histories.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

As we enter the 21st century, utility companies and local municipalities are faced with the tremendous task of maintaining and expanding their underground utility infrastructures (i.e., power, telecommunication, sewer and water main). While there is no firm estimate of the current status of underground infrastructure systems across North America, preliminary investigations indicate that degradation is extensive, impacting nearly every municipality on the continent. The cost for bringing the infrastructure system up to design capacities ranges in the tens of billions of dollars.

Traditionally, the installation, inspection, repair and replacement of underground utilities are carried out using open-cut construction methods. Such operations may prove to be expensive, particularly in congested urban areas, as the contractor must cautiously dig around existing utilities to achieve the required depth, which in turn impedes the operation. Additional costs are typically incurred by the need to restore landscape features (i.e., sidewalks, pavement, brick paving) and implement extensive traffic control measures. Aside from the associated high agency costs, open cut trenching operations often result in high user ("social") costs due to the disruption of traffic and an adverse impact on nearby businesses (McKim, 1997b; Boyce and Bried, 1994; Pau et al., 1993).

Faced with an urgent need to rehabilitate or replace their aging utility systems on the one hand, and dwindling budgets, tight environmental regulations and an increased emphasis on user costs on the other hand, owners of utilities networks are seeking alternate methods for repairing, replacing and expanding their underground assets. One such alternative are trenchless technologies, defined by the North American Society for Trenchless Technology (NASTT) as "a family of methods, materials, and equipment capable of being used for the installation of new, or replacement or rehabilitation of, existing underground infrastructure with minimal disruption to surface traffic, businesses and other activities".

A recent survey of current trenchless construction practices by Canadian municipalities reveals that trenchless methods have been utilized extensively over the past decade by cities such as Vancouver, Edmonton, Calgary, Winnipeg, Toronto and Montreal (Ariaratnam et. al., 1999). The percentage of municipal projects utilizing trenchless construction methods has grown dramatically between 1992 and 1997. The number of rehabilitation projects using trenchless methods has increased by 180% while the increase in the utilization of trenhless methods in new installation has soared by 270%. Comments received from survey respondents indicate that while the use of trenchless technology is on the rise, there are still obstacles to be overcome before this technology can be more widely accepted. Two such challenges identified by the survey's respondents are the absence of construction guidelines and design specifications and the need for an effective tool for selecting the most suitable construction method for the project at hand.

These needs are echoed by a recent initiative for the development of a 'Best Practices National Guide for Infrastructure Rehabilitation' by the Federation of Canadian Municipalities (FCM), the National Research Council (NRC) and fifteen professional organizations (CSCE, 2000). The main objectives of the new guide are to: (a) identify innovative methods to either develop new infrastructure or rehabilitate it; and, (b) develop methods to justify the choices made by municipal engineers.The guide's ultimate purpose is to restore the authority municipal engineers have lost over the last few decades to make engineering decisions by developing new tools that will consider the overall cost-benefit of the project rather than only the direct costs.

The objective of this research is the development of a framework for a computerized decision-support system capable of identifying the most suitable construction method for the installation or replacement of buried pipelines or conduits. It is envisioned that the theoretical framework presented herein will serve as the basis for a full-scale application to be used by practicing professionals in the underground infrastructure industry.

1.2 PROBLEM STATEMENT

When considering the utilization of trenchless technology for a particular project, one must compare the associated overall costs and impacts with those incurred utilizing an open-cut method. Since many benefits associated with trenchless construction are in the form of reduced indirect costs incurred by the agency and the public, a methodological approach that considers multiple aspects of underground utility projects must be developed. Furthermore, even in the case where the advantages offered by trenchless construction are obvious, one may find that selecting the most suitable method for the project is not trivial. There are seventeen different trenchless methods that can be used for the installation or replacement of pipes and conduits, many of which have several subclasses. Therefore, the selection process requires the matching of project design parameters (e.g., product diameter/material; installation length/depth; geological conditions) with the characteristics of the construction method in such a way as to obtain a sound technical solution while minimizing the overall costs and adverse impact to the agency and the public. Recent examples of municipal projects utilizing trenchless construction methods that have experienced severe cost and schedule overruns due to inadequate subsurface investigation, poor choice of construction method or inadequate risk assessment have been reported by Allouche and Ariaratnam (1999) and Allouche and MacAulay (1999).

In recent years, a number of automated and semi–automated decision-support systems have been developed by various researchers to assist construction practitioners in the determination of the most suitable method for a given project. These models typically utilize the Analytical Hierarchy Process (Hastak, 1998; McKim, 1997a), an expert system shell (Ueki et al., 1999; Russel et al., 1997) or the utility theory (Moselhi and Sigurdardottir, 1998). A detailed review of decision-support models in general, and models developed for the selection of construction methods in particular, is given in Chapter 2. The review shows that most existing methods do not account for the inherent uncertainty in the input data, while none enable the user to specify a given attribute as a function of other attributes or to specify multi-attribute constraints. Also, input data for these models are limited to deterministic values (i.e., an attribute's value cannot be specified as a probabilistic distribution). These shortcomings limit a model's flexibility and reduce the ease with which it can be adopted to describe real world problems.

It would be beneficial to develop a methodology for a decision-support system that can assist practicing professionals in matching project parameters with the characteristics of the various methods, evaluating the degree to which each method satisfies the user's requirements, and selecting the most suitable method for the project. In particular, the methodology should exhibit the following features:

1. Enable the comparison of several competing methods simultaneously.
2. Accommodate tangible as well as non-tangible attributes.
3. Account for uncertainty in the estimate of the method's attributes.
4. Enable trade-offs among preference attributes to be conducted in a quantitative manner.
5. Enable attributes to be expressed in units of time, space, monetary value or descriptive language, and to be presented as either a discrete value or a statistical distribution.

The current work presents the framework for such a model, named the 'Integrated Modular Procedure for Evaluation of Construction Technologies (I.M.P.E.C.T)'.

1.3 INTEGRATED MODULAR PROCEDURE FOR EVALUATION OF CONSTRUCTION TECHNOLOGIES

There is a broad spectrum of trenchless technologies from which a municipal engineer can choose when considering the installation, replacement or rehabilitation of underground infrastructure systems. Due to the large number of trenchless technologies available in the marketplace, the decision as to which method, or combination of methods, to use for a specific infrastructure project is not trivial. Each method offers specific advantages and limitations. The inappropriate selection of a construction method can result in construction difficulties, cost and schedule overruns, excessive disturbance to the surrounding environment and secondary damage to surface improvements and nearby utilities and foundations.

This work presents a framework for a comprehensive decision-support model for practitioners involved in the planning, design and construction of buried infrastructure projects. The Integrated Modular Procedure for Evaluation of Construction Technologies (I.M.P.E.C.T) uses an extensive database of construction methods' characteristics, a comprehensive risk analysis module and a unique decision-making algorithm to evaluate the technical suitability of competing construction methods and to compute the probability that a given method will satisfy the user's performance requirements. Specifically, I.M.P.E.C.T provides:

1. The identification of those construction methods that are capable of performing the project at hand based on technical capabilities related to diameter, maximum drive length, depth, accuracy, anticipated subsurface conditions, site constraints and other project specific parameters.
2. A realistic range estimate for various project parameters.
3. An estimate of the relative level of risk associated with the utilization of each technically sound construction method as a function of subsurface conditions, the method's capabilities, project parameters, confidence in subsurface data, and the user's risk attitude.

4. Computation of the probability that a given construction method will satisfy the user's performance requirements including cost, duration, environmental impact, loss of income and social costs.

Task (4) is accomplished using a unique decision-making algorithm named the Domain of Compliance Utility Model (DCUM). DCUM is an innovative multi-objective evaluation technique that utilizes concepts from artificial intelligence, linear algebra and applied statistics to determine the likelihood that a particular alternative (e.g. construction method) will satisfy one or more set(s) of performance requirements (i.e., constraints). In DCUM an attribute's value can be: a) expressed as a function of the value of one or more different attributes; b) specified either as a probability distribution or a deterministic value; c) be part of any number of 'global constraints' placed on the acceptable solution; and, d) expressed in any unit of measurement. These characteristics make DCUM a powerful algorithm capable of modeling complex decision-making scenarios encountered in real-world applications with little need for idealization.

1.4 OVERVIEW OF THESIS

The thesis is divided into eight chapters. Chapter 2 provides an extensive overview of decision support systems in the area of construction management with an emphasis on those models developed for selection of an underground construction method. Three widely accepted decision-making theories, namely, 2-D utility theory, expert systems and the Analytical Hierarchy Process, are described in detail. These generic theories form the basis for nearly all of the models described in Chapter 2.

The advantages and limitations of each decision-making model are identified and discussed.

Chapter 3 provides an overview of seventeen trenchless construction methods and their subclasses that can be used for the installation or in-line replacement of buried infrastructure as well as three open-cut construction methods. Chapter 4 presents a summary of the operative and technical characteristics of each of the construction methods covered in Chapter 3. The information is summarized in a series of tables that form the core of the database for the proposed model. An extensive review of trenchless technology literature and company brochures was supplemented by research of historical project records and several industry surveys to facilitate the development of the database. Additionally, parameters that may influence the selection of a construction method for a given project scenario are presented and discussed under four categories: design requirements; site conditions; administrative constraints and impact. The parameters are summarized using tree-type hierarchy diagrams, where high-level elements are defined by lower-level constitutive criteria. The identification of the various aspects of buried infrastructure construction projects and their components is a necessary step before one can start formulating an evaluation and selection scheme. Also, the understanding of the various aspects of a project and their makeup are important for proper set up and implementation of the Domain-of-Compliance Utility Model.

One of the overriding factors for the selection of an underground construction method is the nature of the subsurface conditions. Sylwester (1997), Capozzoli (1996) and Mathy and Nielson (1999) recognized the susceptibility of trenchless methods to buried obstacles and adverse soil conditions, and suggested that this risk may be mitigated by acquiring in advance detailed knowledge of subsurface conditions along the entire proposed route. However, in many cases current site characterization methods are unable to provide detailed subsurface information regarding the presence of specific hazards at an acceptable cost. Consequently, the uncertainty associated with subsurface conditions may lessen the practical usefulness of the proposed model (or any other model for that matter). The first half of Chapter 5 is devoted to a state-of-the-art review of 'horizontal sampling and logging techniques', a term referring to the deployment of specialized sampling tools, contact sensors and borehole geophysic probes along small-diameter exploratory horizontal bores drilled across the zone of interest using the directional drilling method. While still in their infancy, these technologies have the potential to provide detailed continuous information regarding subsurface conditions in an economical manner. However, the challenge still remains to assess the reliability and to integrate information obtained from various sources in order to create a comprehensive picture of the underground conditions. The second part of Chapter 5 describes a methodology developed for the integration of subsurface information obtained from horizontal sampling and logging tools, surface geophysics as well as traditional site characterization techniques. The methodology, named EXESIble, estimates the amount of uncertainty reduction regarding the presence of specific hazards within the volume of the subsurface medium intended to host the proposed pipe/conduit as a result of the utilization of a particular site characterization scheme. Also presented is an equation to compute the cost-benefit obtained from a given level of investment in subsurface investigation. EXESIble is intended to ultimately assist in the processing of geotechnical data and will provide input to I.M.P.E.C.T.

I.M.P.E.C.T uses a two-step method selection process, namely a technical evaluation and a preference evaluation. At the technical evaluation stage, described in Chapter 6, characteristics of each construction method are compared with the project qualifying attributes to ensure technical soundness of the method. Parameters considered at this stage include product diameter, maximum single drive length, installation depth, installation tolerances and other design parameters. Additionally, an elaborate procedure was developed to evaluate the compatibility of each candidate construction method with anticipated subsurface conditions. The methods found to be technically unsound are eliminated at the end of the technical evaluation.

The preference evaluation process, covered in Chapter 7, includes parameters not associated with the technical soundness of the method, and therefore considered to be controlled by the decision-maker. The model considers eight such parameters including cost, duration, environmental impact, loss of income, replacement of surface improvements, ground movement, traffic interference and business losses. The anticipated range of values and associated probabilities can be estimated based on historical data, user's own experience or prediction models reported in the literature. Preference attributes associated with trenchless construction methods may be sensitive to the apparent level of risk associated with the project. The range of values and their associated probabilities for the preference attributes can be better defined in light of a comprehensive risk analysis. For every candidate method, an Overall Risk Index (ORI) is computed based on the degree of compatibility with the anticipated subsurface conditions; the ratio between the project design parameters and the method operating capabilities; and the ease of accessibility to the installation alignment from the surface. The output is used together with historical data to derive statistical parameters such as mean and standard deviation for various performance parameters (e.g., cost, duration, social costs).

The final component in I.M.P.E.C.T is an algorithm, named the Domain-of-Compliance Utility Model, that estimates the likelihood of each construction method satisfying the user's preference attributes and constraints. Specifically, the model estimates for each construction method the percentage of all possible outcomes that are deemed by the user as desirable, acceptable and not acceptable. The model, implemented in MATLAB Version 5.3 Computer Language, calculated four parameters for each competitive construction method, namely:

1. The likelihood that the utilization of a construction method will result in an outcome that lies within the desired solution space (domain-of-compliance).
2. The likelihood that the utilization of a construction method will result in an outcome that lies within the tolerable solution space.
3. The likelihood that the utilization of a construction method will result in an outcome that lies outside the tolerable solution space.
4. The overall utility score (OUS) for a particular candidate method, that is equal to the Euclidean distance of the 'centre-of-gravity' of the method solution subspace from the origin of the Domain-of-Compliance.

The Domain-of-Compliance Utility Model was derived from the theory of Constraint Satisfaction Problems (CSP), a mathematical approach that enables computational problems to be expressed in a natural way (Lottaz, 1999). The solution to a constraint satisfaction problem involves the assignment of a domain value to each variable that satisfies all constraints simultaneously. DCUM can be viewed as the inverse of CSP because the solution space is predetermined by the user and the model computes the likelihood that the various outcomes will fall within the solution's boundaries. It should be noted that while developed and refined within the context of construction management, DCUM is a general decision-making algorithm that can be applied to various decision-making problems involving multiple interrelated attributes and/or uncertainty in the input data.

The strength of I.M.P.E.C.T is that it is not a 'black-box', but an 'open' process involving a detailed examination of the project characteristics and the level of knowledge of the user regarding his or her project. The risk analysis component of the model 'penalizes' a candidate method for a lack of information, or an increase in risk. Thus, the fact that a particular method was found to have a low probability of satisfying the user's desired outcome may not necessarily indicate that it is a 'bad' method, but rather may be the result of a lack of sufficient information regarding subsurface conditions, underestimation of the degree of difficulty associated with the project (e.g., lack of surface access) or unrealistic optimism by the user regarding the project's true impact.

Chapter 8 concludes the work by presenting the conclusions from this investigation as well as recommendations for future work. The latter is aimed at transforming the theoretical development of I.M.P.E.C.T into an effective, user-friendly application, as well as further exploration of some of the theoretical aspects of DCUM including problems with multi-origin domain-of-compliance (e.g., more than one ideal outcome) and further development of a check for the condition of an empty solution set.

1.5 KEY CONTRIBUTIONS

The main contributions of the work in this thesis are four-fold:

1. The development of a comprehensive database that covers the characteristics of seventeen trenchless construction methods and their subclasses for installation of new or in-line replacement of existing underground utilities. To the best of the author's knowledge it is among the most comprehensive database developed to date in North America in this area.
2. Development of a rational approach for estimating the reduction in the degree of uncertainty regarding the presence of specific hazards along the proposed route based on an approximation of the quality and quantity of subsurface data obtained from a given site characterization scheme. The model also estimastes the anticipated cost-benefit ratio from a given level of site investigation effort.
3. Development of the framework for a comprehensive decision-support system for the selection of a construction method for a project involving the construction of new or replacement of existing pipelines and conduits below ground level.
4. The theoretical development and codifying of the Domain of Compliance Utility Model (DCUM), a novel methodology for evaluating competing alternatives that utilize the concept of solution spaces and a modified arc-consistency algorithm.

Additionally, significant related industrial contributions were accomplished during the course of the work. Two such major contributions are the development of a patent pending horizontal sampling device (Allouche et al., 1998; Appendix 'A') and the development of a set of construction specifications for horizontal directional drilling that was adopted by a number of organizations across North America including the California Department of Transportation, Missouri Department of Transportation, the City of Edmonton and the City of San Diego (Ariaratnam and Allouche, 2000).

CHAPTER 2

LITERATURE REVIEW

2.1 DECISION SUPPORT SYSTEMS IN CONSTRUCTION

2.1.1 Introduction

Construction managers are faced with decision-making on a daily basis. While in many cases decision-making is performed based on prior experience, some circumstances require a detailed analysis. Computerized decision support systems can prove to be useful, particularly in situations that are characterized by inherent uncertainty, complexity or multiple objectives and attributes. Decision analysis techniques can play an important role in such situations by assisting a decision-maker in analyzing the problem's overall structure, formulating a systematic evaluation scheme, incorporating preferences and uncertainties and evaluating the overall rating of the various alternatives. Decision analysis techniques provide a means to achieve a better understanding of the decision problem and perform a systematic evaluation process in order to arrive at the optimum solution. During the selection process, decision-makers must consider the anticipated project conditions based on the capabilities and limitations of the various alternatives in order to identify the best method for a specific project. A number of tangible and intangible criteria need to be considered in the evaluation process to arrive at a justifiable decision in many cases (Norris, 1994).

2.1.2 Overview of Decision Support Algorithms

Approaches to the development of decision support algorithms were classified by Moselhi (1998) under the following three categories:

1. Algorithmic procedures, where solutions are obtained essentially by processing numerical data and applying a set of equations in a structured and systematic manner. Fuzzy set theory is included in this category as it can be considered to be a generalization of statistical decision theory.
2. Reasoning by deduction, where solutions are gathered using heuristics and rules-of-thumb based on experience (typically named expert systems).
3. Reasoning by analogy, where solutions are generated based on analogy with similar problems in a holistic manner (i.e., neural networks).

The two latter approaches represent an area known as artificial intelligence.

An expert system, or knowledge-based computer programs, attempt to capture the cumulative knowledge gained by several experts in a particular field and formulate it in a manner that allows a less knowledgeable user to arrive at the same conclusion as the expert given a particular set of parameters. Expert systems employ a series of rules-of-thumb, typically structured in an IF-THEN-ELSE format, to deduct a particular conclusion from the status of a predetermined set of parameters using a heuristic approach. The model presents the user with requests for information and eliminates less likely possibilities by means of reasoning until a final conclusion is reached. As a general rule, expert systems are designed to give an acceptable solution that may or may not be the optimal one.

Neural networks, on the other hand, attempt to mimic the human brain. Neural networks consist of a number of processing elements (nodes) linked with a set of interconnections similar to neural cells and connectors in the human brain. The processing elements can be arranged in various forms depending on the type of network used. Neural networks can be trained to establish a relationship between a particular input and output in the form of weights that are assigned to the various interconnections. The system uses the "experience" gained to provide solutions to new problems. Neural networks are particularly effective for types of problems where input data may be incomplete. This methodology relies on pattern recognition and an inter-variable relationship rather than a structured solution algorithm.

As for algorithmic procedures, a large number of such methods were developed over the past 50 years to suit various applications, mainly in economics and social studies. Three recently emerged approaches, that may be suitable for method selection are the utility theory model, the Analytical Hierarchy Process (AHP) and Constraint Satisfaction Techniques (CST). The first two were widely used in the past for the development of various applications for the selection of construction methods (Moselhi and Sigurdardottir, 1998; Hastak, 1998). CST, on the other hand, is an emerging approach that only in recent years has found application in artificial intelligence, concurrent engineering and business decision-making (Lottaz et al., 1999; Ward et al., 1995). A short description of these methods follows. Additional information regarding AHP and two-dimensional utility theory is given in Sections 2.2.1 and 2.3.2, respectively. The constraint satisfaction technique is covered in detail in Chapter 7.

The philosophy behind AHP is that in decision-making, both data and experience play equally important roles. AHP uses a three-level hierarchy-based model that reflects the goals and concerns of the decision-maker. The hierarchy is arranged in a descending order from the overall focus to the criteria, subcriteria and alternatives. The hierarchy is then systematically evaluated using pairwise comparison of various criteria, matrix manipulation and eigenvalue computations to obtain a final score for each alternative. AHP provides a systematic methodology to organize tangible and intangible factors and provides a structured, yet relatively simple, analysis algorithm to the decision-making problem. AHP is particularly suitable for comparison between two competing alternatives, but can become cumbersome when a large number of technologies, each with many specific attributes, need to be evaluated simultaneously.

Utility theory, developed for economic models in the mid-1800s, is now a well-accepted methodology for the development of evaluation models (Willenbrock, 1973). It enables one to attach a measure to attributes (objective as well as subjective) as a function of the user's resources and his inclination towards risk. For every attribute to be considered during the decision-making process a utility function is constructed that represents the increase in the attribute's value as a function of the user's corresponding utility value; i.e., the user's ability/desire to accommodate that increase based on his current level of resources. With the utility functions constructed one can calculate the total utility value for a given alternative by adding the individual utilities associated with the values of the various attributes. Utility functions are non-negative and non-decreasing and the attributes considered must be statistically independent due to the additive nature of the model.

Much of the knowledge in Civil Engineering is expressed in terms of constraints, including design codes, behaviour models and construction specifications. Many of the previously described evaluation techniques require a transformation of this knowledge into other forms such as rules and directed relationships. Direct use of constraint representation results in an easy to understand model that requires little preliminary data manipulation. Constraint Satisfaction Problems (CSPs) consist of a set of variables and a set of constraints - numerical relationships that dictate the allowable values (domains) of the variables. Sets of constraints ($R_1 \ldots R_n$) and variables ($V_1 \ldots V_m$) together with their permissible domains ($D_1 \ldots D_n$) can be represented using graphs called constraint networks. A solution to a CSP is a subset that contains all acceptable members to the constraints. The process of defining the solution subspace that satisfies all of the constraints is termed a constraint check and the values within this subset are called consistent.

2.1.3 Applications of DSS in Construction Engineering

A significant number of automated and semi-automated decision-support systems have been developed over the last twenty years by various researchers to assist construction professionals in areas such as bid/no-bid and bid markup decision (Moselhi et al., 1993; Ahmad, 1990), renovation of existing facilities (Reddy et al., 1993), identification of automation needs (Guo and Tucker, 1993), equipment selection for transporting and placing of concrete (Alkass et al., 1994), foundation design and construction (Yeh et al., 1991; Mohan, 1990) and building construction scheduling (Kahkonen, 1994).

Another area that has attracted the attention of researchers is the need to evaluate and compare competing construction techniques for particular project conditions. The following sections present a state-of-the-art review of decision support models developed for the evaluation and ranking of construction methods in general, and trenchless construction methods in particular. While evaluation methodologies utilized in these models include several algorithmic procedures (e.g., AHP; utility theory), neural networks and expert systems, no model that utilizes Constraint Satisfaction Techniques (CSTs) was found.

2.2 APPLICATIONS OF DSS FOR METHOD SELECTION

The goal of DSS in this category is to aid construction practitioners in the assessment of anticipated project conditions based on the capabilities, limitations and benefits of available techniques in order to determine the best method for a specific project. While in many cases it is impractical to develop a system capable of considering all of the factors that influence the selection of the most suitable construction method, a good model should simulate real world situations by considering key parameters and all available alternatives. While some of the models proposed use only qualitative analysis to evaluate the various attributes associated with different alternatives (McKim, 1998), others attempted to quantify the various attributes involved (Moselhi and Sigurdardottir, 1998). Still other researchers proposed methodologies to account for the risks associated with various construction alternatives (AbouRizk et al.,1994; Ioannou, 1988). The following sections describe four generic approaches for the evaluation of construction methods proposed by various researchers over the past decade. All models can handle multi-attribute problems but the amount of detail and degree of subjective input from the user can vary significantly.

2.2.1 AUTOCOP (Hastak, 1998)

AUTomation Option evaluation for COnstruction Processes (AUTOCOP) is a general decision support system developed to assist construction managers in systematically evaluating whether to choose a conventional construction process or an automated system for a given project. AUTOCOP utilizes the Analytical Hierarchy Process (AHP) to analyze tangible and intangible criteria involved in the decision problem. The model enables the user to evaluate two methods at a time with respect to five groups of criteria:

1. Need-base (e.g., labour intensiveness, skill requirements, repetitiveness).
2. Technological (e.g., material handling, precision work, quality requirements).
3. Economic (e.g., productivity improvement, initial investment, operating costs).
4. Safety/Risk (e.g., operating hazards, performance reliability).
5. Project specifics (e.g., site constraints, schedule constraints).

A list of the criteria and subcriteria arranged in a hierarchy to establish their interdependencies, is shown in Figure 2.1. A a linkage is shown between all the subcriteria and the available alternatives to illustrate that the relevance of each subcriterion should be evaluated with respect to each alternative.

AUTOCOP consists of two models: a group decision model and an analytical model. The group decision model was developed to assist the primary decision-maker in collecting and evaluating opinions of other team members in regard to establishing the relative preference among criteria, subcriteria and alternatives. Team members are evaluated with respect to four criteria: 1) technical knowledge, 2) experience, 3) current project knowledge, and 4) knowledge about the firm. The evaluation of the team members is then used to weigh the input provided by each team member and to arrive at a group decision.

The analytical model is designed to evaluate the input provided by the group members and to establish the group's preference among the various criteria, subcriteria and alternatives. The Analytical Hierarchy Process (AHP) utilizes a pairwise analysis in which the importance of each criterion (or subcriterion) is assigned in comparison with each of the other criteria/subcriteria/alternatives at that level (e.g., A1/A2 = 2/7). The relative weights are used to construct the relative weight matrix. The analysis starts at the criteria level and is carried out down the hierarchy. The comparison matrix for the criteria level is evaluated to establish the weight vectors, i.e., eigenvectors, corresponding to the maximum eigenvalue. The analysis is then moved to the next level. The weight vectors obtained at the second subcriteria level are weighted by multiplying them with the weight of the corresponding criteria from the preceding level, thus defining weighted priority vectors. A similar procedure is employed at each level of the hierarchy. Aggregate vectors are computed by adding the weighted priority vectors for all subcriteria related to a particular criterion. Next, the aggregate matrix is prepared where the rows consist of the aggregate values for each criterion as calculated for each of the alternatives (represented by the columns in the matrix). The final priority vector is computed by adding the column entries of the aggregate matrix. The final priority level defines the preference among the alternatives with respect to all of the criteria and subcriteria. The larger the value, the more suitable is the method for the project under consideration based on the user's preference, expertise and experience.

Sensitivity analysis can be performed by modifying the weights (or preferences) in the comparison matrix and repeating the analytical process to obtain a final priority vector. AUTOCOP was utilized by Gokhale et al. (2000) to develop a decision model to evaluate competing alternatives for sewer pipeline installation. Two case studies involving the analysis of two gravity interceptor projects in Westfield, Indiana, and Dayton, Ohio, were presented and evaluated using the model.

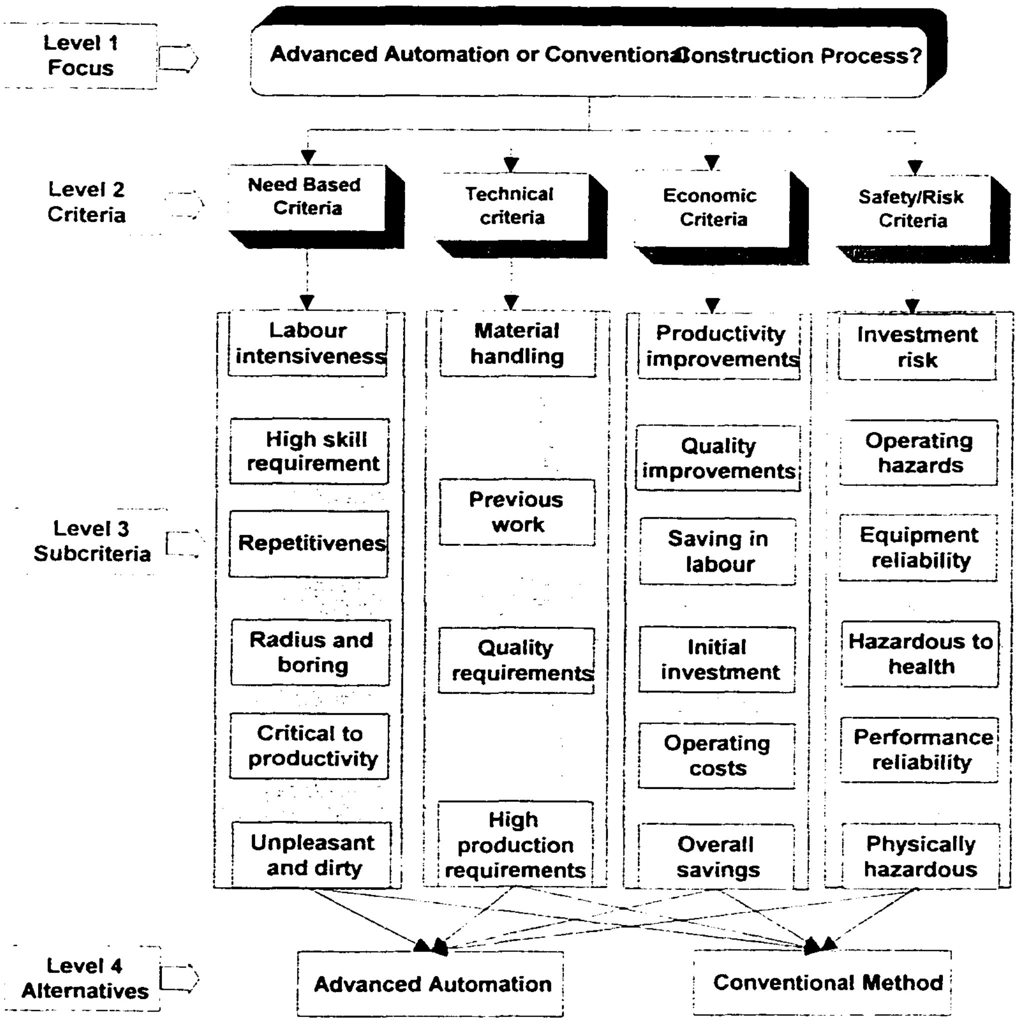

Figure 2.1 Sample Hierarchy for Analyzing Decision Problem (after Hastak, 1998)

2.2.2 Analysis and Evaluation of Alternative Technologies (AbouRizk et al., 1994)

AbouRizk et al. (1994) presented a quantitive approach for the comparison of alternate technologies based on the objectives of the decision-maker and the merit of the various technologies. The approach involved identification of the basic risk factors associated with each technology, setting the criteria to be used in the analysis, quantification of the risk factors with respect to each criterion, and aggregation of all criteria's scores for each alternative to produce a final score for the alternative.

AbouRizk et al. (1984) proposed a modification to the multi-attribute decision-making process (MADM) as described by Zimmerman (1987) by incorporating the effect of risk factors on the various criteria and performing a pairwise comparison of the relative importance of every criterion in comparison to others utilizing the AHP (Saaty, 1978). An outline of the proposed method follows.

Step 1: Alternative technical options, criteria to be used in the analysis and risk factors associated with the alternatives are identified.

Step 2: The AHP method is used to perform a pairwise comparison among the criteria, and the relative importance of a given criterion to others is obtained by calculating the preference weight vector [CW] corresponding to the maximum eigenvalue of the resulting matrix.

Step 3: A procedure similar to Step 2 is performed to establish the relative importance of each risk factor to others with respect to each criterion.

Step 4: Criteria preference weights and risk factors are combined to form a single matrix [S] with m columns and k rows representing the various risk factors and criteria, respectively. The matrix's entries represent the relative weights of the risk factors with respect to the various criteria.

Step 5: Technical alternatives are evaluated by obtaining the impact of risk factors on each alternative in a similar manner to the way that the relationship between the risk factors and criteria were established in Step 3 and Step 4 to give the matrix [A]. The matrix entries represent the relative weights of the risk factors with respect to the various technical alternatives.

Step 6: Using [CW] and [S], developed in Step 2 and Step 4 respectively, the risk-factor weight vector [F] is computed for each risk factor.

$$[F_j]=[S_j]\cdot[CW] \quad \text{where } j = 1\ldots m \qquad \text{(Eq. 2-1)}$$

Using the matrix [A] from Step 5 a score is computed for each alternative by weighting the elements with the corresponding risk-factor weight F_j.

$$[AW_j]=[A_j]\cdot[F_j] \quad \text{where } j = 1\ldots m \qquad \text{(Eq. 2-2)}$$

Alternatives are then ranked according to their respective value of AW score. The authors pointed out that the model is sensitive to changes in criteria weights and care should be exercised when selecting the scale used for measurement.

2.2.3 Evaluation of Advanced Construction Technologies (Skibniewski and Chao, 1992)

Skibniewski and Chao (1992) proposed an analytical approach for assessing the intangible aspects of technical innovations. The proposed model utilizes a modified cost-benefit analysis approach where instead of comparing the monetary costs and benefits of each alternative technology the model compares the relative influence or contribution of each alternative on the decision-maker's goals and concerns using the analytical hierarchy process (AHP) technique.

The first stage in the model calls for the decomposition of the problem into a hierarchy with enough levels to include all attributes in order to reflect the goals and concerns of the user. Tangible (e.g., initial investment; operating costs) as well as intangible attributes (e.g., quality improvements; risk) are considered. Pairwise comparison of criteria and sub-criteria, calculations of eigenvector values and aggregation of comparison results were performed following the classical AHP method in a manner similar to that described in (Saaty, 1980) and in Section 2.2.1. The authors stressed the need to perform a sensitivity analysis to evaluate the impact of attribute ratings in the comparison matrices on the alternatives' overall scores.

2.2.4 Evaluation of New Building Technology (Lutz et al., 1990)

Lutz et al. (1990) developed a generic model for the evaluation of new building technology systems based on technical, economical and risk considerations. The evaluation scheme consisted of a series of worksheets designed to assist the user in: 1) assigning a rating to the various criteria and subcriteria; 2) computing an overall rating for the proposed system, and; 3) a comparison index with alternate methods.

The technical assessment phase included a technical attribute matrix that contains a list of pertinent technical subattributes. Rates and weighting factors are assigned to each of the subattributes based on an expert opinion. Weight attributes are determined by multiplying the subattribute rating by the assigned weighting factor. The sum of the weighting factors for all of the relevant subattributes gives the score for a given attribute. The total weighted factor for all of the attributes, defined as the technical assessment factor (TAF), is calculated by the following equation:

$$TAF = \frac{\sum_{i=1}^{n} W_i A_i}{2} \qquad \text{(Eq. 2-3)}$$

where W_i = attribute weighting factor; A_i = attribute scores; and, i = number of attributes.

An economical assessment and a risk assessment are performed in a similar manner to obtain the saving assessment factor (SAF) and the risk assessment factor (RAF). The overall measure of the estimated utility of the technology, OAF, is equal to the product of the previously computed factors:

$$OAF = (RAF) \times (TAF) \times (SAF) \qquad \text{(Eq. 2-4)}$$

Generally, technologies with OAF equal to or greater than unity are considered promising while those OAF less than unity should be dropped from the evaluation program.

Another measure is the technology index (TI) defined as:

$$TI = \frac{OAF_{Proposed}}{OAF_{Existing}} \qquad \text{(Eq. 2-5)}$$

A TI value less than 1.0 indicates that the technology currently utilized by the user is superior to the proposed one, while TI values greater than 1.0 indicate that the proposed technology offers overall benefits beyond current practices and should be considered for either trial or full scale implementation.

The authors acknowledge the tedious manual process associated with the method and recommend that the system be fully automated. Also, concern was expressed due to the heavy reliance on expert opinion that may introduce subjectiveness into the evaluation process. Thus, the development of a more numerically objective decision analysis framework for the implementation of innovative technologies was recommended.

2.2.5 Knowledge-based Approach to Modular Construction (Murtaza et al., 1993)

Murtaza et al. (1993) proposed a decision-making methodology that assists in deciding during the conceptual design stage whether or not to use modular construction techniques in building a petrochemical or power plant. The methodology was automated in the form of a computerized knowledge-based system that performs a feasibility analysis based on five factor categories: location; labour; organization structure; project characteristics and project risks. The system also performs an economic analysis to evaluate the impact of modularization on schedule and cost. The model utilizes a three-stage analysis scheme, namely prescreening, a detailed feasibility study and an economic study. During the prescreening and detailed feasibility stages a weighted-factors method is used to determine initial feasibility and evaluate the confidence of recommending the utilization of modular construction on a particular project. The final stage is an economic analysis performed using a heuristics driven knowledge-base containing decision-rules on modularization with an database containing past records of relative cost and schedule advantage from realized modular construction projects.

2.2.6 Neural Network Method for Estimating Construction Technology Acceptability (Chao and Skibniewski, 1995)

Chao and Skibniewski (1995) developed a neural network based approach for predicting the potential acceptability of new construction technologies such as slip-form paving machines and specialized excavators by the construction industry. The acceptability of a technology is defined as the proportion of users that choose to use the technology for a particular operation instead of a status-quo technology. The first step involves identifying all alternative technologies for a particular operation and, as well, those factors that are relevant to the success of the operation in question. The performance characteristics for each alternative construction method are evaluated using Saaty's analytical hierarchy process (AHP) and are stored in a vector comprised of eigenvalues. The eigenvalues are then used as input parameters to train a neural network to recognize general performance-acceptability relationships that are applicable across multiple applications. The trained network can then be used to predict the acceptability potential of a new technology given its performance attributes.

2.3 APPLICATIONS OF DSS IN TRENCHLESS CONSTRUCTION

This section reviews previous work performed by researchers in North America and Europe directed at the development of methodologies for selecting the most appropriate construction method for a project involving the installation or rehabilitation of buried infrastructure networks. Some of these methods were transformed into computerized systems while others involved a series of tables and charts.

2.3.1 Iseley and Gokhale, 1997

Iseley and Gokhale (1997) conducted an extensive literature review of trenchless methods for the National Cooperative Highway Research Program (NCHRP). The review included a summary of available technologies, range of applications, basis of application selection, design factors, construction processes and sample applications and specifications. The data collected was arranged in a series of tables that was designed to assist highway engineers in the selection of trenchless methods for specific projects based on:

1. Product characteristics - length, diameter and material.
2. Design parameters - depth, grade and line tolerances.
3. Site Characteristics - soil conditions, work space constraints, and
4. Cost.

Other considerations such as social costs and possible damage to surrounding structures and utilities were also discussed. The proposed Trenchless Technology selection process is shown in Figure 2.2.

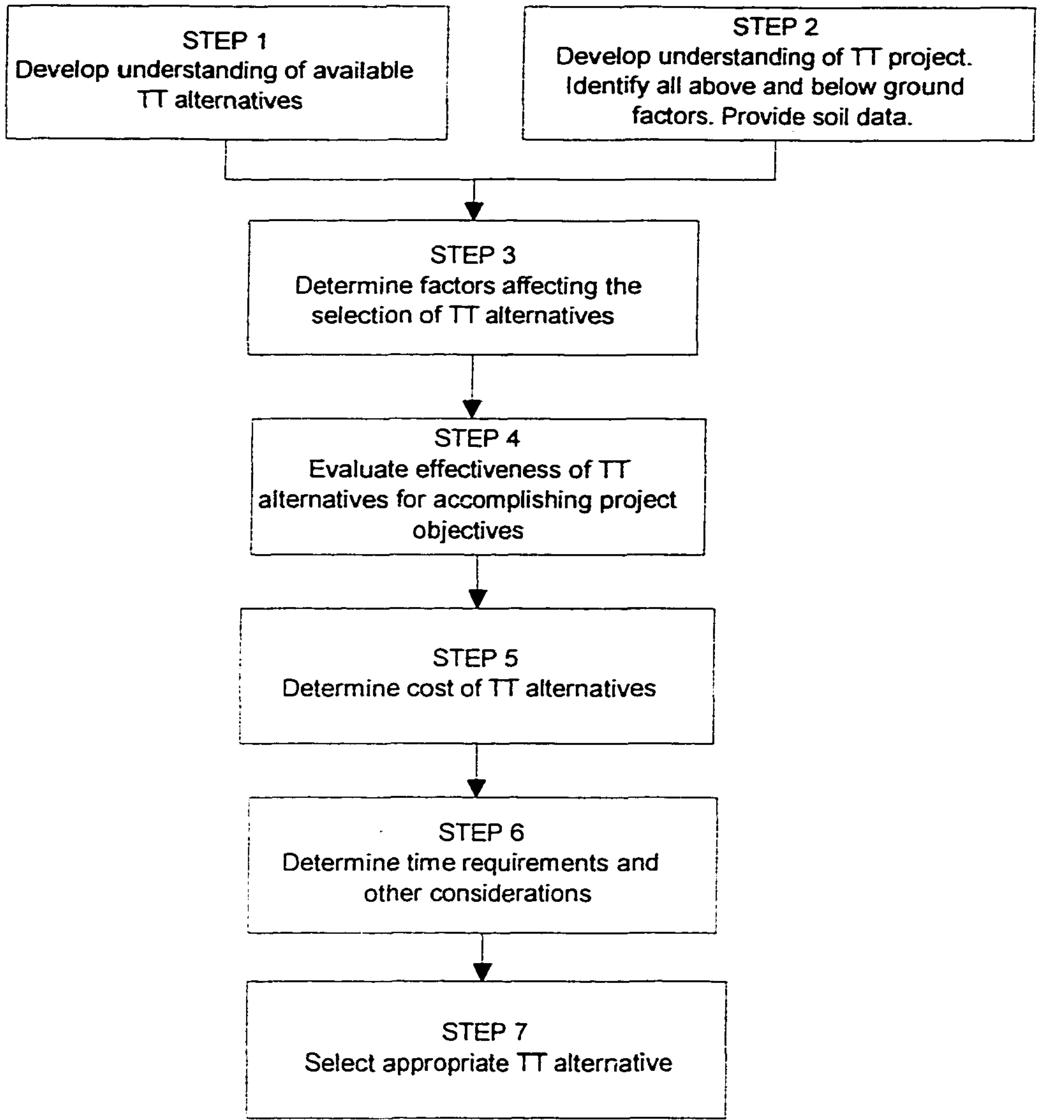

Figure 2.2 Trenchless Technology Selection Process (after Iseley and Gokhale, 1997)

2.3.2 REHAB SELECT (Moselhi and Sigurdardottir, 1998)

REHAB SELECT is a decision support system used to select a trenchless pipeline rehabilitation technique developed by Moselhi and Sigurdardottir (1998). This expert system was developed using an object oriented programming approach that employs a generic decision support system based on a multi-attribute utility model. REHAB SELECT consists of two major components, a method database and a method selection module. The database contains information regarding the specifics of twenty-two different trenchless rehabilitation or replacement methods, including general product/method description, applications, cost, complexity of installation, product durability and state of the technology. Additional general information can be obtained from an on-line glossary of trenchless terms.

REHAB SELECT's main component is the method selection module that utilizes an additive multi-attribute utility model. In the decision-making process two types of attributes are considered, namely qualifying attributes and preference attributes. Qualifying attributes can be described as characteristics or parameters that are deterministic in the method selection process, thus qualifying or disqualifying a particular method in the case of a specific set of project characteristics. Examples of qualifying attributes are type of installation (e.g., gravity-based, pressurized-pipe) and discharge changes. Preference attributes are those characteristics and parameters used to rank those methods that meet the minimum requirements (i.e., satisfy all of the qualifying attributes). Examples of preference attributes are innovation (how inclined is the user towards new technologies), cost, durability and social costs.

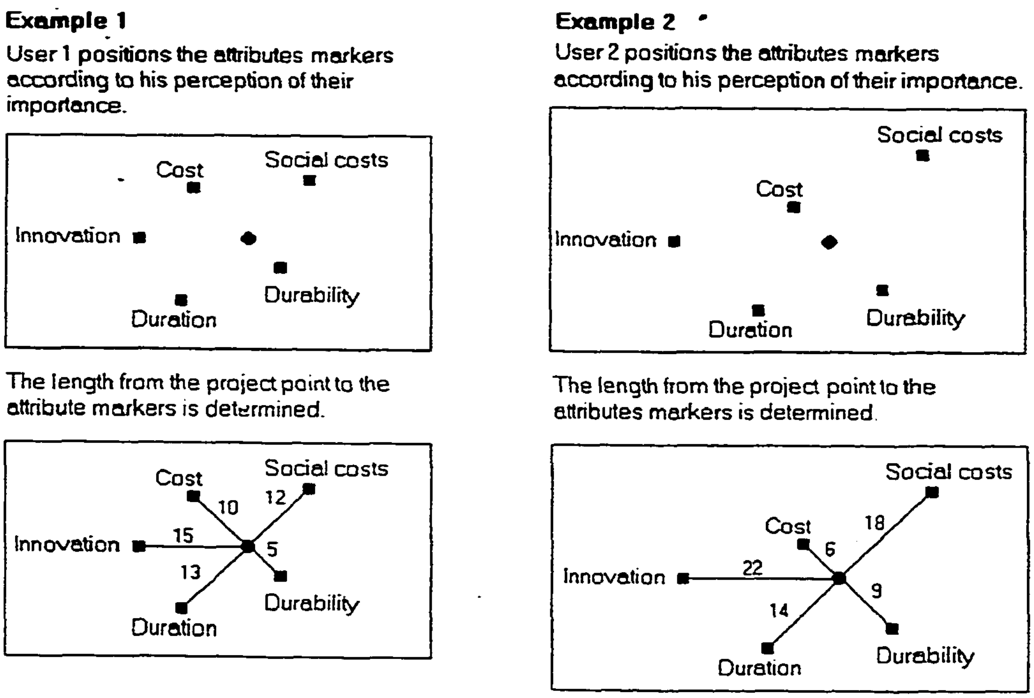

Figure 2.3 Weight Diagram Method (after Moselhi and Sigurdardottir, 1998)

REHAB SELECT's processing model uses an additive multi-attribute utility model in order to establish the overall value of the various alternatives and to select the one that most closely suits the user's needs and inclinations.

The method selection process consists of six steps:

1. Obtain information from the user regarding the project particulars such as type, size, length and depth of the proposed installation.
2. Eliminate construction methods whose qualifying attributes do not meet project requirements.
3. Determine the relative weights of each preference attribute to be taken into consideration. The user is asked to position markers that represent different attributes around a point at the centre of the diagram that represents the project (Figure 2.3). The closer the attribute's marker to the project point, the greater its

relative importance to the user. The program determines the respective length for each attribute and assigns relative weights based on the sum of the reciprocal lengths.

4. Construct the utility functions for each attribute. The utility function represents the satisfaction of the decision-maker over the range of achievement levels attainable for each attribute. REHAB SELECT uses the following form of normalized exponential utility function (Eq. 2-6):

$$U_i(t) = \frac{1 - e^{-\gamma t}}{1 - e^{-\gamma}} \Big| \gamma \neq 0 \qquad and \qquad t = \frac{x - x_0}{x_{100} - x_0} \qquad \text{(Eq. 2-6)}$$

where:

$U_i(t)$ = utility function of attribute i with a value from 0 to 1.

t = the value of attribute i at which the utility function U is evaluated.

γ = risk adversity factor; the higher its value the higher the risk aversion. For $\gamma = 0$ the curve is linear.

x_0 = the value of attribute i that the user associates with a zero utility value, U=0.

x_{100} = the value of attribute i that the user associates with a maximum utility value, U=1.

The values of x_0 and x_{100} are user defined and the value of γ is between 0 and ∞.

5. Determine the utility value for each method using the relationship

$$U_i = \sum_{j=1}^{n} W_j \times u_{ij} \qquad \text{Eq. (2-7)}$$

where:

Wj = relative weight assigned to the j[th] attribute (from Step 3)

u_{ij} = value of the j^{th} attribute utility function associated with the i^{th} method (from Step 4); and

n = is the number of attributes associated with the i^{th} method.

Equation (2-7) assumes statistical independence, preferential independence and utility independence among the various attributes.

6. Selection of the most suitable method is based on the utility value obtained. The higher the utility value the closer the method is to meeting the user's requirements.

2.3.3 GSTT Guide for Pipe Construction and Rehabilitation (Stein , 1998)

The German Society for Trenchless Technology (GSTT) in collaboration with industry, developed a basic guide for pipe construction and rehabilitation in the mid-1990s. This guideline enables the user to evaluate (for specific problems) available methods to repair, renovate or renew utility networks using either open trench or trenchless construction methods. In order to make the guide user friendly and readily available, the printed version was converted to a computer-based, expert-rule-base decision support system. The system features multi-media capabilities with a limited in-house library of various methods and hyperlinks to external sources of information.

2.3.4 Computer System for the Selection of Trenchless and Conventional Methods for Underground Utilities (Russel et al., 1997)

Russel et. al. (1997) proposed a framework for the development of a knowledge-based method selection tool designed to serve the utility installation industry. The system attempts to capture the experience and expertise of practising individuals in the form of rules and reasoning mechanisms for determining when a method statement is feasible in a specific construction context. The components of the proposed computerized environment were classified under three main headings, namely standard level, project level and the interface between the two. Standard level refers to the documentation, representation and manipulation of knowledge and data that describes the physical characteristics of different types of projects and the methods available to carry them out. The project level consists of four components namely:

1. Physical view - representation of the physical project including project requirements, surface and a subsurface conditions and multi-media description of the project and site.
2. Process view - methods statement along with a plan and schedule, that integrates these methods into an action plan.
3. Performance evaluation - a multi-criteria assessment of the Process View in terms of cost, performance, risk, environmental impact and safety.
4. Output - findings from the performance evaluation process, project method statement, project plan and schedule; resource summary; and, cost summary.
5. The researchers outlined several research challenges that still need to be overcome, including the development of a standard 'language' for describing methods and their components and the development of an evaluation module that can accommodate different user perspectives. To date, only selected components of the systems have been implemented.

2.3.5 Selection Method for Trenchless Technology (McKim, 1997a)

McKim (1997a) proposed a selection method for evaluation of trenchless technologies utilizing a hierarchy-based model that separates the elements of the technology under consideration into physical components that describe their capabilities, and compares these capabilities to the project's requirements. The model does not address economic considerations, but rather focuses on the technical issues associated with the decision. Additionally, the model is limited to applications associated with the rehabilitation and replacement of gravity-driven hydraulic systems.

The method selection process uses a classification system that identifies the needs of the system and the capabilities of available methods and separates them into a three-level hierarchy, namely performance, function and capacity. Two performance attributes are used to describe the system's performance characteristics, namely flow performance (i.e., hydraulic surface, internal diameter and grade) and structural performance (i.e., pipe material, wall thickness and pipe diameter). Functionality for both the system and the method is characterized as either repair or upgrade. Capacity refers to a need to address the entire pipe (MH to MH) versus an isolated section.

A preliminary analysis is performed to determine if any of the two preference attributes (flow or structural) needs attention. If the performance of the system is inadequate (e.g., below-design flow rate; structural deficiencies) the specific attributes that impact the system performance are identified. Next, the functional requirements (repair or upgrade) and capacity requirements (full or partial) of the system are established. Once the needs have been identified, the method selection process proceeds to identify which methods (if any) are suitable, by defining the capabilities of the candidate methods and matching them with the system's predetermined needs.

The capability of each available rehabilitation or replacement technique to repair, upgrade or replace part of the entire pipe is summarized using a method capability code. For example, the abbreviation (H,G,P/U,R/P), indicates that the method is capable of performing an upgrade (U) or rehabilitation (R) on the hydraulic surface (H), pipe geometry (G) or pipe properties (P) for part of the pipe length (P). The method selection process ensures that the set of characteristics of the selected method includes the set of characteristics identified in the need analysis. The selection process does not intend to identify the optimal method, but rather to provide the decision-maker with a starting point by eliminating some of the more inappropriate methods.

2.3.6 Decision Tool for Micro-Tunneling Method Selection (Ueki et al., 1999)

Ueki et al. (1999) proposed an expert-rule-based decision procedure for the selection of a microtunneling construction method for a particular project. The method enables the user to check and calculate the suitability of various microtunneling boring units for a particular set of project conditions. The decision procedure was implemented using the MS Excel spreadsheet application.

The model input includes depth of invert, inside diameter of pipe, maximum single drive length, level of GWT below ground level, site conditions (i.e., urbanized; environmentally sensitive; road/utility crossing(s); contaminated ground; and utility conflict) and soil information. The user is asked to choose up to two possible soil types in the soil information section from seven alternatives (e.g., rock, sand, clay, silt), as well as to indicate the expected size of boulders to be encountered during the boring process, if any.

The method selection process consists of three processes: method selection, pipe selection and machine selection. The method selection process determines which of the following three alternatives, traditional open cut, slurry-based microtunneling or earth pressure balance (EPB) microtunneling is the most suitable for the project at hand. This is done by comparing project parameters and anticipated site conditions to two criteria, namely technical difficulty and economic feasibility. Technical difficulty is represented by a minimum cover to diameter ratio of three and a minimum height of cover = 1.5m, while economic feasibility is represented by a minimum installation depth of 6m and cover of 4.5m. Project conditions that satisfy both criteria are given a rank of three, while those that satisfy only the technical criteria are assigned a rank of two. If project design characteristics do not satisfy the technical criteria, the project is assigned a rank of one.

As for site conditions, the project is assigned to one of four categories ranging from normal (Rank = 4; no special objection to excavation) to extremely sensitive (Rank = 1; excavation nearly impossible), based on a score that is equal to the sum of the applicable site condition weighting factors (SCW). For example, a pipe to be installed in a site located in the downtown area (SCW = 1) beneath existing utility lines (SCW = 1) will have a total score of 2, and will be classified as highly sensitive (Rank = 2). The third parameter used in the determination of the most applicable construction method is the location of the GWT with respect to the pipe invert. Once again, a rank is assigned based on whether the pipe invert is to be located more than 3m above the GWT (Rank = 1), less then 3m above the GWT (Rank =2) or below the GWT (Rank = 3).

Based on the combination of the depth rank (1-3), site sensitivity rank (1-4) and groundwater level rank (1-3), feasibility values were pre-assigned to the slurry microtunneling method, EPB microtunneling method and open-cut construction. A sample from the decision data method selection is presented in Table 2-1.

Table 2-1 Decision Data for Method Selection (After Ueki et al., 1999)

Depth Rank	Site Sensitivity Rank	Water Level Rank	Slurry Method	EPB Method	Open-cut Construction
1	1	1	0.9	0.0	0.0
1	1	2	0.8	0.6	0.0
1	1	3	0.7	0.9	0.0
1	2	1	0.6	0.8	0.2
1	2	2	0.5	0.3	0.4
1	2	3	0.4	0.5	0.6
1	3	1	0.3	0.0	0.7
1	3	2	0.2	0.0	0.8
1	3	3	0.1	0.0	0.9
1	4	1	0.0	0.0	0.8

A score of more than 0.8 means that the system recommends the method, while a score between 0.6 and 0.8 implies that while the system recommends the method some difficulties may be encountered. A score below 0.6 implies that the system does not recommend the method. The score for the microtunneling methods is fine-tuned to account for anticipated soil conditions as well as the presence of boulders (if any expected). Adjustment is made using predetermined adjustment factors derived independently for each of the methods. The selection process ends at this point if microtunneling is not a suitable alternative. The model advances to the pipe selection stage if microtunneling is suitable.

The model presents the user with suitable types of pipe based on the required pipe inner diameter, and the user is asked to select a particular pipe type during the pipe selection stage. The microtunneling machine outside diameter is then calculated based on the pipe outside diameter and over-cut requirements. Next, available machines suitable for the project are identified based on machine type, outside diameter, allowable jacking loads, and required drive length. The system lists and ranks up to six suitable microtunneling machines according to an overall confidence score.

Shortcomings of the above described decision system include: 1) failure to consider other trenchless technologies aside from microtunneling; 2) only a limited number of parameters are considered: due to the system structure no additional parameters can be considered by the user; and, 3) the use of predetermined evaluation scores for a particular set of parameters implies low system flexibility in terms of accommodating new factors.

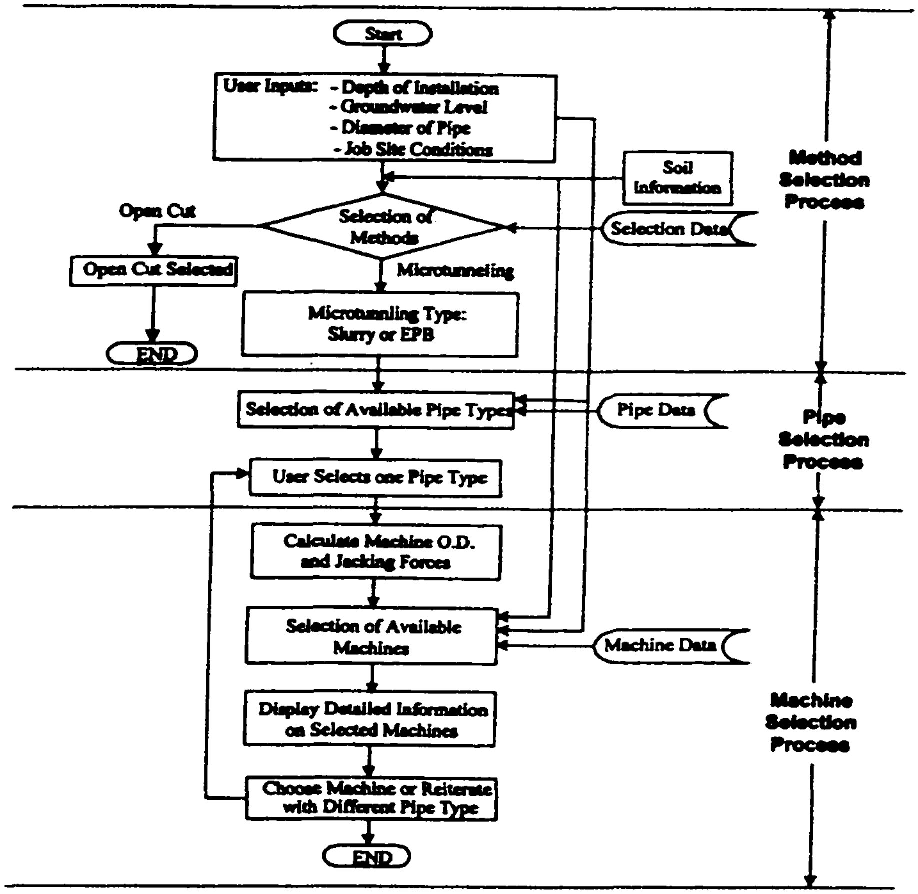

Figure 2-4 Microtunneling Selection Process (after Ueki et al., 1999)

2.3.7 Selection Process for Trenchless Pipeline Rehabilitation Methods (Norris, 1994)

Norris (1994) expressed concern regarding the tendency of municipalities to allow price to determine the final decision regarding the method used on rehabilitation projects. He argued that this tendency is primarily due to a lack of the experience and technical expertise needed to evaluate the various relining methods available in the marketplace for sewer line repair/upgrade. Norris (1994) described key considerations in the evaluation process of pipe rehabilitation methods. These included the nature of the pipe deficiency; expected service life of the rehabilitated pipe; material properties (e.g., resin/base material); the pipe's diameter/length/ovality; the number of service connections; the acceptable reduction in diameter; environmental impact; and cost. Owners are advised to consider all of the above factors when selecting the correct technical solution for a particular problem.

2.3.8 Decision-Making Mechanism for Sanitary Sewer Management (TTC, 1999)

The Trenchless Technology Center, located at Louisiana Tech University, is developing a Sanitary Sewer Management System (SSMS) that will combine functional and structural assessment of the condition of the host pipe; deterioration curves for various types of pipes; and cost studies to recommend the most economical rehabilitation method based on a given service life duration. The model is currently under development and research focuses on collection of the data needed to develop the deterioration models. The data collected is summarized in the form of a structural condition matrix that provides the likelihood that a particular pipe will experience a transition from a given condition to another condition over a five-year period. A Markovian chain-based model will be utilized at the next stage to predict the pipe deterioration rate based on its current condition, operating conditions and the nature of the surrounding soil.

2.3.9 Decision Support System for Drilled Shapts (Fisher et al., 1995)

Fisher et al. (1995) developed an heuristic, knowledge-based expert system to assist decision-makers in the design and construction of drilled shafts named DS'2. DS'2 consists of five modules including three expert systems (DS'2-GEO, DS'2-CON and DS'2-DIAG), a database (DS'2-COST) and a simulation program (DS'2-SIM). DS'2-GEO utilizes user input regarding geological data to suggest a suitable drill shaft construction method based on 475 heuristic rules that cover various combinations of geologic and site-specific conditions. The end result of DS'2-GEO are recommendations to the user specifying which construction methods the system perceives to be most suitable for the project at hand, and the degree of confidence the model associates with each recommendation. DS'2-CON uses 145 rules to provide specific recommendations on the construction details for the method selected in DS'2-GEO, including specifications and tolerances for shaft dimensions, inspection procedures, choice of excavating tools, suitable types of drilling fluids, suitable types of casings and more.

DS'2-COST provides the user with an estimate of excavation, steel placement and concreting costs as well as the expected total cost for the project. The cost database was constructed from published data as well as costs collected from specific projects. DS'2-SIM simulates the drilled shaft operation using several possible conventional methods and automated technologies in order to predict expected duration for costing purposes. The fifth module is DS'2-DIAG, a diagnostic expert system developed for the purpose of evaluating strategies for adjusting construction methods when unanticipated subsurface conditions are encountered in the field. DS'2 utilizes the EXSYS Professional expert system shell in combination with several spreadsheet, database and graphic software packages.

2.4 DISCUSSION

Methodologies developed for decision support and evaluation models in construction can be classified using three general categories namely: algorithmic procedures (mathematical models), reasoning by deduction (i.e., expert systems) and reasoning by analogy (pattern recognition).

For the purpose of method/equipment selection, pattern recognition techniques (e.g., neural networks) are the least utilized. This can be mainly attributed to:

1. The need for a large amount of data to train the network due to the wide range of available methods and the large number of factors that need to be considered.
2. Difficulties in accounting for user preferences, a major consideration in decision-making.
3. A lack of intermediate feedback as the model only provides the user with output at the end of the run. This "black box" approach is not easily accepted by decision-makers, as the model recommendations are difficult to support and verify.

Reasoning by deduction methods, better known as knowledge-based (or expert) systems, are commonly used as a platform for the development of evaluation models for construction methods. Examples of such models covered in this review include those by Ueki et al. (1999), Fisher et al.(1995), Russel et al. (1997) and Stein (1998).

Knowledge-base models may serve as an effective tool for providing insight into various aspects of a single speciality construction operation as demonstrated by Fisher et al. (1995). However, the application of such systems to wider problems such as the selection of the most suitable construction method for an underground construction project may prove to be a tedious and cumbersome task as the number of rules and statements could be very large and the flow of data through the decision tree structure could be complex. Additionally, expert systems have limited flexability. Adding new factors or alternatives require a rather extensive modification of the code language, a task unlikely to be undertaken by the average user.

As for mathematical evaluation models for construction techniques, the first generation of such models was adopted from traditional generic theories in the field of economics, and was based primarily on monetary values. Two such methods are: 1) return on investment (ROI) and, 2) net present worth (NPW). However, these models can be deemed ill-suited for comparison of competing construction methods and evaluation of the economic feasibility of new construction methodologies, as they are incapable of accounting for intangible benefits and unfavourable factors such as long-term opportunities, business competitiveness and risk (Sullivan and LeClair, 1985; Miroslav and Chao, 1992).

Researchers have realized the shortcomings of monetary value-based models and have turned to another powerful concept developed in the field of economics – utility theory. The utility theory is capable of accounting for tangible as well as intangible attributes and provides an ideal tool for incorporating user preferences into the decision-making process. Moreover, the concept of expected utility theory enables the user to incorporate probability, and thus uncertainty, into the model, which better reflects real-world situations. On the down side, decision-making models based on the utility theory necessitate the establishment of utility functions that represent the decision-maker's value scales for different criteria or goals. Often utility functions are difficult to formulate and can change over time. Also, in decision models based on utility theory, risk is treated as perception rather than using a rational assessment method. This may result in non-optimal decisions (McKim, 1997). Utility models are additive in nature, which implies independence among the various attributes. However, real world situations involve a trade-off among attributes as the utility value of a particular attribute may best be expressed as a function of the value of one or more other attributes. Finally, the inflexibility of this approach causes difficulty in adapting to changes in either the attributes or the utilities of the model.

The analytical hierarchy process (AHP) techniques attempt to overcome the need for the expensive and time-consuming collection of data required for the development of a utility model. Similar to the expert system, AHP uses the practical experience and knowledge of various professionals and experts, and streamlines it towards a particular conclusion or recommendation. The method enables preference input, can handle tangible as well as intangible attributes, encourages group discussion and multi-expert input, can account for risk associated with the various alternate methods (AbouRizk et al., 1994), conducts computations in a systematic manner and the mathematics involved are rather simple.

AHP's weakness is in its strength, the complete reliance on expert rating and pairwise comparison. Given the same problem, experts with different backgrounds and experiences will often give different ratings during the pairwise comparison, although they may intend to describe the same strength relationship. Moreover, some of the pairwise comparison may be irrelevant resulting in an arbitrary pairwise comparison of preferences (Haddawy and Hanks, 1998). Another source of concern is the manner in which the attributes ratings and the scale used in the analysis are derived, as the results of the analysis might be sensitive to the value of the rating and the scale used (Hastak, 1998; AbouRizk et al., 1994). Another possible disadvantage may include difficulty in interpreting the model output. For example, if the final scores from two competing options are 0.45 and 0.43 respectively, to what degree is the former preferred over the latter, and what is the confidence interval associated with that score? Finally, if the score is less than 1.0, there is no guarantee that either option fully satisfies the user's requirements.

The above literature review and discussion demonstrated that even well-established and widely accepted decision-making methodologies such as rule-based expert systems, utility theory and the AHP suffer from some inherent shortcomings when used as a framework for the development of construction methods evaluation models. As a result, model performance is limited even before development commences. A summary of leading decision-making algorithms in terms of scope, structure, data requirements, capability and flexibility is presented in Table 2-2.

Consequently, it was decided to seek an alternate methodology for the purpose of developing a construction method evaluation model for underground construction. It was envisioned that the model be generic in nature, flexible, mathematically and logically sound, simple to use, and allow trade-offs among preference attributes to be conducted in a quantitative manner. To accomplish this, a new concept named the Domain of Compliance Utility Model (DCUM) was developed. The model combines features from Zimmerman's (1987) multi-attribute decision making (MADM) two stage process, AHP, as well as multi-dimensional utility theory together with constraints satisfaction techniques in order to achieve the above target characteristics. It also recognizes that the development of a single model that features all the modules, sub-modulus and databases required to cover every aspect associated with the planning, design and construction of underground pipe installation/replacement projects is beyond the scope of a single research program, or even a single agency.

Instead, it was decided to focus on the development of the evaluation and decision-making procedure, that will serve as the kernel of the system. External modules can then be attached to provide estimates of duration, direct cost, social costs, etc. A detailed description of the proposed model is provided in Chapter 6 and 7. A comparison of the features of the proposed model, named Innovative Modular Procedure for Evaluation of Construction Technologies (I.M.P.E.C.T), with existing method evaluation models reported in this chapter is presented in a matrix format in in Table 2-3

Table 2-2 Features of Methodologies Used for Comparison of Competing Methods

Method	Account for User Preference	Intermediate Feedback	Amount of Data	Type of Data		Flexibility	Risk Analysis
				Subjective	Objective		
Neural Network	N	N	Large	Y	Y	Low	Y
Expert System	Y	Y	Large	Y	Y	Medium	Y
Analytical Hierarchy Procedure	Y	Y	Low	Y	N	High	Y
Utility Theory	Y	Y	Large	Y	Y	Medium	Y
Return on Investment (RIO)	N	Y	Medium	N	Y	Low	N
Net Present Worth	N	Y	Medium	N	Y	Low	N
Constraint Satisfaction Technique	Y	Y	Medium	Y	Y	High	Y

Table 2-3 Comparison of Various Method Evaluation Models

Model	Method	Flexibility	Handle Multiple Methods	Tangible / Intangible Attributes	Trade-off Among Attributes	Uncertainty	Automated
AUTOCOP	AHP	High	X	3	X	X	3
AbouRizk et al., 1994	AHP	High	X	3	X	3	X
Skibniewski & Chao, 1992	AHP	High	X	3	X	X	X
Lutz et al., 1990	---	Low	X	3	X	X	X
Iseley et al., 1997	---	Low	3	X	X	X	X
Rehab Select	Utility	High	3	3	X	X	3
GSTT	Expert-system	Medium	3	3	X	X	3
Russel et al.	Expert-system	Medium	3	3	X	X	3
McKim, 1997	AHP	Low	3	X	X	X	X
Ueki et al., 1999	Expert-system	Low	X	3	X	X	3
DS'2	Expert-system	Medium	X	3	X	3	3
I.M.P.E.C.T	Utility / CST	High	3	3	3	3	3

CHAPTER 3

OVERVIEW OF TRENCHLESS TECHNOLOGIES

3.1 BACKGROUND

The majority of the models developed for evaluation of trenchless technology construction methods either deal with the rehabilitation of existing underground pipes (McKim, 1997a; Moselhi and Sigurdardottir, 1998) or with a single construction methodology (Ueki et al., 1999; Fisher et al., 1995). None of the models covered in the literature review deal explicitly with the large number of trenchless construction methods that can be used for new installations. The need to develop such a model was expressed by several Canadian municipalities (Ariaratnam et al., 1999), as well as by a number of consultants and other practising professionals across western Canada. Thus, it was decided that a model capable of evaluating trenchless construction methods for new installations would be a suitable application for demonstrating the proposed Domain of Compliance Utility Model methodology. Aside from meeting current industry needs, the decision was based on the following considerations:

1. Numerous construction methods were developed over the past decade for trenchless installation of new pipes and conduits. Thus, the ability of the proposed approach to screen and rank multiple technologies must be tested.
2. The decision process required consideration of many attributes, both tangible and intangible. Once again, the ability of the model to handle multiple attributes measured using various scales and units of measurement will be tested.

3. The increased awareness of environmental impact, social costs and business losses necessitates a total impact assessment, rather than a simple comparison of direct cost and schedule. The ability of constraint satisfaction techniques to express permissible domains of one attribute in terms of the values of other attributes provides the flexibility required for a comprehensive total impact assessment.
4. The need to address risk and uncertainty associated with various construction methods was recognized by previous researchers (AbouRizk et al., 1994; Ioannou, 1988). This is particularly important when selecting an underground construction method because the nature of the subsurface conditions may prevail. The need to account for the uncertainty associated with the subsurface conditions poses another challenge to the model.

The next section provides an overview of the current level of utilization of trenchless technology methods in Canadian municipalities as well as future trends and needs. Next, a short description of various trenchless and open-cut methods used for the installation or replacement of pipelines and conduits is provided, enabling the reader to gain a better understanding of the various technologies available in the marketplace, their capabilities and limitations. The review presented in this chapter serves as the basis for a summary of the operating and constructability characteristics of trenchless construction methods presented in Chapter 4.

3.2 TRENCHLESS CONSTRUCTION IN CANADA

In 1997, a survey examining deployment of trenchless construction methods was sent to 87 municipalities across Canada that represented a wide range of population size, geological conditions and geographical areas. The purpose of the survey was to provide an indication of current and future trends in the application of trenchless construction technologies in the municipal arena including type and frequency of technologies employed, percentage of projects that employed trenchless technologies, and contractor selection methods (Ariaratnam et al., 1999). The survey attempted to sample municipalities of all sizes and all regions of the country. Responses were received from 53 municipalities (a response rate of 61%), including Canada's major metropolitan centres - Toronto, Montreal and Vancouver. Table 3-1 summarizes the breakdown of survey respondents by region, while Table 3-2 presents the breakdown by size of populations.

Table 3-1 Distribution of Surveys and Responses by Region

Region	Number of Surveys Distributed	Number of Surveys Received	Response Rate
Western Canada	37	26	70%
Prairies	16	7	44%
Central Canada	31	17	55%
Maritimes	3	3	100%
Totals	87	53	61%

Table 3-2 Distribution of Responses by Municipality Size

Population Range	Number of Responses	Percent of Responses
Under 20,000	14	26.4%
20,000 – 49,999	10	18.9%
50,000 – 99,999	9	17.0%
100,000 – 249,999	4	7.5%
250,000 – 499,999	6	11.3%
500,000 – 999,999	7	13.2%
Over 1,000,000	3	5.7%
Total Responses	53	100.0%

This review is concerned only with findings related to current degree of utilization of trenchless technology in Canada, industry rate of growth, dollar value associated with the industry and the level of utilization of individual construction methods.

The survey indicated that trenchless construction methods are known to most municipalities across the country as 94% of the respondents indicated that their municipality had utilized trenchless technologies at least once in the past. Furthermore the use of trenchless technology is on the rise and is increasingly viewed as an alternative to conventional open-cut methods. To evaluate the growth of the trenchless construction industry in Canada's municipal sector, one can compare its level of utilization by municipalities for new construction and for rehabilitation of existing lines in the years 1992 and 1997. A comparison of the percentage of trenchless technologies utilized in new construction in Canadian municipalities in 1992, versus 1997 is presented in Figures 3.1a and 3.1b, respectively. Ten percent of the respondents indicated that they used trenchless technologies in 10% or more of their new construction projects in 1992. In 1997 this fraction increased to approximately 28%. This represents a 280% increase in the use of trenchless technologies in new construction over a five-year period. Similarly, Figures 3.1c and 3.1d illustrate the percentage of all repairs and rehabilitation to pipeline and utility conduits utilizing trenchless construction. Approximately 18% of the respondents indicated that they used trenchless technology in 10% or more of their projects in 1992. In 1997 this figure rose to 37% indicating a growth of 205% over the five-year period in the area of trenchless technology rehabilitation. From the results of the survey, it is apparent that there has been a significant increase in recent years in the utilization of trenchless methods of construction in Canada for both new and rehabilitation projects.

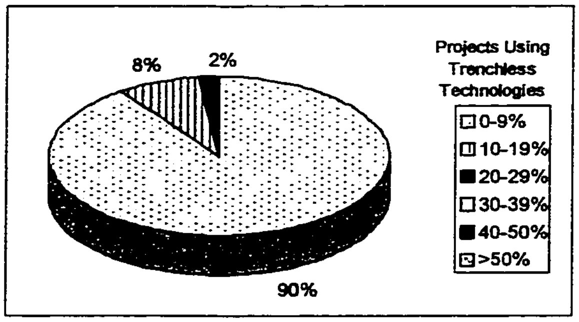

Fig.3.1(a) New Construction 1992

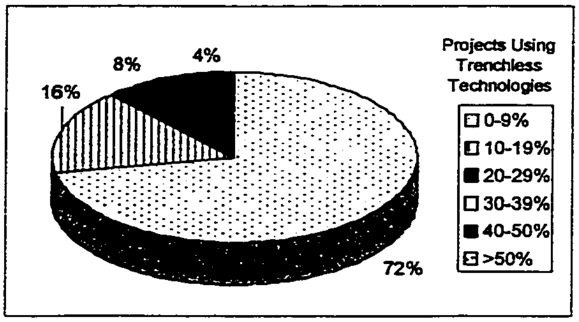

Fig.3.1(b) New Construction 1997

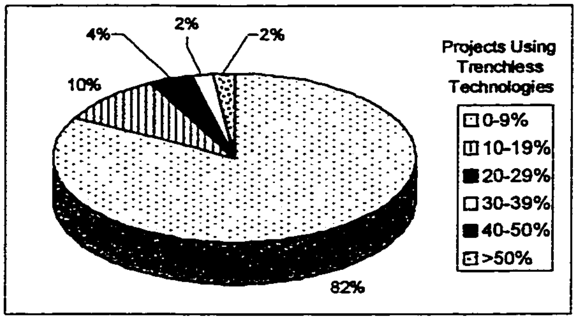

Fig.3.1(c) Rehabilitation 1992

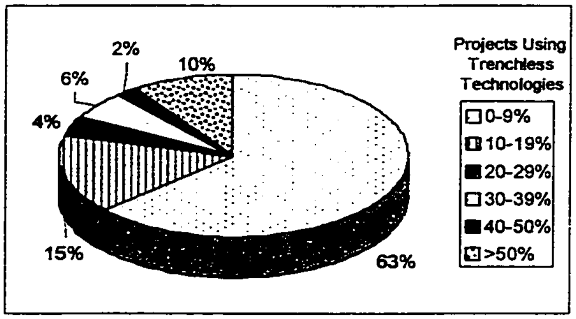

Fig.3.1(d) Rehabilitation 1997

Figure 3.1 Comparison of the utilization of trenchless technology in new and rehabilitation construction in 1992 versus 1997 (After Ariaratnam et al., 1999)

The distribution of the utilization of various trenchless methods is displayed in Figure 3.2 and presents the percentage of respondents that have used each technology. It can be seen that lining of pipe (LP) was the most widely used method with 66% of the respondents indicating that they had used this method. The second most popular technology was auger boring (AB) with a 47.2% response rate. This is not surprising considering that these two technologies were among the first trenchless technologies to be introduced, with auger boring dating back to the 1940's while pipe lining started to gain acceptance in the early 1970s. Pipe jacking (PJ) was the third most popular technology (43.4%), followed closely by pipe scanning and evaluation (PS&E) (41.5%). Among the new trenchless construction methods horizontal directional drilling (HDD) is the most widely used technology, followed by pipe bursting (PB). The least utilized technology was microtunneling (MT) (22%). The specialty nature of microtunneling and the limited number of contractors who have the capacity to perform this type of work may account for the lower utilization of this method. Robotic spot repairs (RSR) were used by nearly 25% of the municipalities surveyed.

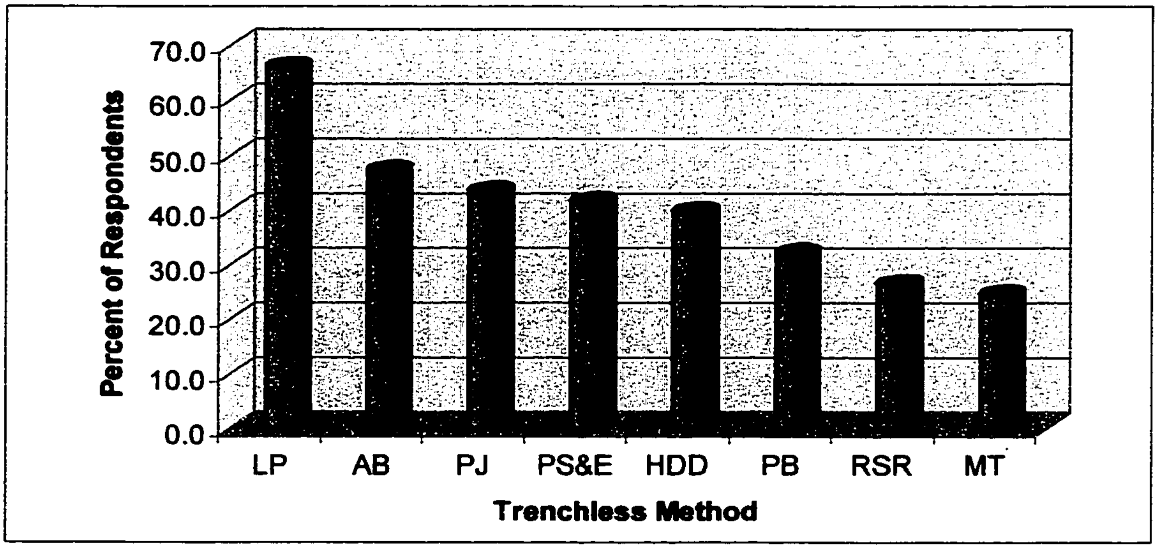

Figure 3.2 Percent of respondents that utilized a given trenchless technology (After Ariaratnam et al., 1999)

As for the volume of trenchless construction undertaken by Canadian municipalities, the survey collected data on the number of linear metres of pipe that was installed or rehabilitated using trenchless methods in the 1996-97 construction season. Data were collected on the volume of installed pipe in linear metres for horizontal directional drilling, auger boring, pipe bursting/splitting, pipe jacking, microtunneling and lining of pipe, as indicated in Figure 3.3.

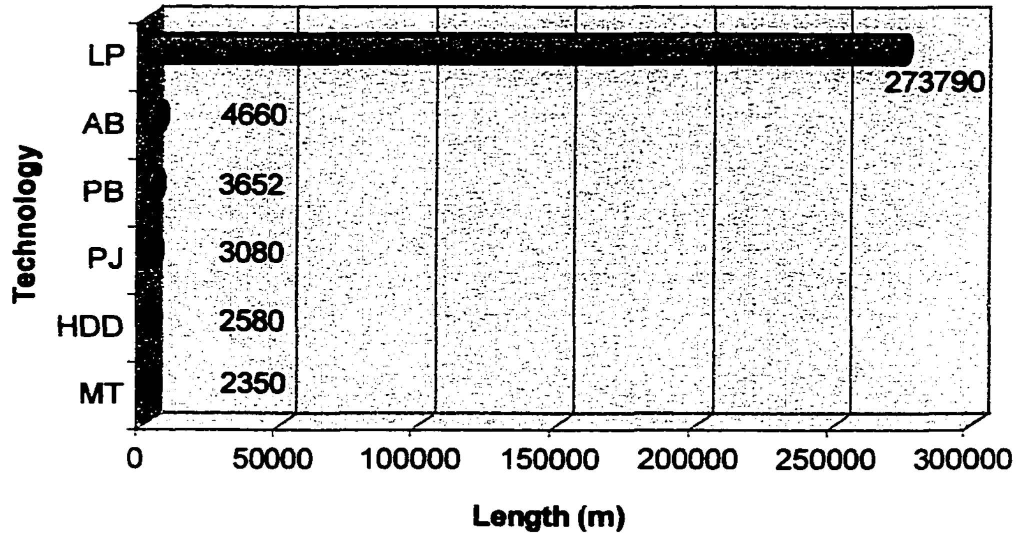

Figure 3.3 Linear meters of pipe installed (After Ariaratnam et al., 1999)

The survey indicated that of the six trenchless construction methods considered, 94% of the total length of pipe installed or rehabilitated was completed using pipe-lining methods. The five other trenchless methods accounted for the remaining 6% of the total length installed/replaced. The large proportion of lined pipe installed may be attributed to the familiarity of the pipe-lining technology and the fact that specifications and construction practices for pipe lining are well established in many parts of the country. It should be noted that the term lining-of-pipe comprises nearly a dozen separate methods including cure-in-place, fold and form, segmental lining and more.

To obtain a cost estimate of the total annual budgets spent on trenchless construction projects in Canada, the budgets for new and rehabilitation construction were converted into budget per capita. Population size information was obtained from the 1996 Canadian census (Statistics Canada, 1997). The mid-range value of the budget categoriy s[pppecified by each municipality was used in producing the budget per capita figure. Figure 3.4 illustrates the distribution of budget per capita for new construction, while Figure 3.5 illustrates the distribution of budget per capita for rehabilitation.

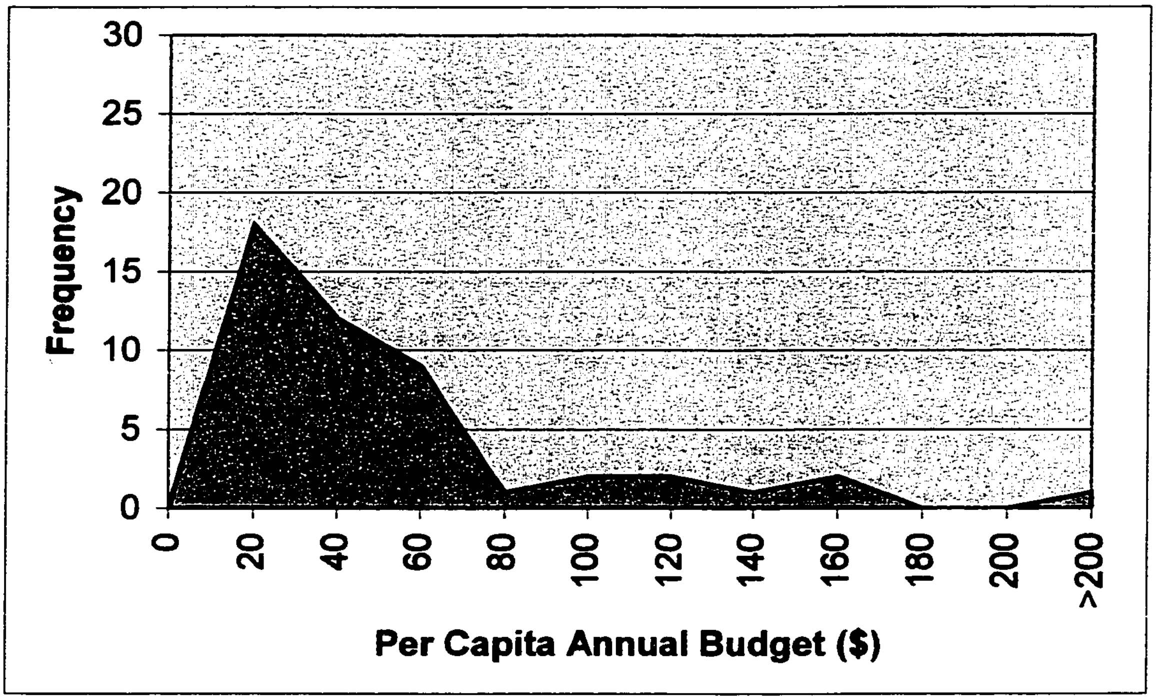

Figure 3.4 Per Capita Budget for New Construction (After Ariaratnam et al., 1999)

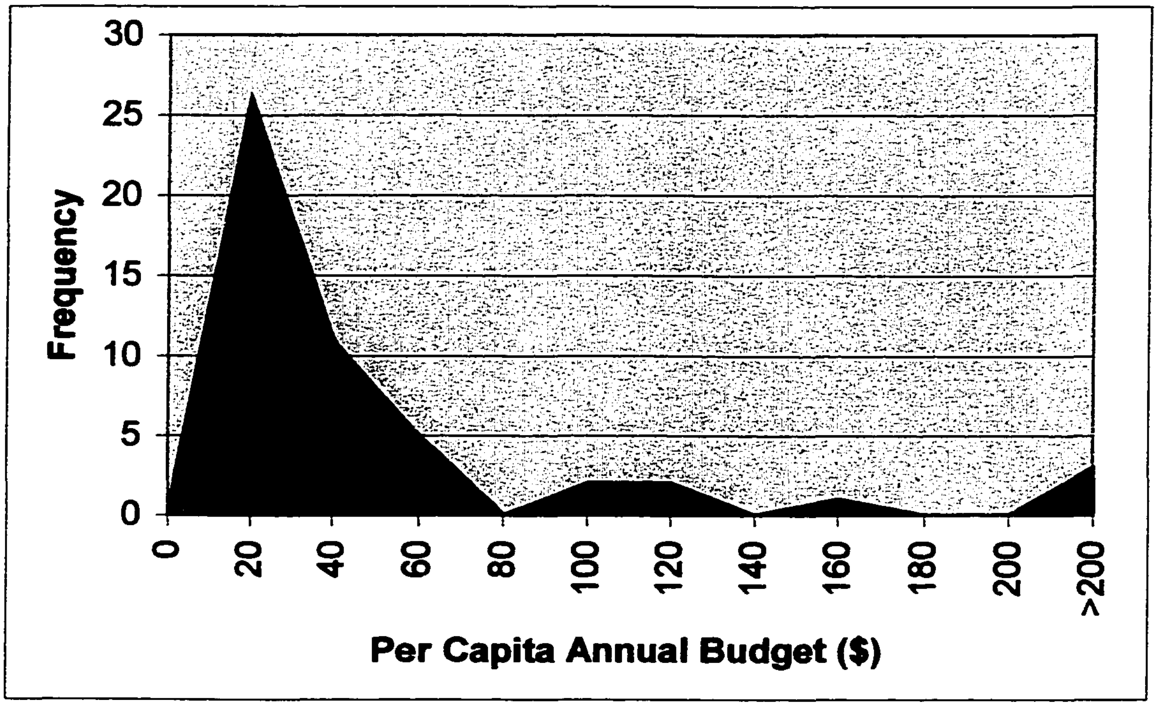

Figure 3.5 Per Capita Budget For Rehabilitation Construction (After Ariaratnam et al., 1999)

The distribution of data for both figures is skewed to the left, with few values greater than $200/capita. These values are considered to be isolated cases that do not reflect the true nature of the distribution. The distribution for new construction reveals an average per capita budget of $55.34, with a standard deviation of $123.52 and a median value of $29.68. The rehabilitation distribution has an average per capita budget of $48.59, a standard deviation of $98.09 and a median of $18.21. The statistical analysis implies that, in general, municipalities are spending a greater portion of their annual budget on new infrastructure rather than on rehabilitation.

Because of the presence of several extreme values (over $200/capita), the median value may better describe the per capita spending for new construction and rehabilitation instead of the average value. Using median values of $29.68 and $18.21

the approximate value of the new construction and rehabilitation markets in Canada can be estimated to be 900 and 550 millions dollars, respectively. The annual expenditure on trenchless construction projects was derived by multiplying the median value by the population of each municipality and by the mid-range value of the percentage of trenchless projects of the total number of projects performed by the municipality. The product represents the total expenditure on trenchless construction projects by the survey respondents. This value was then multiplied by the ratio of the total Canadian population to the sum of the population in the surveyed municipalities to obtain an approximation of the total expenditure on trenchless construction projects by Canadian municipalities. The values computed for new construction and rehabilitations were 65 and 93 millions, respectively. It can be seen that while the new construction market is nearly double the size of the rehabilitation market, the majority of spending on trenchless projects occurred in the rehabilitation market. This conclusion is in agreement with Figure 3.5.

3.3 OVERVIEW OF TRENCHLESS CONSTRUCTION METHODS FOR INSTALLATION OR REPLACEMENT OF UNDERGROUND PIPELINES

3.3.1 Introduction

The use of trenchless techniques dates back to the 1860s when the Northern Pacific Railroad Company pioneered the use of pipe jacking techniques. By the 1930s, reinforced concrete pipe ranging in size from 1070 mm to 1830 mm in diameter had been installed using this technique. Thereafter, other methods of trenchless construction began to be used including auger boring (1946) and impact moling (1962). (Ariaratnam et al., 1999).

A new wave of trenchless development took place around 1960 in response to the changing needs and economics of utilities and society, as a national effort was made to provide all unserved communities with utilities. Technologies such as rod pushing and slurry horizontal drilling were developed during this period. A second move towards the use of trenchless technologies for the installation and replacement of existing utilities occurred in the mid to late 1980s as a result of higher standards of living and increasing industrial and commercial demands. The focus this time was on underground construction in highly urbanized areas, where competition for limited underground space and the need to minimize surface disruption made cut-and-cover construction methods undesirable. The installation of pipelines that extended for appreciable distances in urban environments first became possible with the introduction of microtunneling in North America in 1984. Pipe bursting/splitting and horizontal directional drilling, both oil field technologies that were adopted in the municipal arena in the early 1990s, brought a new dimension to underground construction. It was now possible to replace or install new conduits from 25 mm to 1200 mm in diameter quickly, with minimal surface disruption, at a cost that was comparable or lower than open excavation. The rapid growth in popularity of trenchless construction encouraged the development of a large number of new technologies and variations of existing methods, each with its own advantages and limitations. The following section provides a short description of seventeen trenchless construction methods capable of installing new pipes or replacing existing ones. These methods were categorized under four major headings: horizontal guided drilling and boring methods; pipe jacking methods; soil displacement methods; and, in-line replacement methods. In addition, three types of open-cut construction method are also described – plows, trenchers and backhoes. As trenchless construction is an alternative to open-cut methods, it is important to recognize and properly evaluate the capabilities of open-cut methods in order to justify the utilization of a trenchless construction method. Chapter 4 provides a detailed summary of the technical and operational features of these technologies in a tabular format.

3.3.2 Horizontal Guided Drilling and Boring

3.3.2.1 Horizontal Directional Drilling (HDD)

Perhaps the fastest growing technology in the trenchless industry is Horizontal Directional Drilling (HDD). HDD has grown from 12 operational units in 1984 to more than 2000 units operating in 1995 in North America (Kirby et al., 1997). The equipment and installation techniques used by HDD contractors evolved by merging technologies from the utility and oilfield industries. Currently, a wide range of directional boring units exists in the marketplace, from mini drilling rigs that are used for the installation of 50 mm utility conduits to maxi rigs that are capable of installing 900 mm high pressure transmission lines. The installation range is determined by several parameters including rig size, soil conditions, and product diameter. Installations as long as 1830 m in length have been successfully completed (Allouche et al., 1998b).

In the HDD method, a bore is launched from the surface and the pilot bore proceeds downward at an angle until the necessary depth is achieved. The path of the bore is then gradually brought to the horizontal, and the bore head is steered to the designated exit point where it is brought to the surface by following a curved path. A directional monitoring device located near the head of the drilling string is used to track the position of the drilling head. After the pilot string breaks the surface at the exit location, the bit is removed from the drill string and replaced with a back-reamer. The pilot hole is then back-reamed, enlarging the hole to the desired diameter while simultaneously pulling back the product pipe behind the reamer (Fig. 3.6).

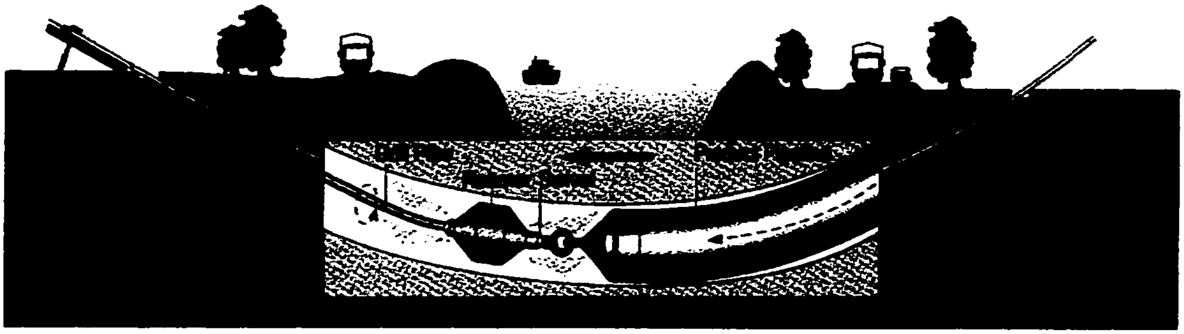

Figure 3.6 Typical Pullback Operation (after DCCA, 1994)

During the boring process, drilling fluid is injected under pressure ahead of the advancing bit. The drilling fluid stabilizes the borehole; cools the electronics located in the front of the drill string; suspends and transports the cuttings to the surface; and then reduces the shear strength of the soil-fluid mixture to enable easier displacement during the pull-back operation.

During the drilling process, the bore path is traced by interpretation of signals sent by electronic sensors located near the drill head. At any stage along the drilling path the operator receives information regarding the position, depth and orientation of the drilling tool that allows him to navigate the drill head to its target. Accuracy of tracking the drill head varies according to the method and type of equipment used and ranges between 2%-5% in terms of the drill head's true depth (Allouche et al., 1998b). Current HDD equipment can operate in a wide range of soil conditions, from extremely soft soils to full-face rock formations with unconfined compressive strengths of 28 MPa. Allouche et al. (2000) reported the results of a survey of 49 directional contractors across North America. The contractors were asked to provide information regarding cost and productivity as a function of pipe diameter and subsurface conditions, respectively. Regression analysis of the average cost data revealed a nearly perfect linear relationship (R^2 = 0.98) that provides the following expression:

Cost, \$ per linear meter = 0.858 x (product diameter, mm) (Eq. 3.1)

Productivity values for various types of soils are given in Figure 3.7.

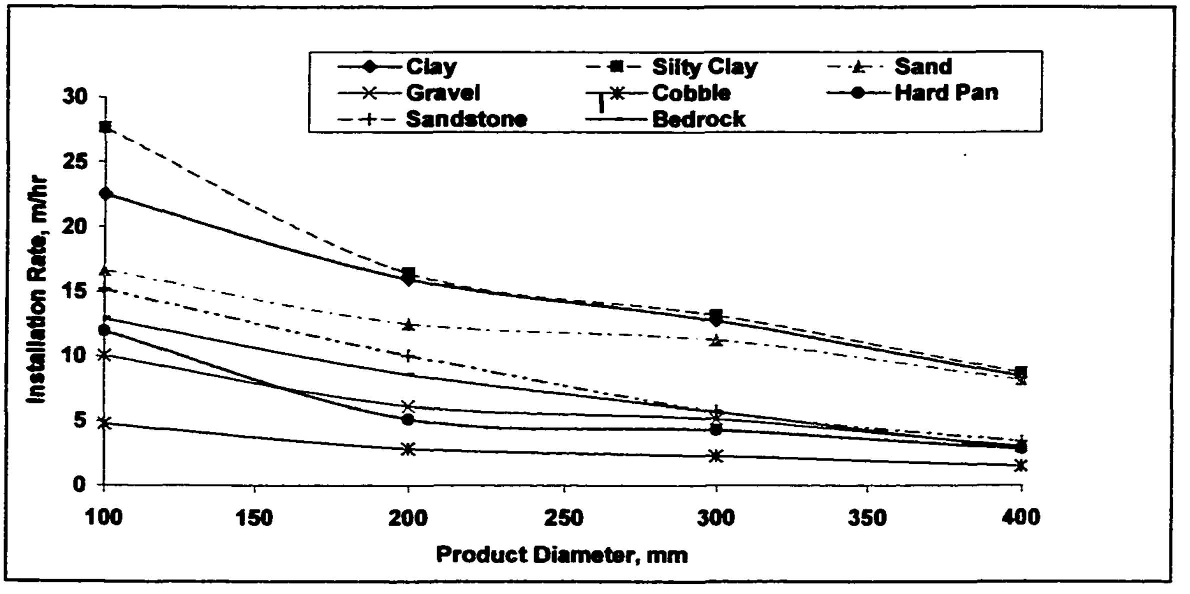

Figure 3.7 Average Productivity (Lm/hr) for Various Subsurface Formations

3.3.2.2 Water Jetting Method

These systems use the principle of soil liquefication to create a borehole. A mixture of water and drilling mud is discharged at a high pressure through jetting nozzles located on the steering head thus eroding the soil. The jetting nozzles are aligned only on one side of the steering head. When the drill rods are rotated and pushed ahead, the rods travel in a straight line. When the rods are pushed without rotation, the jetting action will form a void on one side of the steering head that causes the bore to steer in that direction. Once the pilot path has been completed, a reamer is attached between the drill rods and the product to be installed. The entire assembly is then pulled back, maintaining rotation, to the entry pit. It is a relatively simple process that requires no special operator skills. Capital expenditure for the equipment is low in comparison with other directional boring methods. However, there is no way to control the amount of over-cut, and the subsequent creation of an unstable bore and ground settlement. Additionally, the process results in the need to dispose of large amounts of water and muck.

3.3.2.3 Dry Boring

Dry boring units do not use drilling fluids to lubricate the bore-head or stabilize the bore, but instead rely entirely on thrust and rotation generated by the rig. Dry boring machines use a high-frequency pneumatic hammer at the bore head to penetrate and compact the ground for the pilot bore. For small diameter pipe, duct or cable installation (up to 65mm diameter) a cone-shaped reamer is connected directly to the drill rods. The expander is fitted with air jets, fed through the drill string, and high velocity airflow cleans out the bore during back reaming. The expander is rotated and pulled back to enlarge the bore with the pipe attached behind it using a swivel connector and a towing head. A pneumatically powered reaming hammer is used to install pipes from 65 to 250mm in diameter. The percussive effect of the reaming hammer rather than the pulling back force of the machine is the main agent in expanding the bore. No rotation is applied during back reaming. Dry boring is best suited for cohesive soils and rock formations. It is not suitable for loose soils such as dry sand or gravel. Since drilling mud is not used, significant savings are realized since mud recycling and disposal costs, as well as capital costs associated with a mud mixing plant are eliminated. Additionally, since no bentonite is required, there is no risk of drilling fluid escaping the bore into the surrounding formation, or finding their way to the surface (i.e., frac-out), and thus a subsequent environmental impact.

3.3.2.4 Pneumatic/Rotary Directional Air Drilling

This method is similar to dry boring, except that the steering head consists of a steerable rotary drill head. The air rotary drill head utilizes an independent rotation capacity of the cutting tool that is used for steering purposes. This method is particularly suitable for hard ground or rock formations, where it provides penetration rates three to four times higher than conventional drilling-fluid assisted HDD equipment. Air drilling is most commonly used in oil and gas exploration in North America, however in Australia, Europe and Asia it is used extensively for horizontal crossings of high strength rock formations.

3.3.2.5 Auger Boring

Auger boring is the process of simultaneously jacking casing through the earth between two pre-sunk shafts while removing the spoil inside the encasement by means of a rotating flight auger. The casing supports the surrounding soil as spoil is systematically removed. As a general rule auger boring has poor steering capabilities. According to Iseley and Najafi (1997), auger boring can be classified into two methods: (1) Track Type, and (2) Cradle Type. The track type auger boring method consists of a track system, machine, casing pipe, cutting head, and augers. The boring operation is cyclic, as pipe segments and auger flights are added after a prescribed auger flight length is installed. Thrust is developed by hydraulic rams located at the rear of the boring machine. One end attaches to the end of the boring machine while the other attaches to lugs that are connected to the track system. The track gets its thrust capability from a thrust block located at the back of the boring pit. Torque provided by the power source is transmitted to the flight auger and from there to the cutting head located at the front of the casings. No rotation is applied to the casing as it is jacked through the soil by hydraulic thrust rams located at the rear of the machine. Lubrication is used to reduce skin friction and to aid with soil cutting and transport. An additional common measure to reduce skin friction includes an over excavation in the order of 25-50 mm. Pipe diameters range from 200 to 1200mm and installation lengths are typically limited to approximately 100m.

In the cradle type auger boring method, the boring machine and the complete casing auger system is held in suspension by construction equipment (i.e. side-booms, excavators or cranes) as the boring operation is executed. There is no requirement for any thrust structures, however, the entire casing length must be assembled outside the launching pit prior to commencement of the boring operation with the complete auger and cutting head unit placed inside the casing. The entire system is then lowered into position in the bore pit via cranes. Once the desired line and grade of the casing are established, the boring process is performed in a continuous manner until completed. Cradle auger boring is commonly used on petroleum product pipeline projects where large rights-of-way are available.

Figure 3.8 Auger Boring Machine

3.3.2.6 Slurry Horizontal Rotary Drilling Method

This method differs from the auger method in that it uses drill bits and tubing instead of cutting heads and augers. A slurry mixture, transferred to the cutting bit through the drill tubing, is used to keep the drill bit clean and assist in spoil removal. Cutting is done mechanically. The mixture of bentonite slurry and borehole cuttings aids in preventing borehole collapse by exerting counterbalance earth pressure on the borehole walls. The casing or carrier pipe installation is independent of the boring operation, as the product is pulled through the bore upon the removal of the drill tubing. The slurry method can be used to install steel, concrete, fibreglass, plastic, corrugated metal and ductile iron pipes as well as cables. It is most effective for products from 25 to 200mm in diameter. The slurry horizontal rotary drilling method is suitable for cohesive soils as well as unconsolidated, non-cohesive soil conditions.

3.3.3 Pipe Jacking Methods

3.3.3.1 Microtunneling

Microtunneling can be defined as a "remotely-controlled, laser-guided, pipe jacking process that provides continuous pressure to the excavation face to balance groundwater and earth pressure" (ASCE, 1999). The first microtunneling machine (the 'Iron-mole') was introduced in Japan in 1975, however the method was not adopted in North America until 1984, when 200m of 1800mm diameter gravity sewer pipe were installed under I-95 in Fort Lauderdale, Florida (Atalah and Hadala, 1996). More than 250 microtunneling projects have been completed across North America since then, with a total length of pipe installed of nearly 170,000 metres (Myers et al., 1999). Microtunneling machines are laser guided and accurate monitoring and adjusting of the alignment and grade can be performed as the work proceeds. This process is used primarily to install sewer lines with diameters that are less than or equal to 1800 mm in diameter, however larger diameter pipes may be installed using this technique. The pipe is installed between two vertical shafts, named the driving shaft and the receiving shaft and the process involves jacking the pipe with simultaneous soil cutting at the face of the boring head and continuous soil removal to the driving shaft and then to the surface. Pressure balance is maintained at the tunnel face to avoid a cave-in. Steering is achieved by means of an articulated head capable of being deflected in all directions by hydraulic cylinders. A typical microtunneling system is illustrated in Figure 3.9.

The microtunneling method can be divided into two principal categories based on the technique used to transport the excavated material from the face of the tunnel to the driving shaft. The slurry removal method utilizes bentonite as a support medium to transport the excavated material to the surface. Pressure balance at the face is provided by slurry pressure. Microtunneling machines that use the slurry method are capable of installing pipes up to 45 m below the ground surface, and up to 225 metres in length from shaft to shaft. They can handle a wide range of ground conditions ranging from soft clay to rock, above or below the groundwater table. The auger system on the other hand uses a continuous flight auger for spoil removal. Pressure balance at the head is maintained using an earth pressure balance system where the amount of soil entering the boring head is controlled by opening and closing 'gates' at the front of the excavating face. Drive length is limited to 125m. These machines are limited to unsaturated cohesive soils. Typical production rates for either slurry or auger type microtunneling units range between 10 and 20 metres of product installed per day, depending on ground conditions and the diameter of the product installed (Boyce et al., 2000). A regression analysis of productivity values for a number of microtunneling projects reported by Klein et al. (1995), provided the following relationship:

Productivity (m/hr) = 0.6+0.0005 x (Pipe diameter, mm) (Eq. 3.2)

Thompson et al. (1998) reported typical cost data for microtunneling installations of large diameter (300mm) pipes obtained during the period 1997-8. Review of the data revealed that it could be expressed using the following relationship:

Cost ($/m) = 1600+1.28 x (Pipe diameter - 300) (Eq. 3.3)

where the pipe diameter is expressed in millimetres and the cost is expressed in Canadian dollars.

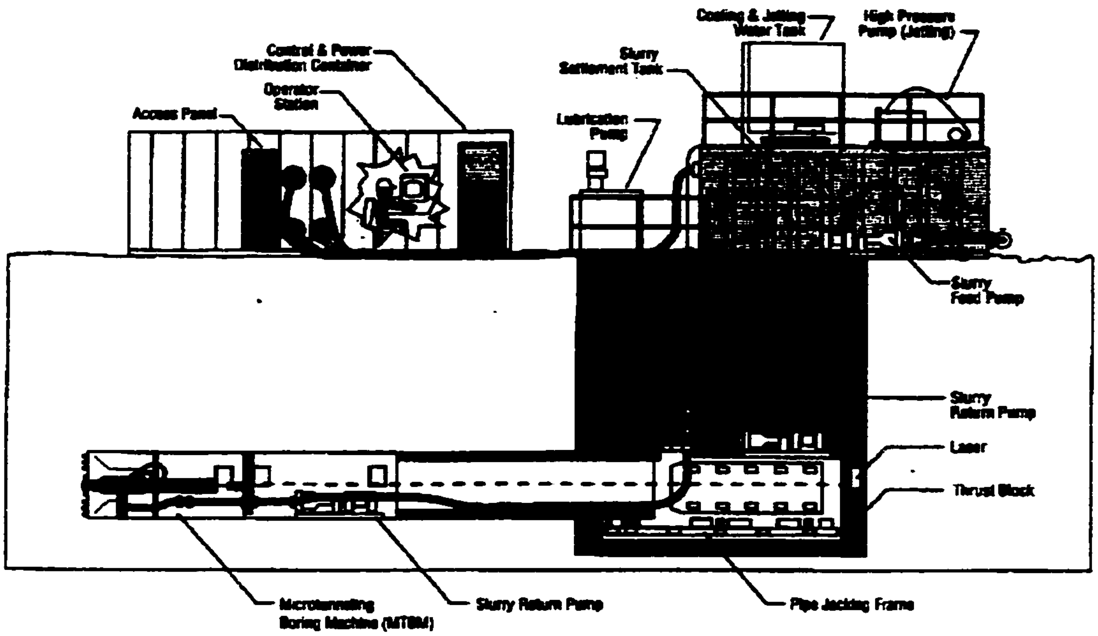

Figure 3.9 A Slurry Microtunneling Boring Machine (after Iseley and Najafi, 1997)

3.3.3.2 Pipe Jacking

Pipe jacking is a man-entry method used for installing a prefabricated pipe through the ground between two vertical shafts, the thrust shaft and a reception shaft. The excavation is performed either manually or mechanically using an auger and takes place in front of an articulated shield that is controlled by hydraulic jacks. The pipe jacking process is a cyclic procedure. A new segment is placed on a cradle at the thrust shaft and high-pressure hydraulic jacks are used to push the entire pipe string through the ground behind a shield at the same time as excavation is occurring within the shield. Next, the hydraulic jacks are retracted and a new pipe segment is added, and the jacking operation starts again. The reaction to the jacking operation is developed using a specially designed thrust block located at the back of the thrust shaft. Small carts, augers or conveyer belt systems are used to remove the spoil. The number of jacks used varies according to the pipe's size, length of installation and anticipated friction due to soil resistance. Typically, two to six jacks balanced about the pipe centreline are used. Intermediate jacking stations may be used for a long installation. The pipe is jacked forward in a step-wise fashion in such cases, from the farthest intermediate station to the thrust shaft.

Pipes ranging in diameter from 1070 mm to 3300 mm are typically installed using this technique (Iseley and Najafi, 1997). Figure 3.10 is an illustration of the components of a typical pipe jacking operation. Bentonite slurry is applied to the skin of the pipe to reduce frictional forces.

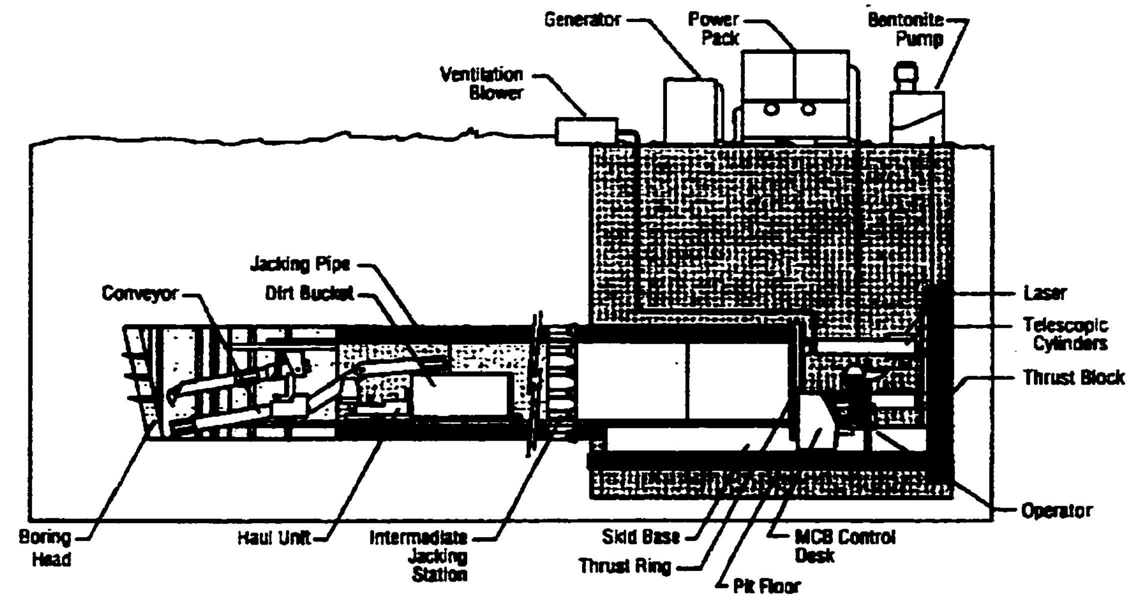

Figure 3.10 Components of a Typical Pipe Jacking Operation (after Iseley and Gokhale 1997)

The jacking pit size is a function of the pipe diameter, length of pipe segment, shield dimensions, jack size and thrust wall design. High jacking forces are required to push large diameter pipes through the ground and so the jacking pit is typically shored and braced unless it is very shallow and in high strength clay.

3.3.3.3 Utility Tunneling

Utility tunneling utilizes conventional tunnel construction methods including manual excavation and self-propelled tunnel boring machines. Conventional tunneling differs from pipe jacking in the way the pipe is installed; that is, the pipe is assembled behind the shield as the tunnel progresses. Excavation takes place within a specially designed shield. The tunneling shield is hydraulically jacked forward as excavation takes place. The jacks thrust against the previously installed liner plates pushing the excavation shield forward. After the shield has been pushed forward a sufficient distance so that a new set of plates can be installed, the jacks are retracted and the workers install the new plates in the tail section of the shield. The cyclic operation is then repeated. Spoil removal is performed using an auger system, carts or a conveyor belt.

The common range of utility tunnels is 1.2 to 3.6 metres in diameter, however tunnels as large as 14m in diameter have been constructed. The driving length has no theoretical limit (Budhu and Iseley, 1994). Common lining material systems include bolted segmental rings, steel ribs and timber lagging and pre-cast concrete segments (Er, 1997). There are various types of tunnel boring machines that can be categorized as either non-shielded open-face TBMs (used in stable soil conditions) or shielded TBMs (used in unstable soil conditions). Tunneling enables a high degree of accuracy in both alignment and grade.

3.3.4 Soil Displacement Methods

3.3.4.1 Impact Moling

Impact moling, also commonly known as 'earth piercing', is a method of creating a bore using a tool comprised of a hammer mounted within a cylindrical casing that is shaped like a torpedo. The hammer may be pneumatic or hydraulic. Impact moles have no steering capabilities, as alignment control is limited to the initial orientation of the pipe as it enters the ground. Impact moles, after being launched, have no rigid attachment to the launching pit, and rely upon the internal action of the hammer and the resistance of the ground for forward movement and alignment. The basic mechanism of impact moling involves a piston, that when driven forward strikes the forward end of the unit, transferring kinetic energy to the body which is being driven forward. The soil is displaced during this operation, in contrast to other methods where the soil is cut and removed. In stable ground an unsupported bore may be formed allowing the pipe or conduit to be inserted. Alternatively, the power of the unit can be used to pull the product pipe or cable through the bore as the device advances. Impact moles have limited drive lengths (<50m) and product diameter. Typically, pipes and cable with outside diameters of 25-75mm can be installed using this method. However, products up to 200mm in diameter may be installed using multiple passes with increasingly larger moles. Main applications of this method include power and telecommunication cables and ducts. Since most moles are operated using compressed air, their application for the installation of potable water and natural gas pipelines is limited due to the potential contamination of the pipe by lubricating oil discharged from the device's exhaust. Impact moling is not suitable for loose or soft soil formations as well as formations that contain cobble or gravel seams.

Figure 3.11 Launching an Impact Mole

3.3.4.2 Rod Pushing

Rod pushing systems form a pilot bore by literally pushing a solid rod with no rotation or impact. The procedure consists of excavating a launching and a receiving pit of an appropriate size, placing the unit in the launching pit and making final grade and alignment adjustment. The rods are then pushed from the launch pit into the soil by mechanical force provided by a hydraulic cylinder. Once a particular rod has been inserted, the cylinder is retracted, a new rod inserted and the push cycle repeated. If the bore must be larger than the rod diameter, an expander is pulled back through the bore by the rods. In recent years, a number of long-range directional rod pushers have been developed. These devices feature a rod rotating mechanism and a steering head that is tapered on one face. The rods are rotated as they are pushed forward.in order to maintain a straight path. The rod is pushed without rotation to change direction with the taper positioned in the desired direction. A beacon located within the boring head transmits information regarding the tool's depth and orientation to a surface receiver. Once the bore has reached its target the steering head is replaced with a reamer and the new pipe is pulled back to the entrance pit. It can be used to install pipe products up to 200mm in diameter to distances up to 125 metres. These systems are suitable primarily for cohesive soils.

3.3.4.3 <u>Pipe Ramming</u>

Pipe ramming is a non-steerable method used to form a bore by driving a steel casing, usually open-ended, with a percussive hammer from a driving pit to an exit pit (see Figure 3.12). The process is similar to pile driving, except the pipe is driven horizontally. There is no mechanical excavation of material from the front of the pipe during the installation process. A close-ended pipe may be used to prevent loss of ground ahead of the cutting edge in non-cohesive soils as the soil moves into the open pipe and flows along it to the driving pit. However, this method is typically limited to the installation of small diameter products.

A solid base, typically a concrete mat, is constructed on the launch side of the installation. Guide rails set to the line of the bore are then installed on the mat. The first length of steel pipe is positioned on the guide rails and a cutting edge ('shoe') is attached to the front end of the pipe with the percussion hammer attached to the rear end. The leading edge of the pipe is fitted with a band for reinforcement and to decrease the amount of friction on the following pipe sections. The hammer action forces the pipe into the soil at the face of the pit along the line dictated by the guide rails. When one pipe section has been driven the hammer is removed and a new pipe section is set on the guide rails and welded to the pipe string. The process is repeated until the leading pipe arrives at the reception shaft. At that point the soil cylinder within the pipe is removed using jetting or compressed air. Lubrication may be applied on the pipe surface to reduce skin friction during the installation process.

Pipe ramming is most often used for short installations (50-70m on average). Common installations include railway and highway crossings. Steel pipe is used for the casing as no other material is strong enough to withstand the impact forces generated by the hammer. Once the steel casing is installed it can be used as a pipeline on its own or as duct for smaller diameter pipes or cables. Pipe products that can be installed using this method range from 200 to 2000mm in diameter. Pipes up to 150mm in diameter are typically installed using a closed end installation while pipes greater than 150mm in diameter are installed using an open ended installation. Pipe ramming presents an economic alternative for the installation of medium size casing when grade and alignment tolerances are flexible.

Figure 3.12 Installation of Steel Casing by a Pneumatic Ramming Hammer

3.3.5 In-line Replacement Methods

3.3.5.1 Pipe Bursting

Pipe Bursting includes various static, hydraulic, and dynamic methods of breaking an existing pipe while simultaneously installing, by pulling or pushing, a new pipe of equal or larger diameter. The process involves the insertion of a conically shaped tool (i.e. bursting head) into the old pipe by pneumatic or hydraulic action. The base of the bursting head is larger than the inside diameter of the old pipe and slightly larger than the outside diameter of the new pipe to reduce friction and provide space for maneuvering the pipe (Strychowskyj, 1997). The process takes place between the machine pit that hosts the pipe bursting equipment, and the insertion pit, from which the new pipe is fed into the host (i.e., existing) pipe. The head is pulled through the host pipe, thus breaking it by brittle fracture while expanding the cavity that houses it. Pipe fragments are forced into the surrounding ground. Concurrently, a new product pipe, of the same or larger diameter, is drawn in behind the bursting head. The bursting head and the new product are pulled from the insertion pit to the machine pit via a chain or a rod assembly that is attached to the front end of the bursting head.

The pipe bursting device may be a static cone pulled in using brute force, a pneumatic mole with forward thrust diverted to give a radial bursting or a hydraulic device inserted into the pipe and expanded to exert direct radial force. Some bursting tools are equipped with expanding crushing arms, sectional ribs, or sharp blades to transfer point or line loads to the old pipes to assist in bursting. (Fig. 3.13).

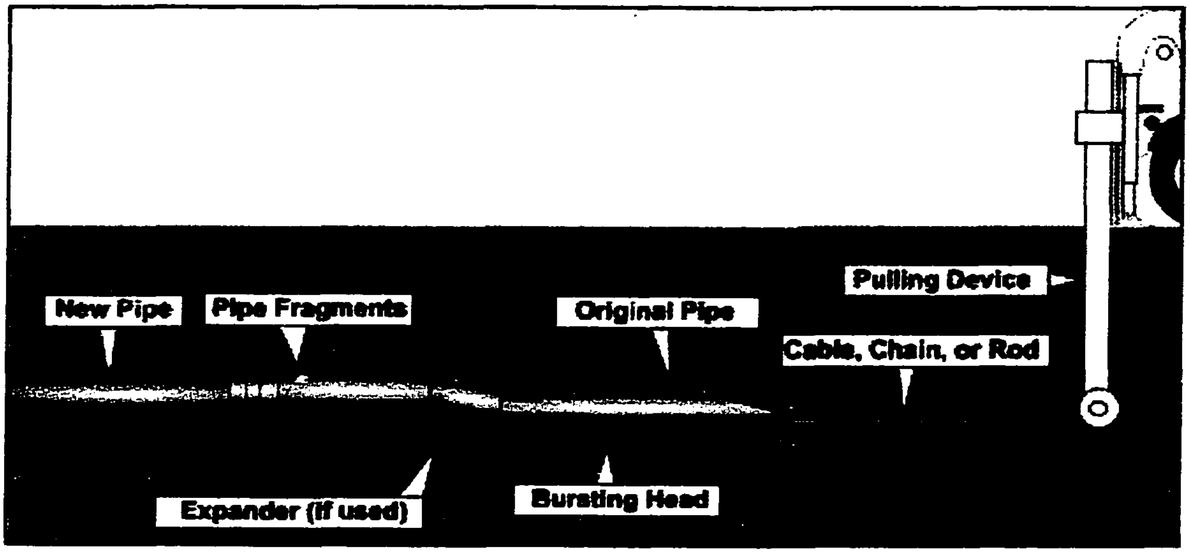

Figure 3.13 Layout of a Pipe Bursting Operation

British Gas first developed the pipe bursting method in the late 1970s for the replacement of small diameter (75-100 mm) cast iron gas mains and distribution lines (Howell 1995). By 1985, the process had been further expanded for replacement of water and sewer lines up to 400 mm in diameter. To date, most pipe bursting applications in North America have been in the replacement of sewer lines.

3.3.5.2 Pipe-Splitting

Pipe splitting is a method that utilizes a cutting blade on an expanding head to cut through the wall of ductile pipe or fitting such as stainless steel collars, saddle clamps or polyethylene repair sections. The head is pulled through the pipeline by a hydraulic head system and slices open the old pipe while pulling a new pipe string behind it. The technique is suitable for pipes made out of steel, ductile iron, repaired cast iron, asbestos-cement, PVC and polyethylene. Product diameter ranges from 50 to 300mm

3.3.5.3 Pipe Eating

Pipe eating is a variation of microtunneling in which the old pipe is consumed by the tunneling machine as the replacement pipe is jacked from behind. A probe-and-packer pilot head guides the machine within the existing sewer, while the microtunneling machine excavates the existing pipe. Typically, the crushing is accomplished using an eccentric-motion cone crusher placed at the face of the microtunneling machine. Specially designed teeth within the cone crusher are used to cut any reinforcement within the pipe, allowing excavation of all of the original pipe material. While the crushing and excavation are taking place at the face of the machine the new product line is simultaneously jacked in behind it, in a similar manner to conventional microtunneling installations. The process also permits realignment and upsizing of the sewer system. Systems are available that allow in-line replacement without flow diversion. The sewer is pumped through the shield during the installation, eliminating the need for a by-pass. Advantages of this process in comparison with pipe bursting include the fact that no fragments are left in the ground and the potential for disturbance to adjacent utilities and paved surfaces is reduced. The process is suitable for the replacement of undersized or damaged sewers made out of clayware, concrete, asbestos-cement, glassfibers reinforced plastic (GRP) and reinforced concrete pipes. This technique is particularly suited to larger diameter pipes and to situations in which heave, caused by expansive upsizing, could risk damage at the surface or to adjacent services.

A variation of pipe-eating is the utilization of a percussion head instead of a micro-tunneling unit. An auger flight is driven through the existing pipe to remove obstructions and cut any intruding roots. Next, the impact head is connected to the auger and pulled from the launch shaft to the auger shaft destroying the old pipe with the auger removing the debris towards the auger shaft. A new pipe is fed simultaneously into the cavity through the pipe launch shaft (rigid pipe is jacked, flexible pipe is pulled-in by the impact head). Finally, the new pipe is checked and the lateral connections re-established. This process is suitable for the replacement of concrete, clay, polyethylene and brick pipes, and can be used to install clay, concrete and polyethylene pipes. The operating range is limited to 100m, and pipe diameters range from 150-500mm. Its main advantage over the microtunneling pipe-eating version is the significantly lower capital cost. However, the percussion head version does not have steering capabilities in the event that correction to the alignment is needed.

3.3.5.4 Pipe Reaming

Pipe reaming is a variation of horizontal drilling technology used for in-line pipe replacement. The system employs a cutter head with spirally placed carbide tipped teeth that grind up the old pipe, while simultaneously drawing in a new pipe of equal or greater diameter. Fragments are suspended in the drilling fluid and transported to the recovery pit where they are removed with a vacuum truck or slurry pump. The system allows upsizing as well as same diameter replacement. Similar to pipe eating, the system places no stress on nearby utilities and surface improvements. It can be utilized for the replacement of shallow utilities under paving, old waterlines and foundations. The system can be employed to replace clay, PVC, asbestos-cement and non-reinforced concrete pipes. High Density Polyethylene (HDPE) and restrained joint PVC pipes can be installed using this system. The process permits long installations thereby reducing costs associated with surface repairs, traffic and business disruptions.

3.3.5.5 Pipe Extraction

Pipe extraction is a method of replacing small diameter, non-segmental pipes with a new product. A steel cable fitted with cones that expand is used to grip the internal wall of the existing pipe. A winching force is applied to the cable and a pushing device is used on the rear of the pipe. As the old pipe is extracted, a new polyethylene pipe attached to the rear end of the existing pipe is pulled in simultaneously. The method is suitable for small diameter services (12-25mm in diameter) and commonly used for replacement of lead pipes. However, larger pipes can also be replaced using this method. In such cases hydraulic rams are located in excavation pits at either end of the pipe to be replaced. The old pipe is extracted from the recovery pit while simultaneously a new product is jacked in from the insertion pit.

3.3.6 Open-cut/Trenching Methods

3.3.6.1 Plowing

Plowing involves installing a pipeline by pulling a plow through the ground while a continuous length of pipe is fed into the top of the plow and buried from the tail. Plowing is suitable for small diameter cables and pipelines (trench width up to 0.4m) that can be placed at a shallow depth (buried depth up to 1.5m). These units can operate in most soil types. Newly developed vibratory plows are capable of operating in soft rock conditions. Plows often provide high productivity at low operating costs and are the most economical method for placing pipelines and cables at shallow depths in green-field conditions.

3.3.6.2 Trenching

The term trenching machine as used in this report applies to both wheel and ladder type machines capable of controling the width and depth of a trench. Trenchers are available in various sizes for digging trenches of varying depths and widths. Ladder type trenching machines utilize an endless chain that travels along a boom, to which cutter buckets equipped with teeth are attached. As the buckets travel up the underside of the boom, the earth is brought out and deposited on a belt conveyor that discharges it alongside the trench. A distinction can be made between track-mount and wheel-mount ladder trenchers. Track-mount units are suitable mainly for green-field conditions and are capable of excavating a trench 0.3-1.2m wide to depths up to 6 metres. Rubber tire trenchers, typically smaller than their track-mounted counterparts, are capable of excavating a trench 0.15-0.45 m wide to depths of up to 1.5 metres and are suitable mainly for urbanized and developed environments,. As a general rule, ladder type excavators are capable of handling a wide range of soil conditions, however, they are not suitable for hard rock conditions or saturated non-cohesive soils such as loose sand or unstable soil conditions.

Wheel-type trenching machines are available with a maximum cutting depth of 2.5 metres, and with trench widths of up to 1.2 metres. The excavation part of the machine consists of a power-driven wheel on which there are mounted buckets equipped with cutter teeth. The machine is operated by lowering the rotating wheel to the desired depth while the unit moves forward slowly. The earth is picked up by the buckets and deposited onto a conveyer belt that discharges it to the side of the trench.

Barras and Mayo (1995) reported the results of an analysis of 430 small projects performed between 1990 and 1993 comparing the installation costs of an electrical conduit configuration of three 76mm diameter conduits installed using urban trenching and rural trenching. They reported the following expressions:

Urban Trenching, \$/m = 6465 + 114*(length of installation, m) (Eq. 3.4)

Rural Trenching, \$/m = 1565 + 31.3*(length of installation, m) (Eq. 3.5)

Trenching costs in an urban environment are higher than a similar installation in green-field conditions. Urban environment installation costs include the restoration of surface improvements (e.g. asphalt, cement).

3.3.6.3 Backhoes

A backhoe is an excavator designed primarily for an excavation below the natural surface of the ground on which the machine rests. A backhoe consists of a track or wheel mounted superstructure to which a boom and a dipper ('stick') are attached. Hydraulic cylinders that control the operation of the boom and the dipper provide the penetration force required to excavate the material. Backhoes offer positive digging action and precise lateral control, and are widely used for trenching work. The width of a trench that can be excavated using a backhoe does not have a theoretical limit, however excavation depth is limited to around 7 metres. Types of formations that can be handled by backhoes include till, clay, sand, gravel and blasted rock. It can perform many other trenching functions in addition to excavating including laying pipe bedding, placing pipe, pulling trench shields, and backfilling the trench.

Cost and productivity associated with backhoe operation tend to vary dramatically as a function of invert depth, head of water, soil stability and project environment (rural versus urban). Thompson et al. (1998) claim that the removal and reinstatement of paved surface can account for up to 75% of the construction costs in an open-cut project. This figure is supported by Barras and Mayo (1995) who reported the cost per linear metre of trenching in an urban environment ($114) to be nearly four times that of projects in rural areas ($31) for similar product types. In urban areas, the following expression for predicting trenching costs was proposed by Boyce and Bried (1998):

Cost ($/m) = 200+25 x (Invert Depth - 2) (Eq. 3.6)

where invert depth is expressed in meters.

3.3.7 Summary

There many methods available for the construction of new buried infrastructure networks. The choice of the most suitable method to be used for placing a buried pipeline or conduit will depend on the diameter and target depth of the utility, soil conditions, the extent to which groundwater is present, the width of the right-of-way, schedule constraints, installation costs, the project environment and more. As each project is unique, the decision-maker must collect and evaluate much of the information needed on a case-by-case basis, a formidable task for most projects. Furthermore, cost, productivity and technical viability of open-cut and trenchless construction methods are determined based on different parameters, making it difficult to draw a direct comparison. A true comparison of the advantages and disadvantages of competing methods requires a comprehensive and systematic evaluation approach capable of accounting for the unique characteristics of each method in an unbiased manner. Additionally, proper evaluation of underground construction methods must account for social and indirect costs as well as the inherent risks associated with underground construction. Automated decision-support systems like the one proposed in this work are designed to assist the decision-maker in meeting this multi-faceted challenge by dividing it into manageable subtasks that can then be automated. The first step in the automation process is the compilation of the available data regarding the capabilities, limitations and characteristics of the various construction methods described in this section. in order to populate the model database. A summary of such a compilation is given in Chapter 4

CHAPTER 4

CHARACTERISTICS OF BURIED INFRASTRUCTURE PROJECTS AND TRENCHLESS CONSTRUCTION METHODS

4.1 INTRODUCTION

The objective of a decision-support system is to assist the decision-maker in selecting the most suitable method(s) for a particular project. The development of a decision model can be described as an iterative process that consists of three steps - basic development, deterministic structuring and basis appraisal. This chapter deals with the basic development stage, namely the identification and capturing of the various alternatives, information requirements and preferences of the decision-maker. The deterministic structuring consists of the development of an evaluation mechanism for the parameters identified in step one, including the development of probabilities, assessment of risk attitude and development of recommended alternatives based on the evaluation criteria. This aspect is discussed in detail in Chapters 5 through 7. Appraisal, which involves assessing the decision model and its predictions, is considered in Chapter 7.

As evident from Chapter 3, there is a large number of methods available for the construction of new buried infrastructure networks. Selecting the most suitable method for a particular project requires a matching process between project characteristics such as job conditions, design parameters and subsurface conditions, and the operating capabilities of the individual methods. The first section of this chapter summarizes the technical and operating characteristics of seventeen trenchless construction methods and their subclasses as well as three open-cut construction methods. The information, compiled from industry surveys, expert opinions, review of historical project records, and an extensive review of the technical literature, is presented in Tables 4-1 through 4-4 under the following categories: general information; performance parameters; compatibility with soil conditions; and constructability parameters.

The remainder of Chapter 4 is devoted to identifying information requirements and preference attributes associated with buried infrastructure projects, that may influence the method selection process. These are presented and discussed under four categories: installation parameters; site conditions; administrative constraints; and, impact. The information requirements and preference attributes are also summarized in tree-type hierarchy diagrams, where high-level elements are defined by lower-level constitutive criteria, in Figures 4.1 through 4.5.

4.2 OPERATIVE AND TECHNICAL CHARACTERISTICS OF TRENCHLESS CONSTRUCTION METHODS

As each project is unique, the decision maker must collect and evaluate much of the information needed on a case-by-case basis, a formidable task for most projects. Furthermore, construction costs, productivity and technical viability of open-cut and trenchless construction methods are in many cases dependent on different parameters, making it difficult to draw a direct comparison. For example, the cost associated with pressure-balance microtunneling installations are nearly independent of the depth, head of water table, project environment and to some extent – soil stability. The main variable is the cost of sinking the shaft (Rasmussen, 1999). By comparison, the cost of trenching will change dramatically depending on depth, soil stability, location of the ground water table and the project environment. Thus, a true comparison of the advantages and disadvantages of a particular method requires a comprehensive and systematic evaluation approach capable of accounting for the unique characteristics of each method in an unbiased manner.

The information presented in this section was obtained from questionnaires distributed to twenty consultants and contractors involved in the trenchless industry based in Alberta and B.C., a survey of 49 directional drilling contractors across North America, interviews with practicing professionals, a comprehensive review of the relevant technical literature and the analysis of nearly 40 projects involving trenchless and conventional open-cut construction methods performed between 1990 and 1999. The tables presented in this section are the core of the 'Method Database' used in the later part of this work as part of the proposed decision support system.

Table 4-1 presents a summary of the various methods, outlines their subclasses (if any) and lists major applications. The cost of installation for the various methods was standardized using units of millimeter of product diameter per meter length. Table 4-2 presents technical information related to installation parameters, accuracy, and specific limitations of each of these methods. Other important parameters that need to be considered when selecting a trenchless construction method are geological and hydro-geological conditions, including types of soil and the location of the ground water table. This information can be found in Table 4-3, where the compatibility of the different trenchless methods with various geological conditions is summarized. Table 4-4 presents constructability parameters such as staging areas and the potential for ground movement or adverse environmental impact. These parameters may preclude the use of selected methods or gives an added advantage to others, depending on the site physical characteristics. Values noted in the tables attempt to indicate performance under normal operating circumstances rather than to capture the technological limits of these methods.

Table 4-1 Trenchless Methods for Installation / Replacement of U/G Pipes and Conduits

Technology	Sub-Classes	Summary of Method	Applications	Cost
Horizontal Guided Drilling and Boring Methods				
Horizontal Directional Drilling	Micro drilling rigs Mini drilling rigs Midi drilling rigs Maxi drilling rigs	Two-stage process: a small diameter directional hole is drilled to provide a pilot hole; a back reamer and the product are then pulled back though the pilot hole.	Force mains, gravity sewers, utility conduits, and pipelines.	\$0.50 - \$0.90/ mm/m length
Pneumatic / Rotary Air Drilling	Pneumatic Rotary air drilling	Operated similarly to other horizontal boring techniques except that the steering head consists of a steerable air rotary drill head.	Used for boring in hard ground or rock.	\$0.60-\$1.10 mm/m length
Water Jetting	None	Use the principal of soil liquification, rather than mechanical cutting, to create a borehole and for steering. Otherwise similar to HDD. Low capital expenditures, but no means to control over-cut.	Force mains, utility conduits and cables	\$0.30-\$0.70 mm/m length
Dry Boring	None	A directional drilling head with a percussion system. Compressed air is used to drive both thrust and pullback actions as well as rotation and percussion at the drill head.	Force mains, utility conduits and cables	\$0.45-\$0.75 mm/m length
Auger Boring	Cradle type Track type	Pipe pushed from a drive shaft to a reception shaft, while a rotating flight auger simultaneously removes the spoil. This method does not apply pressure to the cutting face.	Relatively short crossings (up to 75m). Diameters from 100mm to 2100mm.	\$1.00 - \$2.40/ mm/m length
Slurry Horizontal Rotary Method	None	A drill bit and a drill stem are pushed from the drive shaft to the reception shaft. Bentonite slurry is used to stabilize the bore, lubricate the drilling stem and assist in spoil removal.	Relatively short crossings (up to 75m). Diameters from 25mm to 200mm	\$1.00 - \$2.00/ mm/m length
Pipe Jacking Methods				
Micro-Tunneling.	Augur flight Slurry system.	Remotely controlled, guided pipe jacking process that provides continuous support to the excavation face. Pipe installed from a drive shaft to a reception shaft. No personnel entry required.	Medium to large diameter (250-1800mm) gravity sewers; driving lengths up to 225m.	\$2.50 - \$4.00/ mm/m length

Utility Tunneling	Hand tunneling TBM Open Shield TBM Closed shield	Man entry only. The tunnel is excavated manually or mechanically. The tunnel liner is added to the face of the tunnel. A temporary casing precedes the liner plates. Only the temporary casing is jacked forwards, not the entire length.	Diameters are typically 1.2-3.6 meters. Driving distance unlimited.	$1.50 - $4.50/ mm/m length
Pipe Jacking	Open shield (hand excavation or mechanical cutter) Closed shield	Pipe is jacked horizontally from a drive shaft to a reception shaft. Workers required in pipe to perform excavation and/or remove spoil. Excavation performed either manually or mechanically.	Gravity sewers, force mains, diversion chambers. 1060mm and larger diameter pipes.	$1.50 - $3.00/ mm/m length
Soil Displacement Methods				
Impact Mole	Hydraulic Pneumatic	A percussive hammer with a cylindrical casing, which relies on the internal hammer action for forward movement. The pipe is drawn in immediately behind the tool.	Small diameter pipes and conduits (25-200mm) over short distances (up to 50m).	$0.30 - $0.60/ mm/m length
Rod Pushing	Non-rotational Rotational ('long-range')	Solid rods are pushed with no rotation or impact from the thrust shaft to the receiving shaft. No steering capabilities. New models offer rotation as well as limited steering capabilities.	Utility conduits and cables	$0.30-$0.50/ mm/m length
Pipe Ramming	Open ended Close ended	Percussive hammer used to drive steel casing from a drive pit to a reception pit. Soil in casing is removed by auguring, jetting or compressed air.	Crossing of railway and roads. Diameters up to 2000mm. Distances up to 50m.	$1.50-$2.60 mm/m length
In-Line Replacement				
Pipe Bursting	Static head Pneumatic head Hydraulic head	The existing pipe is burst with the use of a conical shaped bursting head, while simultaneously a new pipe of equal or greater diameter is pulled behind the bursting head.	Force mains and gravity sewers up to 600mm in diameter. Driving lengths up to 350m.	$0.90 - $1.35/ mm/m length
Pipe Splitting	N/A	A bladed expanding head is used to slice open the existing pipe while pulling a new pipe string behind it.	Replacement of flexible pipes and pipes with stainless steel clamps	$0.90 - $1.30/ mm/m length

Pipe Eating & Replacing	Microtunneling Percussion head and auger	A crusher-type micro-tunneling machine is used to literally mine the existing pipe, while a new pipe is simultaneously jacked in from behind.	Replacement of large diameter clay, concrete asbestos cement and reinforced concrete pipes.	$1.70-$2.50 mm/m length
Pipe-Reaming	N/A	A horizontal-boring machine pulls a special reamer through the old pipe, grinding it, while simultaneously installing a new pipe.	Replacement of concrete and clay pipes up to 500mm in diameter.	$0.90-$1.60 mm/m length
Pipe Extraction & Replacement	N/A	The existing pipe is extracted using steel cable fitted with an expanding cone, which expands and grips the pipe's internal wall. The new pipe is pulled in using the same cable.	Lead water mains and service lines.	$0.30 - $0.60/ mm/m length
Cut-and-Cover Methods				
Backhoe	Various subclasses	A bucket attached at the end of a hydraulic arm. Attached to a vehicle that resides on wheels or tracks.	All type of utility installations to a maximum depth of 7m.	$0.90-$1.50 mm/m length (2.5m deep in a paved road)
Trencher	Wheel trencher Chain trencher	A saw-like device that cuts a narrow trench in the ground within which the product is placed.	Small diameter pipes and direct-buried cables (≥200mm) max. depth 4m.	$0.50-$0.90 mm/m length
Plow	Various subclasses	A wedge that is dragged through the ground, creating a ditch which simultaneously installing a product in the ground.	Small diameter pipes and direct-buried cables (≥150mm) max. depth 3m.	$0.30-$0.50 mm/m length

Table 4-2 Performance Parameters of Various Trenchless Methods

Technology	Installation Parameters				Accuracy	Limitation
	Length, m	Depth, m	Dia., mm	Type of Pipe		
Horizontal Guided Drilling and Boring Methods						
HDD (micro)	5 - 50	10	≥100	Steel, PE, HDPE, PVC	Medium	Limited steering capability; Susceptible to Electro-magnetic interference; Drilling fluids must be managed.
HDD (mini)	10 - 100	15	≥150	Steel, PE, HDPE, PVC	Medium - High	Susceptible to Electro-magnetic interference; Drilling fluids must be managed.
HDD (midi)	50 - 350	< 30	50 - 300	Steel, HDPE, PVC, PE	Medium - High	High skill operators; Susceptible to Electro-magnetic interference; Drilling fluids must be managed.
HDD (maxi)	100 - 1500	< 50	100 – 1200	Steel, HDPE	Medium - High	High skill operators; Susceptible to Electro-magnetic interference; Drilling fluids must be managed.
Rotary Air Drilling	100 - 1500	< 50	100 - 900	Steel, HDPE	Medium - High	High skill operators; Susceptible to Electro-magnetic interference; hard formations only.
Water Jetting	10 - 100	15	≥150	Steel, PE, HDPE, PVC	Low-Medium	No control over amount of over-cut – risk of creating cavities and subsequent ground settlement. Large amount of mud to dispose of.
Dry Boring	10-100	15	25-250	Steel, PE, HDPE,	Medium-High	Compressible, cohesive soils only.
Auger Boring (track type)	12 - 100	Varies	200-1200	Steel; RCP	Medium	A thrust block must be constructed in back of the excavation pit
Auger Boring (cradle type)	12 - 150	Varies	200-1500	Steel; RCP	Low	Large right-of-way is required to accommodate entire length of casing and power plant
Slurry Horizontal Rotary Boring	12 - 100	Varies	25-200	Steel, Concrete,DI ,GFRP,PE, PVC, Corrugated metal	Medium	Limited product diameter

Pipe Jacking Methods						
Micro-Tunneling (Auger method)	25 – 120	Above water table	250 -1800	Steel, Concrete, RCP, VCP, PVC, GFRP, DI, Asbestos-cement	High	High skill operators; Cannot be set in a backward motion; Limited to unsaturated cohesive soils; Minimum soil cover = 1.5m; Minimum excavation diameter to cover ratio= 3:1.
Micro-Tunneling (Slurry method)	25 – 250	Up to 30m	250 -2700	Steel, PCP, VCP, PVC, GFRP, DI, Asbestos-cement	High	High skill operators; Cannot be set in a backward motion; Minimum soil cover = 1.5m; Minimum excavation diameter to cover ratio= 3:1.
Pipe Jacking	25-300	Varies	1060–3300	RCP, VCP, Steel, GFRP, DI,	High	Limited to stable soils
Utility Tunneling	No theoretical limit	Varies	1200-3600	steel plates, pre-cast concrete segments, ribs and laggings	High	High cost
Soil Displacement Methods						
Non-steerable Impact Mole	12 – 30	Min. of 10mm for mm dia.	25 – 75	Clay, Steel, PE, HDPE, PVC cables,	Low	Non-steerable; minimum cover is required to prevent heave; not suitable for loose or soft soils. Minimum cover of 1m for 100mm of tool dia.
Steerable Impact Mole	12 - 50	Min. of 10mm for mm dia.	25 - 75	VCP, Steel, PE, HDPE, PVC Cables,	Medium	Minimum cover is required to prevent heave; not suitable for loose or soft soils; Minimum cover of 1m for 100mm of tool dia.
Rod-pushing (non-rotational)	50	Varies	25-100	Steel, PE, HDPE,	Low	Non-steerable; limited installation length; Self-supporting soils only
Rod-pushing (long-range)	125	Up to 4m	25-200	Steel, PE, HDPE	Low-Medium	Self-supporting soils only
Pipe Ramming	12 - 60	Varies	100 - 1800	Steel	Low	Non-steerable; care must be taken in construction of launch pit and alignment of guide rails.

In-Line Replacement						
Pipe Bursting	10 - 350	Varies	50 - 600	RCP, Concrete, Cast iron, Spun iron, Clayware	----	Heaving of surface; damage to nearby utilities, foundations and pavement; high number and frequency of laterals can increase cost substantially. Not suitable for flexible pipes. Should not be used for lead pipes. Must follow existing alignment and profile.
Pipe Splitting	10 - 350	Varies	50 - 300	HDPE, Steel, ductile iron, PVC, asbestos-cement,	----	Heaving of surface; damage to nearby utilities, foundations and pavement; high concentration of laterals can increase cost substantially. Must follow existing alignment and profile.
Pipe Eating Microtunneling	25 - 225	Varies	250 - 1200	RCP, Clayware, Concrete, FGRP, Asbestos-cement, brick	High	Relatively expensive in comparison with other replacement methods
Pipe Eating Percussion head	25 – 100	Varies	150 - 500	Clayware, Concrete, FGRP, Asbestos-cement, brick, PE	----	Must follow existing alignment and profile.
Pipe-Reaming	25-200	Varies	150 - 600	Concrete, clay, PVC. Asbestos-cement	----	Must follow existing alignment and profile.
Pipe Extraction & Replacement	10 - 30	Varies	12 - 25	Lead, cast iron	----	Must follow existing alignment and profile.
Cut-and-Cover Methods						
Plows	No theoretical limit	Up to 1.5m	Up to 150mm	Cables, PVC, PE, Casr Iron, Steel	Low-Medium	Generally not suitable for rock formations; larger units suitable mainly for green-field conditions

Trenchers – Ladder Type Track-mount	No theoretical limit	Up to 6m	Up to 400mm	All types	Medium - High	Primarily green-field conditions; Limited depth and product diameter;
Trenchers Ladder Type Wheel-mount	No theoretical limit	Up to 1.5m	200mm	All types	Medium - High	Limited depth and product diameter; not suitable for loose soils.
Trenchers Wheel type	No theoretical limit	Up to 2.5m	Up to 300mm	All types	Medium - High	Primarily green-field conditions; not suitable for loose soils.
Backhoes	No theoretical limit	Up to 7m	No theoretical limit	All types	High	Needs significant amount of working space; large amount of soil is excavated; Noise; Dust.

Definitions and Acronyms:

1. Accuracy

Designation	**Description**
Low	No steering capabilities after leaving launching pit
Low-Medium	Limited steering capabilities after leaving launching pit
Medium	Dedicated tracking and steering capabilities after leaving launching pit
Medium – High	Capable of max. deviation of ± 100mm in term of alignment and grade of pilot bore/product
High	Capable of max. deviation of ± 50mm of alignment and grade of pilot bore/product

2. Pipe Materials – Acronyms

RCP - Reinforce Concrete Pipe
PGRP - Fiberglass Reinforced Polymers
PE - Polyethylene
HDPE - High Density Polyethylene
PVC - Polyvinyl Chloride
VCP - Vitrified Clay Pipe
DI - Ductile Iron

Table 4-3 Compatibility with Various Soil Conditions (format after Iseley and Gokhale, 1997)

Soil Type (define using SPT blow count; N value as per ASTM 1452) / **Technology**	Cohesive Soils (Clay)			Cohesionless Soils (Sand/Silt)			Gravel	Cobble† Boulder	Sandstone Bedrock	Bedrock (MPa)	High GWT Classification*
	N<5 Soft	5<N<15 Firm	N>15 Stiff-Hard	N<10 Loose	10<N<30 Medium	N>30 Dense					
Horizontal Guided Drilling and Boring Methods											
HDD Maxi / Midi	✔	✔	✔	P	✔	✔	P	P	✔	<80	C1
HDD Mini/Micro	✔	✔	✔	P	✔	✔	✗	✗	✗	✗	C2
Pneumatic/Rotary Air Drilling	✗	✗	✔	✗	✗	✗	✗	✗	✔	✔	C3
Water Jetting	✔	✔	✔	✗	P	P	✗	✗	✗	✗	C2
Dry Boring	✔	✔	✔	✗	P	✔	✗	✗	✔	✔	C2
Auger Boring (Track Type)	P	✔	✔	✗	✔	✔	✔	< 0.3D	✔	<80	C2
Auger Boring (Cradle Type)	P	✔	✔	✗	✔	✔	✔	< 0.3D	✔	<80	C2
Slurry Horizontal Rotary Method	P	✔	✔	P	✔	✔	✔	< 0.3D	✔	<80	C1
Pipe Jacking Methods											
Microtunneling (Auger system)	✔	✔	✔	✗	P	✔	✗	< 0.3D	✔	<200	C2
Microtunneling (Slurry system)	✔	✔	✔	P	✔	✔	✔	< 0.3D	✔	<200	C1
Pipe Jacking (Hand Excavation)	✗	✔	✔	✗	✔	✔	P	< 0.95 D	P	✗	C3
Tunneling - TBM	P	✔	✔	P	✔	✔	✔	P	✔	✔	C1
Tunneling - Hand Excavation	✗	✔	✔	P	✗	✔	✔	<0.95D	✗	✗	C3

Soil Displacement Methods											
Impact Mole	✗	✓	✓	✗	✓	P	✗	✗	✗	✗	C2
Pipe Ramming	✓	✓	✓	✓	P	P	✓	<0.9D	✗	✗	C2
Rod-Pushing	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	C2
In-Line Replacement											
Pipe Bursting	✓	✓	✓	✓	P	✗	P	✗	✗	✗	C1
Pipe Splitting	✓	✓	✓	✓	P	✗	P	✗	✗	✗	C1
Pipe Eating	✓	✓	✓	P	✓	✓	✓	✓	✓	✗	C1
Pipe-Reaming	✓	✓	✓	P	✓	✓	✗	✗	✓	✗	C1
Pipe Extraction & Replacement	✓	✓	✓	P	✓	✓	P	✗	✓	✓	C1
Cut-and-Cover Methods											
Plow	✓	✓	P	✓	P	✗	✗	✗	P	✗	C3
Trenching	✓	✓	✓	✗	✓	✓	✗	✗	✓	✓	C3
Backhoe	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	C3
Dragline	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	C3

✓ = Suitable ; ✗ = Not suitable ; P = Possible ; < 0.3D = Boulder diameter as a function of Casing Diameter†.

*Method Classification for High Water Table Conditions

C1: suitable or possibly suitable for construction at invert depth of 3m or more under the groundwater table.

C2: suitable or possibly suitable for construction at invert depth up to 3m below the groundwater table.

C3: suitable or possibly suitable for construction at invert depth up to 1m below the groundwater table.

Table 4-4 Constructability Parameters

Technology	Staging Area			Potential for Ground Movement	Potential for Adverse Environ. Impact	Potential Short /Long Term Adverse Effects
	Entry Pit	Exit Pit	Equipment Setup			
Horizontal Guided Drilling and Boring Methods						
HDD - Micro	Length 0.5 -1 m Width 0.5 -1 m	Space to string product or place a reel	2mx3m (rig/mud mixing system/ extra rods	Low	Low	Settlement/Heave at Surface
HDD - Mini	Length 0.5 -1 m Width 0.5 -1 m	Space to string product or place a reel	3mx5m (rig/mud mixing system/ extra rods	Low - Moderate	Low - Moderate	Settlement/Heave at Surface; Frac-out
HDD - Midi	Length 2 -3 m Width 1 -2 m	Space to string product and/or drilling rods equal to length of bore	15mx30m (rig/mud mixing system/ extra rods/crane	Moderate – High	Moderate	Settlement/Heave at Surface; Frac-out;
HDD - Maxi	Length 5 -15 m Width 10 -30 m	Space to string product and/or drilling rods equal to length of bore	25mx50m (rig/mud mixing system/ extra rods/crane/recyclin g system	Moderate – High	Moderate – High	Settlement/Heave at Surface; Frac-out;

Pneumatic/ Rotary Air Drilling	Length 5 -15 m Width 10 -30 m	Space to string product and/or drilling rods equal to length of bore	25mx50m (rig/mud mixing system/ extra rods/crane/recycling system	Moderate	Moderate	Settlement/Heave at Surface
Water Jetting	Length 2 -3 m Width 1 -2 m	Space to string product and/or drilling rods equal to length of bore	15mx30m (rig/mud mixing system/ extra rods/crane	High	High	Settlement/Heave at Surface; Frac-out;
Dry Boring	Length 2 -3 m Width 1 -2 m	Space to string product and/or drilling rods equal to length of bore	15mx30m (rig/ air compressor / extra rods/crane	Moderate	Low	Settlement/Heave at Surface
Auger Boring (Track)	Length 8 - 11m Width 2.5 - 3.5m	Length: 8 - 11m Width: 2.5 - 3.5m	5mx5m	Low	Low-Moderate	Settlement/Heave at Surface; Fluid loss
Auger Boring (Cradle)	Equal to length of crossing length	Length: 8 - 11m Width: 2.5 - 3.5m	Equal to length of crossing	Low	Low-Moderate	Settlement/Heave at Surface; Fluid loss
Slurry Horizontal Rotary Method	Length 8 - 11m Width 2.5 - 3.5m	Length: 8 - 11m Width: 2.5 - 3.5m	5mx5m	Low	Moderate	Settlement/Heave at Surface; Fluid loss
Pipe Jacking Methods						
Micro-Tunneling	3-10m in diameter depending equipment dimensions	3-10m in diameter depending equipment dimensions	Space for slurry tanks, pipe storage, operator shake Length 25 -50 m Width 7 -12 m	Low	Low	Settlement/Heave at Surface; Fluid loss
Pipe Jacking	Jacking pit function of pipe size. Varies from 3-9 m.	Receiving pits vary from 2-6m.	Space for hydraulic jacks, compressor , crane and pipe segments	Low	Low	Settlement/Heave at Surface

Utility Tunneling	Similar space requirements as pipe jacking. Access pit varies from 2.7-7.5m.			Low	Low	Settlement/Heave at Surface
Soil Displacement Methods						
Impact Mole	From 0.2 x 0.9m to 3 x 9m. (1.5 x length of tool).	From 0.2 x 0.9m to 3 x 9m. (1.5 times length of tool).	Space for air compressor and pipe product; 5x3m	Moderate – High	Low-Moderate	Settlement/Heave at Surface; ground contamination
Pipe Ramming	Relatively large area is required to accommodate bore pit excavated soil, air compressor, pipe etc. Length of tool plus pipe segment; minimum 2mx2m.			Moderate	Low	Heave at surface; damage to nearby utilities; damage to nearby foundations
Rod-pushing	Length: 1.6-2.5m Width: 0.4-0.6m	Length: 1.6-2.5m Width: 0.4-0.6m	Space for hydraulic system and pipe product; 5x3m	Moderate – High	Low	Settlement/Heave at Surface
In-Line Replacement						
Pipe Bursting	Length 4.0 m Width 2.5 m	Length: 12x(O.D.)+1.5xH Width: 1.5 m	10x10m; Space for compressor and pipe rack	High	Low	Heave at surface; damage to nearby lines; damage to nearby foundations
Pipe Splitting	Length 3.5 m Width 2.5 m	Length: 12 times pipe diameter; Width 1.5 m	10x10m; Space for compressor and pipe rack	High	Low	Heave at surface; damage to nearby lines; damage to nearby foundations
Pipe Eating	3-10m in diameter depending on equipment dimensions	3-10m in diameter depending on equipment dimensions	Space for slurry tanks, pipe storage, operator cabin Length 25 -50 m Width 7 -12 m	Low	Low	Settlement/Heave at Surface

Pipe-Reaming	Length 2 -3 m Width 1 -2 m	Space to string product and/or drilling rods equal to length of bore	15mx30m (rig/mud mixing system/ extra rods/crane	Moderate	Low	Settlement/Heave at Surface; Frac-out
Pipe Extraction & Replacement	Length 0.5 -1 m Width 0.5 -1 m	Length 0.5 -1 m Width 0.5 -1 m	Space for hydraulic system and pipe product; 3mx5m	Low	Low	Settlement/Heave at Surface
Cut-and-Cover Methods						
Plow	N/A	N/A	N/A	High	High	Settlement / Noise Dust/ Damage to crossing utilities.
Trenchers	N/A	N/A	N/A	High	High	Settlement / Noise /Dust /Damage to adjacent utilities and foundations; reduced pavement life; Social costs
Backhoe	N/A	N/A	N/A	High	High	Settlement / Noise/Dust/ Damage to adjacent utilities and foundations; reduced pavement life; Social costs

N/A – Not applicable O.D. – Pipe outside diameter H = Depth of excavation

4.3 PROJECT PARAMETERS

Twenty-six parameters that may influence the selection of a construction method for a given project scenario were identified and divided into five categories, namely: installation parameters; site conditions; geological conditions; administrative constraints; and, impact parameters. The 'installation parameters' category consists primarily of project design parameters including:

- maximum single drive length,
- product diameter,
- product material, and
- alignment and installation tolerances.

Site conditions refer to potential constraints imposed by the project environment. The agency has typically no control over these parameters, but must take them into account during the design and construction stages of a project. The 'site conditions' category includes:

- staging areas,
- width of right-of-way, p
- roximity to existing installations,
- ease of access to route, and
- presence of above ground structures.

Geological conditions can be considered part of site conditions, however their relative importance and multi-attribute nature justify placing them in a seperated category. The 'geological conditions' category include:

- dominent formation,

- type of interbeddings,
- large obstructions (natural or manmade), and
- hydrogeological conditions.

In contrast to site and geological conditions, administrative constraints are comprised of parameters over which the agency may have a high degree of control, including:

- project duration,
- project budget, and
- costs associated with the restoration of surface improvements.

Also in this category are long-term maintenance costs and safety aspects of the project. Impact parameters include losses incurred by the agency and the public that are not directly related to the project. More specifically:

- productivity losses (i.e., industrial facility),
- social costs, and
- environmental impact.

The term social costs refers to costs that are incurred by the agency as well as other parties that cannot be classified as direct or indirect costs. Examples of social costs include traffic delays, business losses, and health hazards due to noise, dust and air pollution. Several studies examining the incorporation of social costs in the project overall costs have reported two main obstacles: a) social costs are difficult to quantify; and, b) quite frequently social costs are found to be greater than the cost of construction, thus becoming the determining factor. As for environmental impact, increasingly tough legislation has resulted in a significant reduction in the utilization of open-cut methods in environmentally sensitive areas and across watercourses.

Even trenchless methods with a relatively high environmental impact potential, such as horizontal directional drilling, may be excluded in a particularly sensitive environment.

For the purpose of the proposed decision-support model the parameters that may have an impact on the suitability of a given construction method for a given buried infrastructure project were summarized in a tree-type hierarchy diagram (Figure 4.1). Of the five principal categories, three were identified as representing qualifying attributes (i.e., geological conditions, installation conditions and site conditions) and two were identified as representing preference attributes (i.e., project parameters and impact parameters). The term qualifying attributes refers to those aspects of the project over which the user has little or no control. Failure of a construction method to satisfy any of the qualifying attributes will result in its disqualification. Preference attributes on the other hand are those parameters that are controlled primarily by the user. It is the ability of a particular method to best satisfy all of the user's criteria rather than its ability to fully satisfy any single cretirion, that makes it the most suitable for the project at hand.

The breakdown of the principal categories into their respective elements is shown in Figures 4.2 through 4.5 using tree-type hierarchy diagrams, where high-level elements are defined by lower-level constitutive criteria. A hierarchy diagram was not developed for the installation condition category, as potential values for the different sub-elements (e.g., pipe material) were dealt with in detail in Tables 4-1 through 4-4.

4.3.1 Installation Parameters

Type of Project: Does the project involve replacement of an existing line or the installation of a new one? The user will be able to perform a comparison between an in-line replacement and a new installation. The model is not suitable for evaluating rehabilitation technologies.

Length of Installation: What is the maximum drive length between the pre-defined start and exit locations (e.g., manhole to manhole; tie-in to tie-in).

Product Diameter : This value refers to the product's outside diameter.

Maximum Invert Depth: The maximum invert depth is used for comparison purposes against the maximum operating depth of each construction method as well as for determining if the installation takes place below the ground water table.

Alignment and Profile of Installation: Does the design call for any bends or curves in the alignment or profile of the pipe?

Accuracy: Tight grade and alignment tolerances may exclude many otherwise eligible methods.

Type of Product: Different trenchless construction/replacement methods can accommodate different types of pipe materials. By specifying a particular type of material (e.g., steel, concrete, clay, HDPE) the user may exclude otherwise eligible methods.

4.3.2 Site Conditions

Staging Areas: Are there any limitations on the staging/pipe laying areas at either end of the proposed alignment?

Right-of-Way (ROW): What is the narrowest location along the right-of-way. Open-cut construction methods require the right-of-way to be at least 4-6m wide.

Proximity of Other Installations: The minimum clearance from the next closest buried service and impact of damage (Catastrophic - high/medium pressure gas line; petroleum line; high voltage line; Dangerous - low voltage; fiber-optic line; Disruptive - water, sewer).

Ease of Access to Route: Is there an access to personnel above the proposed alignment? Can an emergency shaft be sunk in case the process jams?

Soil Conditions and Obstructions: What is the anticipated predominant type(s) of soil(s) at the site? What are the secondary type(s) of soil(s) at the site? Is the presence of gravel, cobbles or boulders suspected? How confident is the prediction of anticipated soil conditions? What is the elevation of the ground water table? Is dewatering a reasonable option for this project? What are the allowable limits for ground or groundwater movement? Is contaminated soil anticipated?

Above Ground Structures: The likelihood of ground movement and its effect on nearby foundations or surface improvements must be considered including heaving, subsidence and vibration.

4.3.3 Administrative Constraints

Duration of Project: Is there a maximum allowable duration for the project? In some cases, the use of open-cut may impose a time-restriction, as partial closure is required, while the use of a trenchless method may have no such time constraint.

Cost of Project: What is the user's budget limit?

Restoration of Existing Surface Improvements: What is the cost of restoring surface improvements such as pavement, sidewalks, and landscaping?

By-Passes and Restoration of Buried Services: What is the cost of providing by-passes for existing services (if any)? What is the cost of restoring interrupted buried services?

Long-Term Restoration Costs: Open-trench road cuts are a common cause for potholes and other form of surface subsidence. The long-term restoration costs of such deficiencies as well as the loss of residual life of adjacent utilities and pavement structures present a direct cost to the agency, and thus should be accounted for (Iseley and Tanwani, 1990).

Construction Accidents – Historically trenchless projects are less prone to construction accidents due to the elimination of deep excavations (i.e., trench collapse), limited utilization of heavy equipment, and fewer workers on site (Barras and Mayo, 1995; Ariaratnam et al., 1998).

4.3.4 Impact Parameters

Productivity Losses: For some industrial facilities the direct cost of the project represents a fraction of the cost associated with productivity losses or temporary shutdown.

Social Costs: The term "social" costs refers to costs that cannot be classified as either direct or indirect costs that are incurred by the owner and other parties as a result of the project being executed. For a municipal owner social costs may include the following:

Traffic interference - The impact on traffic including delays, loss of parking space, increased fuel consumption, increased likelihood of road accidents, and increased pollution. These factors are a function of the project's location (e.g., downtown, suburbia, rural) and the extent and duration of anticipated rerouting and lane/street closure. A common approach for computing the cost of traffic interferences is the 'Lane Rent' method, which accounts for the average daily traffic, average delay, local average wage, and the anticipated closure duration (Budhu and Iseley, 1994).

Accelerated Deterioration of Side Roads- Most detour roads are not designed for heavy traffic loads. These detours may suffer significant damage during lengthy construction periods.

Business loss - Includes decreased revenue of nearby businesses and loss of parking revenues due to decreased accessibility and unused parking meters. Business loss is a function of the number and type of businesses at the project location and the nature of the project location (i.e., congested urban area versus a rural location).

Reduction in Quality of Life – Commonly, major rights-of-way in urban environments are converted into recreational areas. Open-cut construction may prevent the use of the recreation area during construction as well as cause significant damage to the eco-system (e.g., removal or damage of mature trees). In some cases a significant premium may be paid for trenchless construction for the sole reason that open-cut may prove to be unpopular among local residents (Gokhale and Abraham, 1998).

Noise, dust and Air Pollution – Heavy equipment, which is used during trenching/excavation operation, causes higher levels of noise and vibration than most types of trenchless construction equipment. Additionally, air pollution in the form of air blown dust is more prevalent in open-cut construction.

Environmental Factors: For the crossing of a stream or another environmentally sensitive area, limited construction window or enhanced restoration requirements may preclude open-cut, although it may offer substantially lower direct costs.

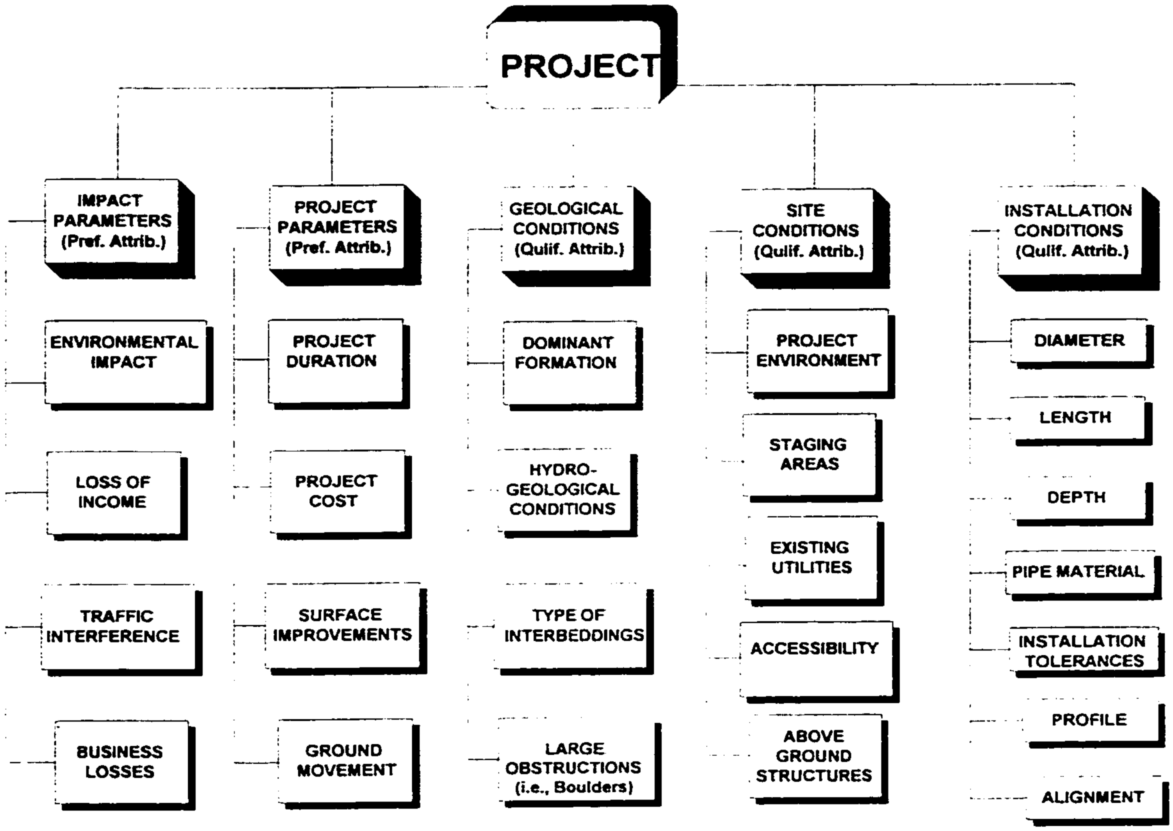

Figure 4.1 Qualifying and Preference Attributes Organized in a Tree-Type Hierarchy

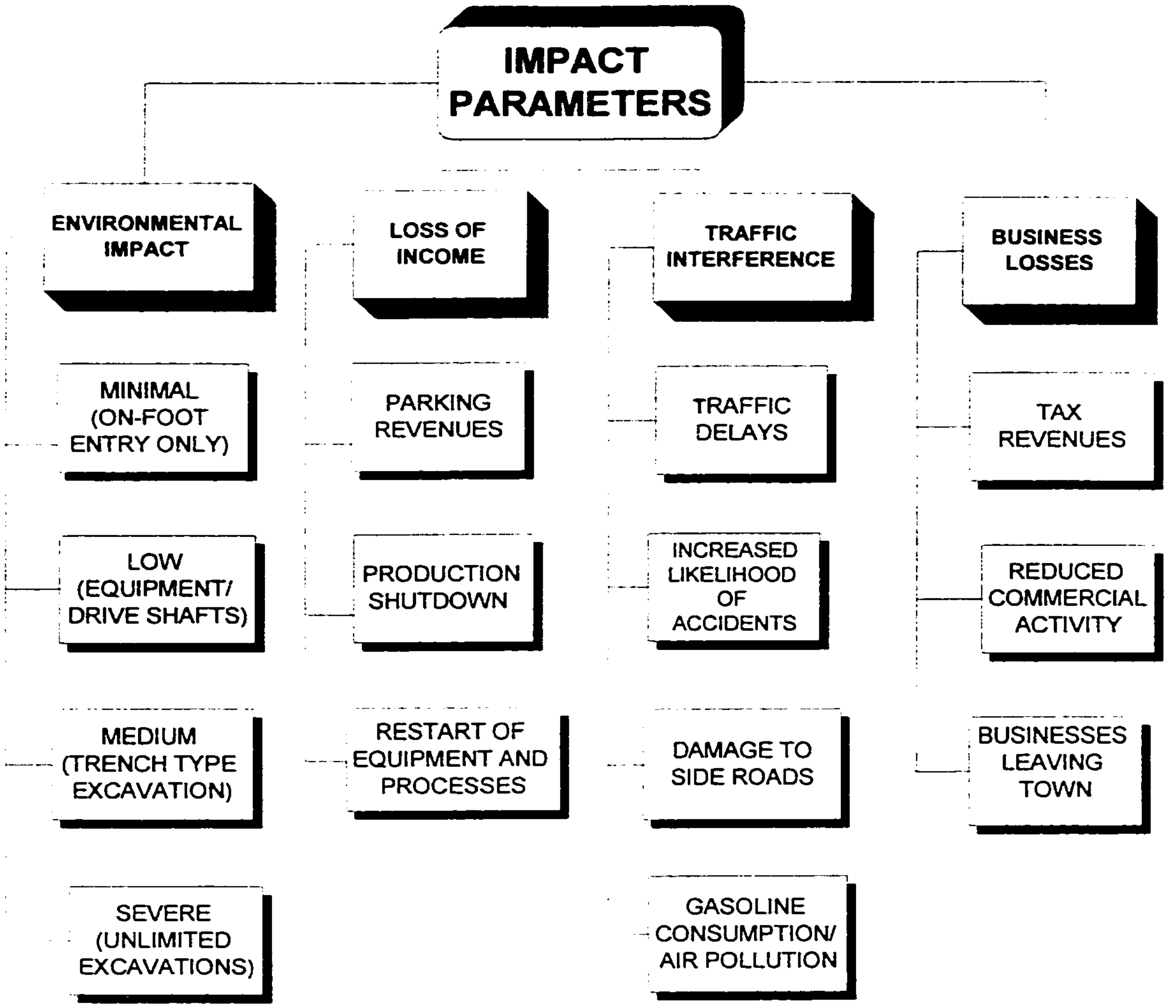

Figure 4.2 Criteria Breakdown for Impact Parameters

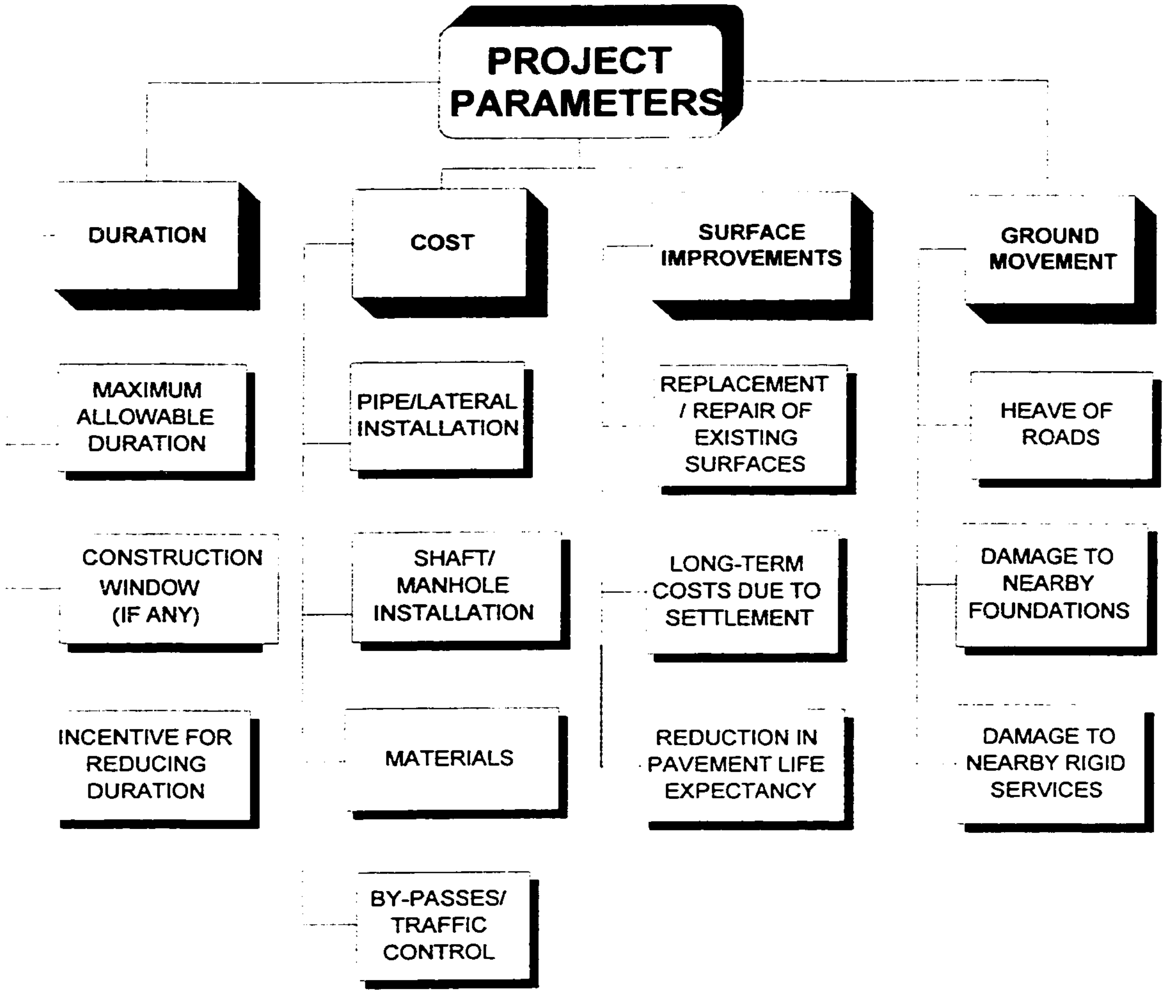

Figure 4.3 Criteria Breakdown for Project Parameter

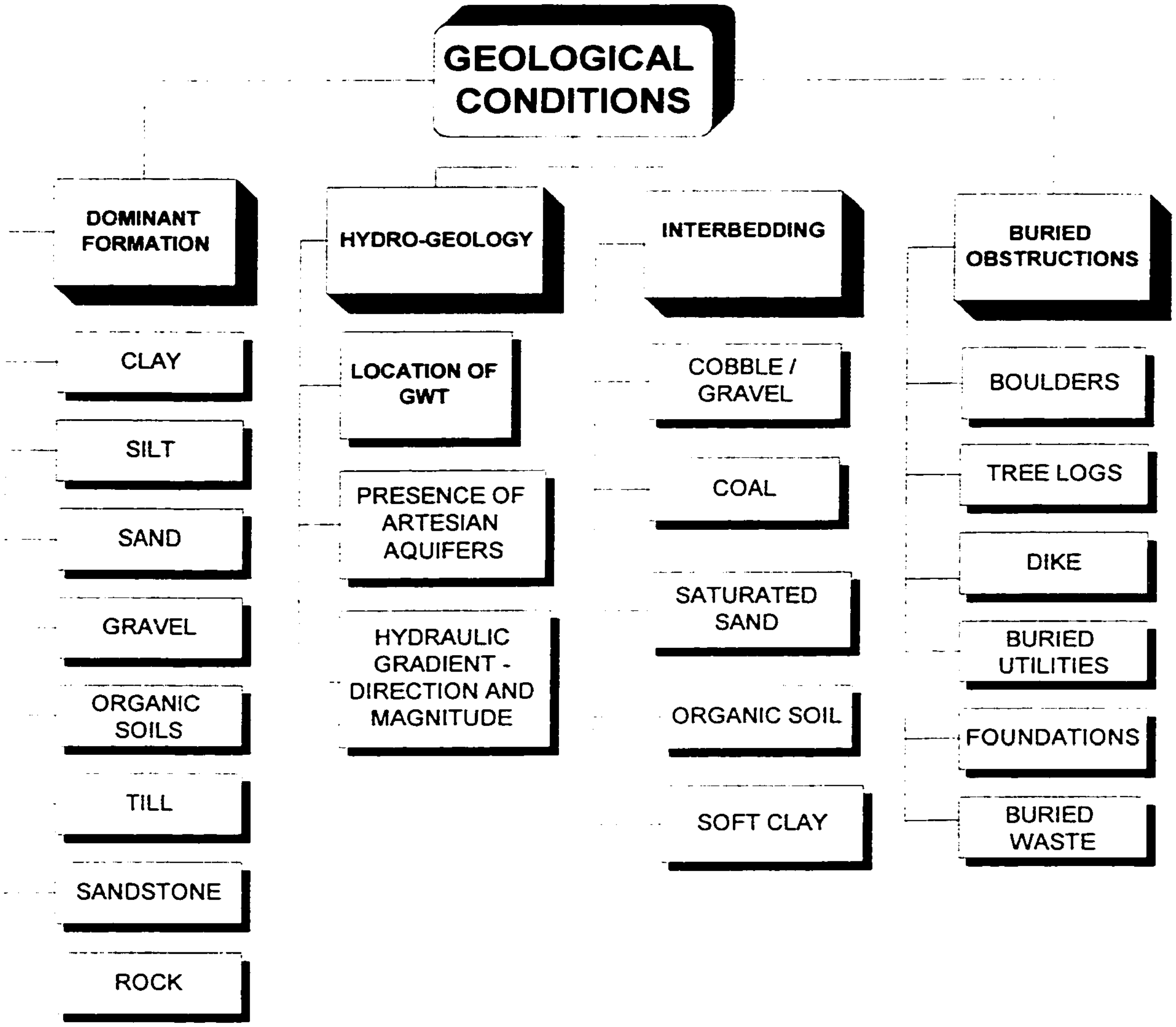

Figure 4.4 Criteria Breakdown for Geological Conditions

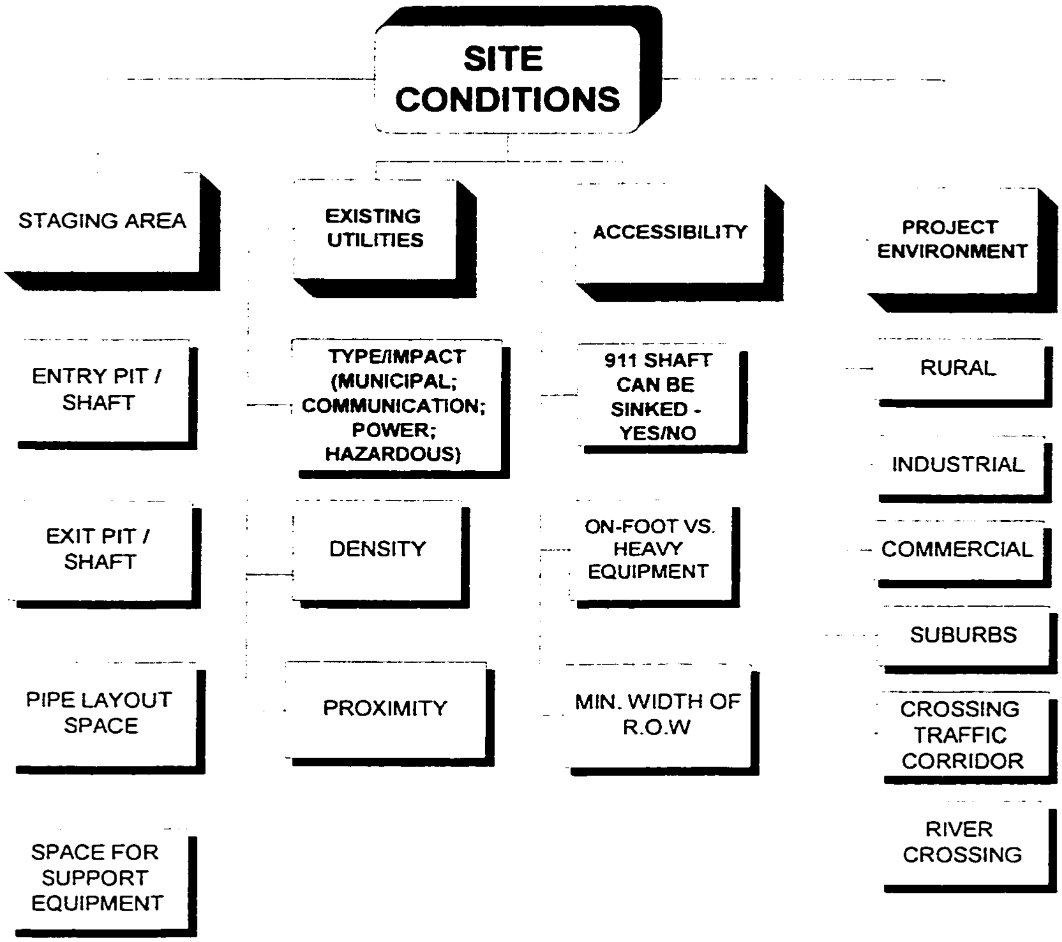

Figure 4.5 Criteria Breakdown for Site Conditions

CHAPTER 5

HORIZONTAL CHARACTERIZATION TECHNIQUES FOR RISK REDUCTION IN TRENCHLESS CONSTRUCTION[1]

5.1 INTRODUCTION

Horizontal site characterization technologies present a rapidly evolving alternative to traditional vertical site investigation methods for subsurface investigations. A state-of-the-art review of horizontal site characterization tools, both currently available and under development, is presented in this chapter. Several case histories in which these techniques were successfully utilized are listed. Additionally, a rational methodology for the selection and deployment of horizontal site investigation techniques in trenchless construction projects is also presented. The methodology enables the user to define and quantify specific risks associated with a particular project, as well as to evaluate the degree to which these risks can be mitigated using various site characterization techniques. The proposed model is demonstrated using a working example. The chapter concludes with a discussion of future trends in this field.

Planning, design and estimating decisions for underground construction are strongly influenced by the uncertainty associated with subsurface conditions. The quality and quantity of geologic information available during the design and bidding phases have a significant impact on the selection of construction methods; estimated

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[1] Submitted for publication consideration in *J.Constr. Engrg and Mgmt*, ASCE, Nov. 2000

production rates, ground movements, jacking forces, shaft design and maximum drive lengths; and, the amounts of contingencies included in the bid (Klein et al., 1996; Capozzoli, 1996). For example, a review of contractor bids submitted for the tunneling of the final section of Boston's new Metro-West aqueduct found them to be within a range of 3%, a value significantly lower than the 20% typically seen on this type of project. This was attributed to continuous horizontal coring data that was made available by the owner during the bid process (Dawson, 2000). The geological information provided might also be used as a basis for claims and lawsuits in case the contractor encountered substantially different ground conditions during construction.

The most suitable method for mitigating risks associated with uncertain subsurface conditions is the performance of an adequate geotechnical site investigation. This is particularly true for trenchless construction methods, a generic term for a number of techniques for conducting underground installations with minimum surface disturbance. The complexity and limited surface access associated with these methods makes them significantly more sensitive to adverse ground conditions in comparison with traditional open-cut methods. Potentially obstructing the advancement of the cutting head, adverse subsurface conditions may result in the halting of the construction process. Consequences may include the excavation of emergency shafts or other costly remediation measures, lengthy delays, abandonment of the alignment, and even the loss of excavation/drilling equipment (Sylwester, 1997; Allouche and MacAulay, 1999). Table 5-1 shows the degree of susceptibility of six underground construction methods to various natural and manmade adversities, defined as safety-critical features that have the potential to do harm. Additional discussion of the impact of various geological factors on different trenchless construction methods can be found in Mathy and Nielson (1999) and Allouche (1999).

Table 5-1 Level of Susceptibility of Trenchless Technology Methods to Potential Adversities

Method	Boulders	Gravel/ Cobbles	Mix Face	Flowing Sand	Coal Seam	Buried Struct.*	Cemented Soils	Artesian Aquifers	High GWT
Microtunneling (Slurry Method)	M-S for > D/3	M	M	M-S	M-S	M-S	M-S	S	L
Microtunneling (Auger Method)	M-S for > D/3	M	M-S	M-S	M-S	M-S	M-S	S	M-S
HDD	M	S	L	M-S	L-M	M-S	L-M	S	L-M
Pipe Ramming	M-S for > 0.9D	M	L	S	L	M-S	M	M	L-M
Pipe Jacking – Hand Excavation	L	M	L-M	S	S	M-S	M	S	M-S
Tunnelling-TBM	M	L	M	M-S	M-S	M-S	M-S	S	L
Tunnelling – Hand Excavation	L	M	L-M	S	S	M-S	M	S	M-S

S = Severe; M = Moderate; L= Limited; D = Diameter of Boring Machine
*Depending on nature of buried structure

The vast majority of trenchless construction methods for the installation of pipes and conduits, such as utility tunnelling, microtunneling, horizontal directional drilling and pipe ramming, are linear in nature and performed horizontally. However, site investigations traditionally are performed using vertical drilling technology, where information provided by a few small diameter vertical boreholes is used to predict the geological conditions expected to be encountered along the entire alignment. Used alone, this form of discrete sampling and data extrapolation relies on the simplistic, and in many cases inaccurate, assumption of homogeneous subsurface conditions between the boreholes. Since only a small fraction of the volume of the proposed excavation is investigated (typically around 0.05%), it is not unlikely that the presence of significant features along the alignment will be missed (Dawson, 2000; Frank et. al, 2000). Additionally, vertical drilling presents several technical limitations, as the drilling rig must be located above the location of interest. Thus, the collection of soil samples from beneath surface bodies of water or large structures, potentially the most critical segments along the alignment, is costly and at times impractical.

A more efficient method to determine the subsurface conditions along the proposed alignment may be by combining horizontal directional drilling technology with devices capable of soil sample collection, horizontally deployed contact sensors and/or the use of borehole geophysical logging tools. Valuable information regarding soil properties and the presence and location of possible obstacles can be obtained continuously along the proposed alignment. The move from discrete to continuous subsurface data collection could result in significant improvement in the quality and quantity of information available to the contractor and consultant. This, in return, may result in a better design, reduction in the average bid price, productivity improvement and elimination of a major cause for claims and lawsuits (Hinze and McClelland, 1997; Ioannou, 1988). The first part of this chaptr provide a state-of-the-art review of current horizontal site characterization techniques including both, commercially available technologies as well as technologies currently under development. A summary of recent projects in which horizontal sampling and logging technology was utilized is also provided.

Horizontal site characterization technology, while a promising field, is still in its infancy. Little published material and field data are currently available to any one who is considering horizontal site investigation for his project. One approach to promote the utilization of these technologies among practicing professionals is the development of a decision support model that will assist in the planning of horizontal subsurface investigations programs. A framework for one such decision support model, named EXSHSIble (EXpert System for Horizontal Site Investigation) is described later in the chapter. This eight-step methodology assists in quantifying the risk and determining the most suitable site characterization scheme for a particular project. EXSHSIble's underlining methodology is demonstrated using a hypothetical 2.4m diameter microtunneling project.

5.2 BACKGROUND – UNFORESEEN SUBSURFACE CONDITIONS

The term 'risk' can be defined as a "chance of loss or injury, the degree of probability of loss" (Webster New Dictionary, 1990), and can be said to be derived from our inability to see into the future (Palisade, 1992). In the context of construction, risk can be described the possible consequences (financial or otherwise) of a decision that was made based on incomplete knowledge regarding site conditions, weather conditions, equipment capabilities, crew experience and other factors that may have an effect on a project's execution. This is particularly true in the case of trenchless construction where planning, design and estimating decisions are strongly influenced by the uncertainty associated with subsurface conditions. In fact, unforeseen subsurface conditions are the prime source of project delays, disputes, claims and cost overruns in underground construction projects (Temple and

Stukhart, 1987; Bartsch and Jergeas, 2000). The annual costs associated with unforeseen subsurface conditions and costly 'emergency' events in underground construction projects across the U.K. alone are estimated at 1.5 billion U.S. dollars a year due to fatalities and injuries, cost and schedule overruns, damage to adjacent buildings, and environment damage and litigation costs. Based on a review of over 150 'emergency events' in underground construction worldwide, Anderson (1998) concluded that the most common primary reason was "failure to perform and plan ahead for critical changes in the properties of the tunnelling medium".

This failure can be attributed to several reasons; namely, owners' attitude, difficulties in quantifying the benefits of a site investigation program and the practical limitations of current site characterization techniques. Some owners attempt to minimize the risk associated with unknown ground conditions by using contractual provisions to shift the entire liability associated with adverse ground conditions to the contractor (Frank et al., 2000). Others either ignore these risks or deal with them in an arbitrary manner by assigning contingency sums in the form of force accounts (Hayes et al, 1987). This approach may not best serve the owner's interests because the contractor, faced with little or no geological information, may simply assume the worst possible ground conditions. Thus, the owner may pay for costs that are never realized (Hinze and McClelland, 1997).

Adams et al. (1993) studied a number of microtunneling projects in Europe and showed that the retention of a significant share of the risk by the owner is likely to reduce the final cost of the project. Also, faced with extreme losses due to unexpected subsurface conditions, the contractor may simply walk away from the job or declare bankruptcy, both undesired outcomes that may translate to delays and additional costs to the owner. Many owners have realized this, and a recent trend is the issuance of a geotechnical baseline report that provides the basis upon which contractors prepare their bids. The second reason for failure to perform adequate site investigation is the limited success of engineers in establishing the added benefits from additional monetary investment in the site investigation program, beyond elementary requirements, in the form of a cost-benefit ratio. Peacock and Whyte (1992) stated that while proper site investigation has a major economic value, its attributes are difficult to quantify. They concluded that the lack of ability of engineers to quantify the benefits of a comprehensive site investigation is a key reason for failure of owners to realize its true value. A method for computing the cost/benefit ratio from a given level of investment in the site investigation program is presented in the second part of this paper.

The third reason is the technical limitations of common site characterization techniques. Currently, geological information provided to bidders is most often obtained from a finite number of small-diameter vertical bores located at intervals along the alignment. Soil profiles between the boreholes are generally considered to be uniform, thus ignoring the heterogeneous nature of many geological formations. Also, it is quite possible that the subsurface investigation may bypass significant underground features that may have an adverse effect on the construction process such as old water courses infilled with coarse soil. However, drilling numerous vertical boreholes in a denser pattern to provide a complete picture of the subsurface conditions is, in many cases, not technically and/or economically feasible.

Additionally, vertical site characterization techniques cannot reach beneath structures, roadways, pipeline-right-of-ways and environmentally sensitive areas, the very same locations where encountering an obstacle or adverse geological conditions will have the most disastrous effect on the construction project (O'Reilly and Stovin, 1992).

A rapidly evolving alternative to traditional site investigation methods are horizontal site characterization technologies, including a family of soil samplers, contact sensing probes and borehole geophysical tools capable of providing information regarding subsurface conditions while traveling along a horizontal bore.

5.3 HORIZONTAL SITE CHARACTERIZATION – AN OVERVIEW

The concept of collecting geotechnical data along horizontal bores is not new. During the mid-1970s the Department of Transportation Federal Highway Administration (FHWA) initiated a research effort to determine the feasibility of horizontal boring for geotechnical investigations as an alternative to vertical boring, prior to the design and construction of tunnels (FHWA, 1976). The study was divided into three separate topics, namely drilling, exploration and economics. Under drilling, preliminary designs were developed for equipment capable of horizontal continuous penetration to a maximum distance of 1500m. Under exploration, the technical feasibility of combining geophysical and contact sensing techniques with horizontal penetration was evaluated. As for the cost of exploration, this was estimated at $5000-$7000 (1999 dollars) per linear meter, and deemed economically feasible only for tunnels deeper than 30 meters, or tunnels located below environmentally sensitive areas.

Rapid development in the areas of steering and tracking capabilities as well as penetration range of horizontal directional drilling equipment over the past ten years have made horizontal site characterization economically feasible. Today it is estimated that the cost of a horizontal site characterization project (including drilling, sampling and geophysical logging and interpretation) is in the range of $250-$500 per linear meter, representing a cost reduction of more than 90% in comparison with the costs estimated by the FHWA report. This has led to renewed interest in this field and consequently to a recent wave of research effort towards the development of effective exploration equipment. Some of these efforts are reported by Miller (1994), Dowell and Tokle (1998), Clementino et. al (1999) and Ariaratnam et. al (2000).

Potential techniques to be used in conjunction with horizontal drilling are derived from the fields of geotechnical and geoenvironmental investigations, oil and gas explorations, and mineral explorations (mining). One possible classification of these techniques is shown in Figure 5.1. Table 5-2 summarizes the properties of horizontal sampling and contact sensing probes either commercially available or under development around the world. Deployment of direct contact sensors, such as Cone Penetration Testing (CPT), in a horizontal bore drilled at the depth of interest increase their accessibility and reduce the cost per test performed, as it is no longer necessary to penetrate the formation above the depth of interest for each data point. In many cases, current technology can be easily adapted for direct deployment in a horizontal bore (e.g., conductivity sensors) while in other cases modification of existing devices is required (e.g., CPT). Additional information regarding the devices listed can be found in the cited references.

Table 5-3 presents the characteristics of several borehole geophysical methods that may be used for the characterization of proposed alignments of trenchless construction projects. Aside from information regarding the location of interfaces between various substrates, geophysical methods may also be used to identify the presence and location of subsurface anomalies in the vicinity of the alignment such as boulders, pockets of saturated sand, large voids, buried structures or metallic waste. In particular, ground penetrating radar (GPR), acoustic imaging, seismic, and magnetic susceptibility can identify the presence of buried objects located as far as 10m away from the centre of the borehole. Resolution is inversely related to depth of penetration and is a function of the target average dimensions, with the upper limit of resolution ranging around 10 times the target average dimensions, depending on the properties of the host formation. Target size can be considered to be the long dimension of the target. For example, in the case of thin but long features, such as pipes and conduits, the upper limit of resolution can be as high as forty times the conduit diameter (Miller, 1994).

The successful application of surface geophysical surveys for site characterization of trenchless pipeline projects performed in green-field conditions was recently reported by various authors (Franck'e, 1997; Sylwester, 1997; Knight, 1999). However, in congested urban environments - common settings for trenchless projects – the usefulness of such surveys is limited by cultural noise from shallow conduits and cables that reduces their effective penetration depth and may mask the signature of deeper subsurface targets. Additionally, the presence of highly conductive substrate medium can significantly limit the penetration depth and resolution of electromagnetic methods. These problems can be overcome by deploying borehole geophysical tools at the level of interest, thus avoiding surface noise, increasing penetration depth and resolution, and focusing only on anomalies along the path of the proposed excavation.

There are two possible methods for horizontal deployment of geophysical tools. For shallow depths, images of the zone between the horizontal bore and the surface can be recorded (Figure 5.2). For deeper alignment a pulse-echo approach (i.e., transmitter and receiver are placed in the same bore) can be used to image the immediate area in the vicinity of the bore. Alternatively, a cross borehole investigation can be performed between two parallel horizontal bores. In any case, adding geophysics to the site investigation effort can result in effectively covering a volume of subsurface space that is two-orders of magnitude greater than if only exploration bores are used.

5.3.1 Recent Case Histories

While still in its infancy, horizontal site characterization techniques already have a track record. A list of sample projects completed in recent years in North America and Norway is provided in Table 5-4. To date, it appears that horizontal sampling in soils is used primarily on environmental projects, while rock coring is used in site investigation for tunnels to be placed in complex geological formations. Geophysical logging is used predominantly for large diameter trenchless projects in soft soils.

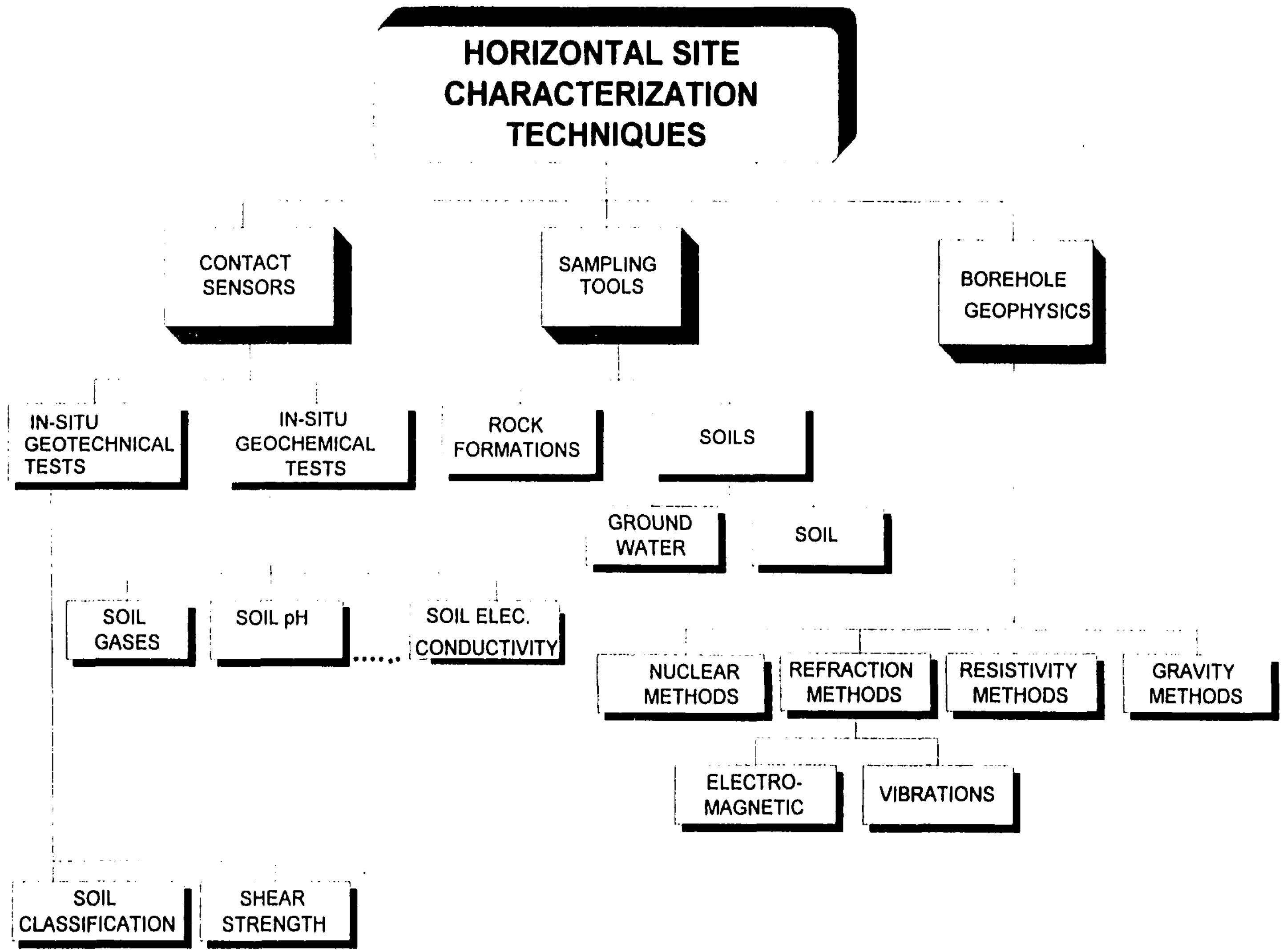

Figure 5.1 Applications of Horizontal Sampling and Logging

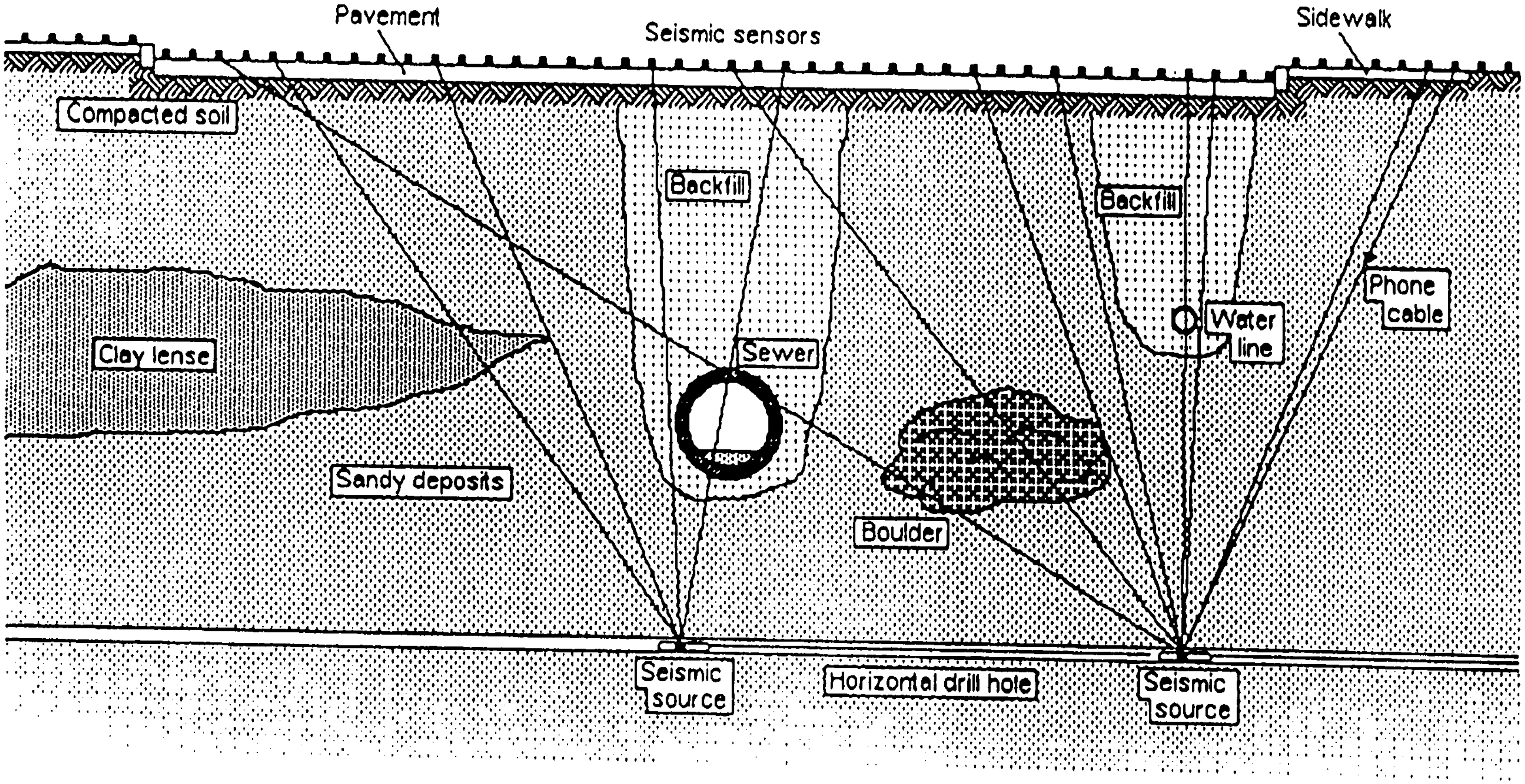

Figure 5.2 Subsurface Imaging Using Seismic Technology Between Surface and Horizontally Drilled Bore (After Miller, 1994)

Table 5-2 State-of-the-Art: Horizontal Sampling and Soil Classifications

Name	References	Description	Comments
Multiple-Port Soil Sampler	Ariaratnam et al. 2000.	A soil-sampler capable of collecting up to six samples from the wall of a horizontal borehole during a single pass. The sampler is controlled from the surface via a laptop computer. High quality samples. Sampler: Length: 1000mm; Diameter: 190mm; Punch Force: 8.8kN; Sampling tube: Diameter: 20mm; Length: 200mm	Deployed in a pre-drilled continuous borehole. Suitable for cohesive and unconsolidated soils. Capable of collecting 6 samples as well as deploying miniature CPT that provides information regarding soil classification, shear strength and unconfined compression strength.
Ditch-Witch Soil Sampler	Ditch Witch, 1996.	After the pilot bore is completed the device is advanced into the borehole following original alignment. A sampling tube is opened using vibration and a soil sample is collected. Soil sample collected is of relatively low quality. Sampler: Length: 0.5m; Diameter: 62mm; Sampling tube: Diameter: 50mm; Length: 305mm	Suitable for soft to firm cohesive soils as well as unconsolidated soils. In soft ground sampler may deviate from path of pilot bore.
Punch-Master 2000	Karlsson, 1993.	After the pilot bore is completed the device is advanced into borehole following original alignment. Operates similarly to a Shelby tube. Activated by hydraulic pressure. Samples collected of high quality. Sampler: Length: 7m; Diameter: 120mm; Max. Punch Force: 105kN; Sampling tube: Diameter: 50mm; Length: 1.5m	Can be used only with medium size or large rigs. Suitable for a wide range of soil conditions.
Devico Continuous Rock Coring Method	Tokle, 1997	Normal rock drilling techniques are used to advance drilling string to target area. Mud motor system then collapsed, pulled to surface through drilling pipe, and replaced with a steerable core barrel. Cores samples are retrieved using a trip-wire. Suitable for competent and weathered formations. Coring tube diameter: 50-150mm; Coring tube length: 3m; Max. range: 1500m	Involves specialty equipment and thus it is a relatively costly method. Suitable only for rock formations.
Standard Core Barrel	Williamson, 1972.	Diamond drilled horizontal holes are performed on a regular basis in the mining industry. Range 300-1000m.	Steel wedges are utilized to steer the drill string that greatly slow advancement and reduced accuracy.
Microdrilling	Albright, 2000.	A 50mm diameter coiled tubing equipped with a drill bit and mud motor. Range 100-150m; suitable for alluvial sediments as well as rock formations; data collection using miniature geophysical tools.	Currently under development by the U.S. Department of Energy / oil and gas exploration industry
Horizontal Directional Pre-bore Cone Penetration	Clementino et al, 1998.	The cone is pulled through a 100mm diameter pre-bored hole. Data related to tip resistance and sleeve friction is transmitted to surface providing information regarding various geotechnical parameters. Length: 1.0m; Diameter: 150mm	Susceptible to the degree of disturbance of the formation caused by the drilling operation as well as the presence of drilling fluids. Currently it is in the experimental stage.

Table 5-3 Review: Borehole Geophysical Tools

Method	Description	Detection Capabilities	Casing	Effect of Drilling Fluid	Depth of Penetration
Ground Penetrating Radar	High frequency electromagnetic signals are reflected and refracted at interfaces between media with contrasting dielectric constants and/or electrical conductivities. Measures dielectric of formation. Can be performed in either a single bore or parallel bores configuration.	Buried man-made objects, drums and utilities; tree logs and boulders; location, extent and orientation of fractures and fracture zones. Inorganic contaminants.	Uncased or cased (non-metallic)	Signal attenuation with highly conductive fluids	Inversely proportional to vertical resolution penetration/ resolution ratio ~ 10.
Acoustic Televiewer	Scans the borehole with a focus beam of ultrasound. Applications in fracture identification and orientation, borehole imaging and downhole stress studies.	-----------	Uncased, water-filled.	Minimal	Inversely proportional to vertical resolution
Seismic	Sound waves omitted from a source, typically an air hammer, are received by a receiver located in a remote location (e.g., parallel borehole). Arrival times of the P and S waves are measured to identify anomalies in the formation (e.g., areas of high/low density).	Capable of indicating presence of obstacles in 3-D space as well as information regarding degree of saturation in sands. Can show interfaces between materials; indication of soil modulus	Uncased or cased (preferred grouted)	Minimal	Deep
Magnetic Susceptibility	Measures variations in a planar magnetic field. Determines the presence and position of magnetic materials.	Inorganic– metallic wastes; Utilities and buried drums	Uncased or cased (non-metallic)	Minimal	Deep
Electro-magnetic Induction	Indirect measurement of water & clay contents. Determines formation and formation's fluid conductivity or resistivity.	Metallic utilities and other manmade objects.	Uncased or cased (non-metallic)	Signal attenuation with highly conductive fluids	1-3m depending on conductivity of surrounding media.
Microgravity	Measures variations in a planar gravitational field. Detect presence of substantial density variations.	Large dense objects or large voids	Uncased or cased	Minimal	Deep

Table 5-4 Recent Case Studies in Horizontal Site Characterization Projects

Name	Description	Comments
Renton, WA (1998)	Pre-construction site investigation for a 1.8m culvert beneath SR 167. Horizontal logging tools include GPR, induction, gamma and seismic.	A large number of targets were identified along the proposed alignment. Promoted change of the crossing's location. Project subsequently completed uneventfully using pipe ramming.
Consort, AB (1998)	Ditch-Witch soil sampler was used to collect a number of core samples from beneath a public facility for the purpose of contaminant identification.	Completed successfully. Shutdown of facility was avoided.
Oak Ridge, TN (1998)	Application of geophysics including induction and GPR for identification of obstructions along a proposed pipe bursting alignment.	Completed successfully. Several metallic obstructions were detected and removed. Pipe bursting project performed uneventfully.
Edmonton, AB (1998)	Demonstration of horizontal bore geophysical logging. Horizontal logging tools include induction, natural gamma and neutron.	The geophysical logs clearly identified the interface between the clay and the sand layers as well as the location of a nearby vertical well with a steel case.
Boston, MA (1997)	Identifying the location of steel tieback cables that might be encountered during the boring of a new sewer alignment.	Magnetic induction, magnetic susceptibility and magnetic logging were used. Completed successfully and resulted in change of alignment.
Everett, WA (1997)	Horizontal logging of a pilot bore drilled ahead of a microtunneling machine, which encountered debris while excavating beneath a four-lane highway.	Several possible targets were identified. Contractor decided to take the risk and continue boring. The TBM was jammed and required the initiation of a costly recovery operation using a pipe jacking technique.
MetroWest, MA (1997)	Devico's horizontal coring system was used to bore a 600m long bore along the proposed alignment of a 4.3m diameter tunnel.	Project completed successfully.
Trekantsambandet Tunnel, Norway, (1997)	The Devico coring system was used to drill two boreholes with a total length of 1800m along the proposed alignment of the undersea tunnel.	A weak zone along alignment was identified, requiring the selection of a deeper alignment.
Elk River, BC (1992)	Ground penetrating radar survey in advance of a proposed HDD pipeline river crossing.	One of the first application of GPR for the purpose of a pre-construction survey in Canada.

5.4 AN EXPERT SYSTEM FOR HORIZONTAL SITE INVESTIGATION (EXSHSIBLE)

5.4.1 Overview

The literature reports several early works related to the development of computer-based decision support systems for evaluation of geologic exploration programs in underground construction. Peacock and Whyte (1992) demonstrated MIRA, a risk analysis program developed to assess the implication of uncertainty in geological parameters on the cost and duration of subsurface-related activities. Work performed by Chan (1981), Kim (1984) and Ioannou (1988), aims at constructing a description of underground conditions based on all available sources of information (e.g., geological maps; borehole logs; and expert opinion). Ashley (1981) proposed a probabilistic approach for evaluation of geologic exploration programs for hard-rock tunnelling projects. The approach described in this paper expands on this previous work by providing the user with the likelihood of detecting the presence of specific geological phenomena or obstacles, within a tunnel medium or in its vicinity that may present difficulties during construction, or may influence the selection of the construction method. Specifically, the objectives of the proposed computerized system, designated EXpert System for Horizontal Site Investigation (EXSHSIble) are as follows:

1. To identify and rank horizontal site characterization tools that can most benefit a given geotechnical investigation program based on: a) the anticipated hazards; b) applicability of the methods to local geological conditions; c) physical properties of the alignment (e.g., length; diameter), and; d) the nature of the required information.

2. To quantify the benefits obtained from the proposed site investigation scheme in terms of uncertainty reduction with respect to the presence/absence of specific hazards along the proposed alignment.
3. To perform preliminary cost estimates and cost/benefit analysis.

The information to be evaluated by EXSHSIble is in part deterministic and in part qualitative in nature. Thus, the proposed model utilizes a hybrid approach where deterministic mathematical relationships are used to quantify risk and to compute the probability of detecting a given risk, while an expert-based system is used to select the best site investigation scheme given a predetermined set of project parameters and user requirements. An expert system approach was selected for this task, because it is capable of reaching an acceptable solution even when limited knowledge exists, as is the case with estimating performance capabilities of the various geophysical methods. A schematic flowchart of the proposed system is presented in Figure 5.3.

In many cases it is not obvious what the optimum level of investment in geotechnical exploration should be, as it is difficult to quantify the benefits obtained from a given exploration effort. As a result, the amounts allocated to site exploration are often less than they should be. One of the goals of the proposed decision support system is to enable the user to quantify the amount of risk mitigation that can be achieved using a particular site characterization scheme. The use of continuous monitoring along a confined space (i.e., proposed conduit cross section area), together with an estimate of the accuracy and effective range of the various characterization methods, provides sufficient constraints to mathematically compute the confidence of detecting the presence/absence of a given phenomenon along the alignment using a given set of site characterization techniques. An eight-step methodology for the decision-support system is demonstrated using a hypothetical project involving the installation, 2.4 m diameter, 192m long, concrete pipe beneath a river. It is assumed that the dominant type of soil is dense silty-sand and the proposed construction method is the earth pressure balance microtunneling technique. It is further assumed that the installation will take place at an average depth of 4 meters.

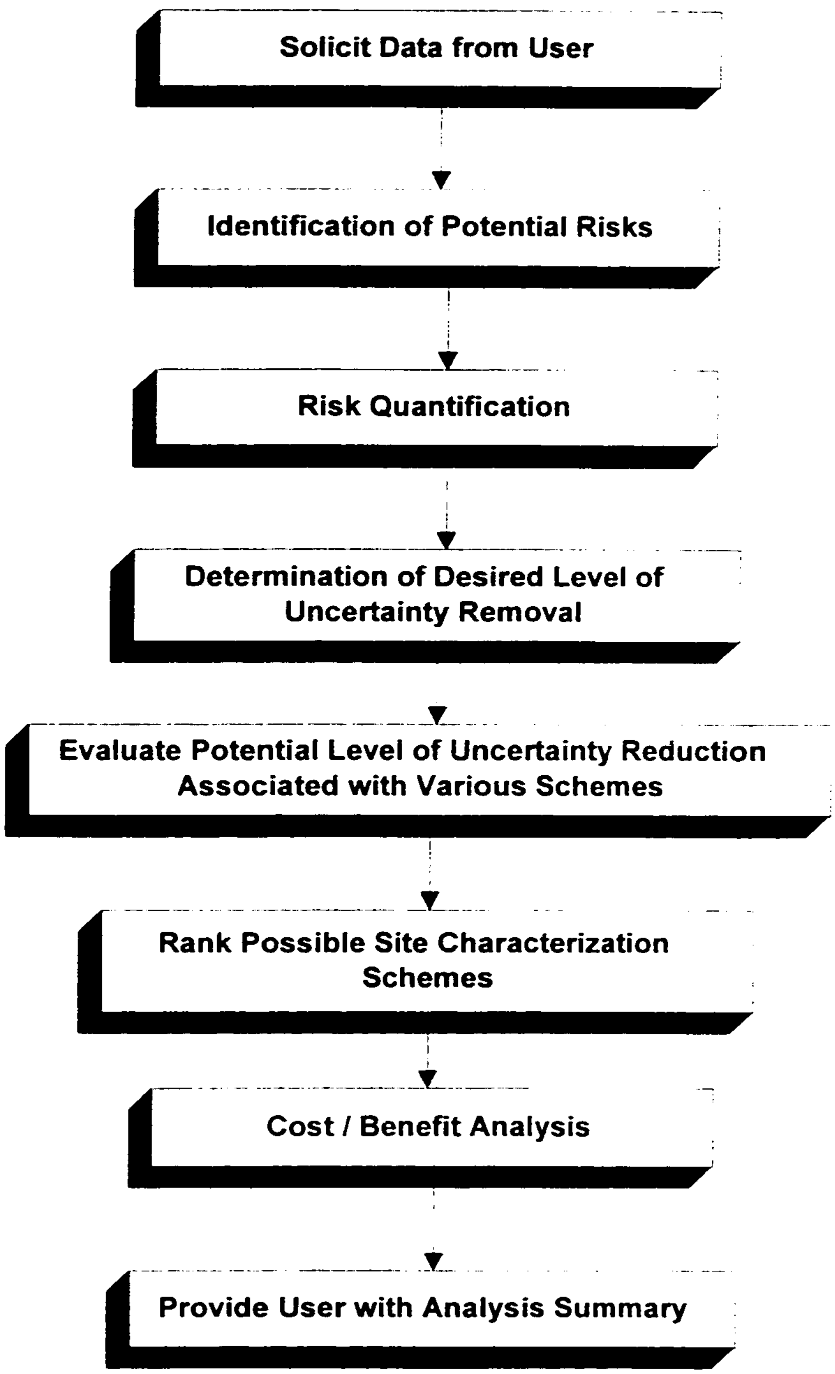

Figure 5.3 Flow Chart of Proposed Decision-Support System

5.4.2 Outline of Proposed Methodology

Step 1: Solicit User Information

One of the first steps in every decision support system is the soliciting of information from the user regarding his/her needs and preferences as well as project parameters. Information solicited from the user includes:

Desired data (e.g., soil classification; delineation of geological units and their engineering properties; groundwater conditions; presence/absence of buried obstacles; contaminants).

1. Installation parameters (i.e., length, diameter, target depth).
2. Expected construction method (e.g., microtunneling).
3. Anticipated dominant formation (e.g., clay, silt; sand; gravel; sandstone; rock).

Step 2: Identification of Potential Risk

Risk can be considered to have four dimensions: perception or identification, likelihood, consequences, and the apparent benefits from taking the risk. In underground construction the apparent benefit is the completed product (e.g., tunnel). As for perception, potential risks that might be present along the alignment are identified based on site conditions, dominant formation type, historical data and the proposed excavation methodology. For the example used, the following five hazards were selected for consideration from Table 5-1: boulders, cobble seam, flowing sand, high groundwater conditions and the presence of an artesian aquifer. Consequences are considered in step 3 while likelihood is dealt with in step 4. The costs given in Table 5-5 as well as the likelihood values given in Table 5-6 are based on the assumed project's characteristics and the limited knowledge of the author in this field.

Step 3: Quantifying Consequences Using A Heuristic Approach

The potential damage (in monetary value) due to an encounter with a given hazard is a function of the potential consequences and their associated costs as well as the susceptibility of the excavation method to the hazard under consideration. For example, the following is a list of potential consequences associated with encountering a hazard along the alignment:

- Delay - downtime / double shifting / loss of opportunities.
- Need for an emergency excavation (i.e., 911 shaft).
- Damage to the excavation equipment.
- Loss of the excavation and the recovery of the excavation equipment.

The cost incurred due to the realization of each of these consequences can be estimated using the expected monetary value (EMV) methodology. Table 5-5 shows a hypothetical series of probabilistic cost estimates for the realization of the various consequences. In practice these estimates will be suggested by experienced field personnel or generated from historical records, with site-specific factors taken into account. For each element the sum of probabilities is equal to 1.

Table 5-5 Estimated Cost Probability Distribution for Various Consequences

Risk	Cost interval ($x1000)							
	$0-10	**$10-25**	**$25-50**	**$50-100**	**$100-250**	**$250-500**	**$500-1M**	**EMV**
Delay	0.30	0.60	0.10	0.00	0.00	0.00	0.00	$15,800
911 shaft	0.10	0.50	0.35	0.05	0.00	0.00	0.00	$26,100
Damage to Equipment	0.00	0.1	0.30	0.5	0.08	0.02	0.00	$72,000
Recovery Operation	0.00	0.00	0.00	0.05	0.45	0.3	0.2	$345,000

* Values in shaded area represent the probability of occurrence

The expected monetary value (EMV) of each potential consequence can be readily calculated as the sum of all the cost elements multiplied by their probabilities. Costs lying in the interval $0-$10,000 are considered to be concentrated at $5,000; for the interval $10,000-$25,000 at $17,500, etc.

Table 5-6 shows the consequences and their associated probabilities for the example under consideration. The probabilities reflect the likelihood that a particular risk (e.g., severe delay) will materialize if a given hazard (e.g., cobble seam) is encountered.

Table 5-6 Likelihood of Consequence Occurance for a Given Hazard

Hazard	**Delay**	**911 shaft**	**Damage to equipment**	**Recovery operation**
Boulder	1.0	1.0	0.10	0.01
High GWT	0.20	0.00	0.00	0.00
Cobble seam	0.75	N/A	0.10	0.20
Flowing sand	0.90	N/A	0.30	0.30
Artesian aquifer	1.0	N/A	0.60	0.50

Thus, the total cost of foreseen damages for a given hazard can be computed by multiplying the probability of occurance of the individual risks by the relevant EMV, as shown in Table 5-7.

Table 5-7 Risk Quantification ($x1000)

Hazard	**Delay**	**911 shaft**	**Damage to equipment**	**Recovery operation**	**Total**
Boulder	15.8	26.1	7.2	3.4	52.5
High GWT	3.2	0.0	0.0	0.0	3.2
Cobble seam	11.8	0.0	7.2	69.0	88.0
Flowing sand	14.2	0.0	21.6	103.5	139.3
Artesian aquifer	17.8	0.0	43.2	172.5	233.5
Grand Total of Foreseen Damages					**$516,500**

Step 4: Determine an Acceptable Level of Uncertainty for Each Type of Risk

The user defines the acceptable degree of uncertainty for a particular risk depending on:

1. Severity of the consequences (e.g., cannot afford any loss of human life or costs above $1,000,000).
2. The likelihood of a particular hazard being encountered based on site characteristics, historical records and the experience of the design team on similar projects. Descriptive terms (e.g., medium) may be used to describe the likelihood of an encounter, because in many cases it is very difficult to quantify prior to the performance of the site investigation program. A more systematic methodology for assigning a given hazard to a particular likelihood category using fuzzy membership functions is currently being developed.

The likelihood of an encounter and the acceptable degree of uncertainty (U/C) for the various hazards are summarized in Table 5-8.

Table 5-8 Evaluating Level of Uncertainty

Hazard	Total Cost	Likelihood	Acceptable Degree of U/C
Boulder	$52,500	High	50%
High GWT	$3,200	High	100%
Gravel seam	$88,000	High	50%
Flowing sand	$139,300	Medium	25%
Artesian aquifer	$233,500	Medium	25%

Step 5:Evaluating the Suitability and Performance of Site Characterization Methods

The suitability of various site characterization methods is evaluated using a rule-based expert system. Based on the anticipated local geological conditions, the proposed construction method, and the user information requirements, the expert system identifies suitable site investigation methods and estimates their effective penetration range, resolution, and detection reliability (discussed in detail later in the chapter). A detailed survey and a literature review were performed to gather detailed information regarding the operational capabilities and limitations of various horizontal sampling devices, contact sensors and borehole geophysical tools in order to construct the required database. Additionally, information was collected regarding the relevance of different types of geotechnical data for the design process of various construction methods (Allouche, 1999). The information collected was summarized in a series of tables and can be found in Appendix 'B'.

Step 6: Determination of Potential Degree of Uncertainty Removal

The proposed alignment is divided into a mesh (similar to a finite element mesh) comprised of cubical elements that are equal to the size of the diameter of the horizontal bore to be drilled (Figure 5.4). This approach views the pipeline alignment in three dimensions rather than the traditional two-dimensional profile.

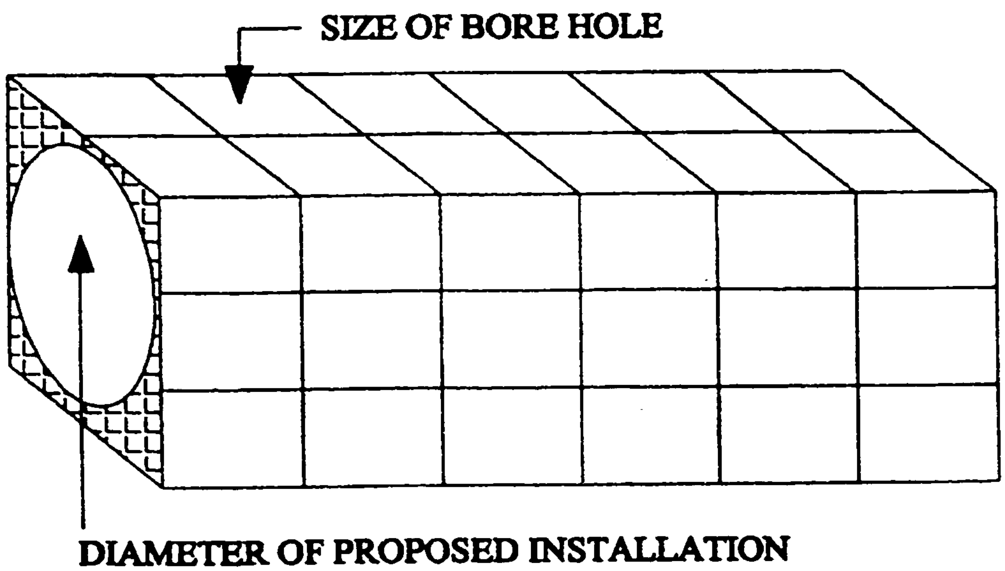

Figure 5.4 Mesh Presentation of a Potential Tunnelling Medium

The probability that a given hazard '*h*' situated randomly in element '*i*' will be detected is a function of the number of applicable detection techniques utilized and their 'detection reliability' values. The detection reliability value for a given method depends on the anticipated site characteristics and the distance between the element in question and the centre of the borehole. If the probability of detecting hazard '*h*' in element '*i*' using method '*j*' is E_{hij}, the probability of non-detection is:

$$\bar{E}_{hij} = 1 - E_{hij} \qquad \text{(Eq. 5.1)}$$

Equation (5.1) can be generalized for the case of *n* methods:

$$\bar{E}_{hi(1..n)} = 1 - E_{hi1} \cdot E_{hi2} \cdot \ldots \cdot E_{hin} \qquad \text{(Eq. 5.2)}$$

The average confidence in detecting the present of a given hazard '*h*' (CD_h) at a particular cross-section along the alignment can be computed by multiplying the number of elements within the operating range of each characterization method by its detection reliability value and dividing the sum by the total number of elements covered by these methods, as shown in Equation 5.3:

$$\bar{CD}_h = \frac{N_1\left(1-\bar{E}_1\right)+N_2\left(1-\bar{E}_2\right)+N_3\left(1-\bar{E}_1\,\bar{E}_2\right)}{N_1+N_2+N_3} \qquad \text{(Eq. 5.3)}$$

where N_1 is the number of elements covered only by method 1, N_2 is the number of elements covered only by method 2, and N_3 is the number of elements covered by both methods. The basic assumptions behind Equation 5.3 are:

1. Statistical independence between the probabilities of detection of the various methods.

2. There are only two possible events where either a hazard was detected or not detected at a given cross-section along the alignment, and these events are both, mutually exclusive and collectively exhaustive.

This concept of a "combined arms" system, where two or more site characterization methods are used in a complementary fashion in the same bore (or between parallel bores) to enhance confidence and avoid false positives and negatives is also discussed in Miller (1993). Equation 5.3 can be extended to compute the combined probability of detection using any number of detection methods (Ang and Tang, 1975).

For the purpose of our example, computations were performed for the detection of a boulder with average dimensions of 0.80m (=D/3) using two different borehole configurations: a) a single borehole at the centre of the proposed tunnel's cross-section; and b) two bores, diametrically opposite, 0.9m away from the tunnel centreline. It was also assumed that two geophysical tools, ground penetrating radar and cross-hore seismic will be employed, with detection reliability values of 0.6 and 0.5 respectively. The detection capability within the horizontal bore cavity is 100% (if a boulder is present, the drill head will encounter it). Using a single borehole at the centre of the proposed alignment, and assuming an effective investigation range of 0.9m, the detection confidence value at each cross-section achieved using two investigation methods (drilling and GPR) was computed to be 36%. Using two bores at 1.8m center to center spacing, and two investigation methodologies (GPR and cross borehole seismic), the average detection confidence was increased to 59%. Determining the effective penetration range (i.e., number of mesh elements covered by a given method) and the detection reliability values for various geophysical methods in different formations is a far from a trivial exercise, and was identified as a future area of research. Assuming a reliability value of 0.75 and a penetration depth of 1.0m, average detection confidence values were determined for the remaining hazards listed in Table 5-7, for the case of three detection methods (GPR, seismic and induction) utilised in two parallel horizontal bores. The results are summarized in Table 5-9.

In its current form EXESIble is mainly concerned with the detection of specific hazards along the proposed route rather than a general description of the subsurface conditions. Consequently, it provides limited weight to intrusive site investigation methods that provide high quality information regarding a small volume of host medium. For example, if the horizontal site characterization scheme described above is supplemented by data obtained from two vertical bores located at the proposed location of the driving and reception shafts, the average detection confidence for boulders will increase by 0.28%, as this is the volume of the proposed alignment actually covered by the vertical bore. A more realistic approach would be to assign an 'influence zone' for data obtained from intrusive site characterization methods, with a reduced confidence derived as a function of the distance from the point of application and the nature of the hazard under consideration. While outside the scope of this study, further investigation of such an approach is recommended in future work.

Step 7: Ranking of Site Investigation Methods

The various site characterization schemes identified by the model are ranked using an 'Uncertainty Reduction Index' (URI) in order to identify the most suitable approach. The value of URI is computed using the following expression:

$$URI = \frac{\sum_i (\text{Acceptable U/C} - \text{Achievable U/C}) * (\text{Anticipated Cost,\$})}{\text{Total of Foreseen Damages}} \qquad \text{(Eq. 5.4)}$$

where i is the number of hazards considered in the analysis; anticipated costs are obtained from Table 5-7, column 7; and the URI for a given hazard i cannot be less than zero. A possible output for our example is given in Table 5-9, where ΔU/C is the difference between the acceptable and achievable degree of risk reduction. The smaller the value of URI the more closely the proposed scheme meets the user's requirements.

Table 5-9 Summary of Model's Output

Risk	Investigation Method	Degree of Risk Reduction		ΔU/C	ΔU/C* Damages
		Achieved	Acceptable		
Boulders	Drilling, GPR & Seismic	59%	50%	-0.09	0
Presence of GWT	Induction	68%	0%	-0.68	0
Gravel Seam	Drilling & GPR	43%	50%	0.07	$6,657
Flowing Sand	Drilling, GPR &Induction	65%	75%	0.15	$21,660
Artesian Aquifer	Drilling	100%	75%	-0.25	0
URI					0.052

Step 8: Cost/Benefit Analysis

Based on the recommended site characterization scheme a preliminary cost estimate and a cost-benefit analysis are performed using generic cost data. This module is described in the next section.

Summary

The proposed combination of site characterization tools for the above example includes the utilization of a borehole GPR, a cross-borehole seismic survey and a borehole induction survey. Two 100mm diameter horizontal bores will be placed 0.9m away from the alignment's centreline, at the level of the proposed pipe's springline. The bore will be cased using a non-metallic pipe such as PE, PVC or fibreglass.

5.4.3 Cost-Benefit Analysis

The cost estimate for the example project considered here is summarized in Table 5-10. The installation costs per linear meter for various diameters of carrier pipes can be derived using the following relationship (Allouche et al, 2000):

Cost, \$/L.M. = 0.858 x (product diameter, mm) (Eq. 5.5)

Table 5-10 Summary of Cost Estimate

Description	Unit Cost	Quantity	Subtotal
Drilling (2 pilot bores; each 100mm in diameter)	\$86/m	384m	\$33,024
Carrier pipe (100mm HDPE SDR 13.5)	\$7/m	390m	\$2,730
GPR (logging + analysis)	\$15/m	384m	\$5,775
Induction (logging + analysis)	\$4/m	384m	\$1,536
Seismic	\$12/m*	384m	\$4,608
TOTAL			**\$46,917**

*Depending on the number of stations

Average costs for the deployment and analysis of geophysical tools were obtained from the model's database (Appendix 'B'). The total cost for investigating a linear meter along the alignment was determined to be approximately $245. Using values of $1500 and $3250 per linear meter for materials and construction costs (Thompson et al., 1998), respectively, and an allowance of 10% for design and supervision, the cost of the project was estimated to be $1,003,200. Thus, the cost of the proposed site characterization program represents about 4.6% of the construction costs.

When evaluating the return on investment in a horizontal characterization project one should consider both the tangible as well as intangible benefits. These include the cost of remediation/losses due to an encounter with an obstacle or adverse ground conditions; potential reduction in bid price; increased effectiveness of the design and construction process; and, the reduced odds of claims and mitigation. As little information is available regarding the relationships between the quality of the geotechnical data and the above mentioned benefits, a simple approach was adapted. The reduction in average bid price is expressed as a percentage of the engineer's cost estimate and is considered to include both the potential for increased effectiveness of the design and construction processes and the reduced contingency. Similarly, the monetary benefit anticipated from reduced odds of claims and mitigation is expressed as a percentage of the average value of claims from similar projects. The cost benefits associated with a reduced likelihood of an encounter with an unknown hazard (due to better subsurface information) can be expressed as the product of the anticipated losses due the occurrence of a given risk event, the probability that the risk event will take place if a given hazard i is encountered, the likelihood of encountering hazard i, and the achievable degree of uncertainty removal by the proposed investigation for hazard i. A mathematical expression of the above derivation is given below:

$$ROI = \frac{\sum_{0}^{I}(A_n * P_{ni} * LOE_i * AR) + (\alpha * EES) + (ACV * \beta)}{C} \quad \text{(Eq. 5.6)}$$

where,

ROI = Return on investment

A_n = Anticipated cost of losses/remediation for a given risk event (e.g., delay),

P_{ni} = Probability of an event n taking place given an encounter with hazard i (e.g. boulder),

LOE_I = Likelihood of encountering hazard i (e.g., medium)

For the purpose of this example, the following ranges were assigned to the descriptive terminology used in Table 5-8:

High - $0.5 \leq$ LOE < 1

Medium - $0.2 \leq$ LOE < 0.5

Low - $0.0 <$ LOE < 0.2

AR_I = Percent of achievable uncertainty removal by proposed investigation for hazard i.

EES = Engineering Estimated cost for project

α = Percent reduction in bid price due to availability of additional subsurface data (estimated or from historical data)

ACV = Average claim value for similar projects (estimated or from historical data)

β = Percent reduction in claims value due to availability of additional subsurface data (estimated or from historical data)

C = Cost of proposed site characterization program.

Assuming α = 5%; ACV = 10% of contract value; β = 0.3; and using the mid-range values for LOE (0.75, 0.35, and 0.1 for High, Medium and Low, respectively), the return on investment (ROI) for the proposed subsurface investigation program was found to be 5.4. The ROI is expected to increase rapidly for longer or larger diameter installations.

5.4.4 Glossary

The field of horizontal site characterization has been developed by merging technologies obtained from the directional drilling industry, geotechnical and geoenvironmental site characterization and borehole geophysics. Many civil, highway and municipal engineers, the target group for the proposed model, have little training in any of the above three fields. In order to fill some of this knowledge gap a glossary was developed. The glossary includes a short description of various horizontal site characterization methods as well as information regarding their capabilities and limitations. A full copy of the glossary can be found in Appendix 'C'.

5.5 DISCUSSION

Traditional vertical site characterization techniques are highly suitable for obtaining the required geotechnical data for vertical excavations such as shafts and launching pits. However, they are less effective in creating a reliable assessment of the subsurface conditions along a proposed horizontal alignment, particularly at substantial depths or beneath subsurface obstacles.

Advantage should be taken of technological progress to assist in resolving uncertainties about the characteristics of the excavation medium along the proposed alignment. In particular, site investigation programs can be greatly enhanced by horizontal site characterization techniques capable of reaching otherwise inaccessible areas. They also have the capacity to economically provide continuous information of subsurface conditions along the zone of interest. Information provided by horizontal site characterization techniques can be used to complement that obtained from vertical boreholes and historical records, thus resulting in a more comprehensive understanding of the subsurface conditions. In particular, horizontal site characterization methods can be used to reduce the uncertainty regarding the presence/absence of specific hazards, in contrast to vertical site characterization methods, which provide stratigraphic details and specific geotechnical design parameters on a small volume of the subsurface medium.

The commercial utilization of horizontal boring as a site characterization tool is coming of age, primarily due to technological improvements of horizontal drilling rigs, a rapid decline in the cost of miniaturized electronic components, and advancements in borehole geophysics. Currently, a site characterization project that involves horizontal boring will likely be economical even for medium scale microtunneling and tunnelling projects. Research efforts are currently underway worldwide for the development of contact and remote sensing probes capable of providing reliable data regarding subsurface conditions.

A key for greater acceptance of horizontal site characterization techniques is information dissemination and design-aid tools such as the decision support system described in this paper. Such tools can offer practising professionals the opportunity to learn about available technologies, as well as the means to assess the benefits offered by these technologies in a quantitative manner. EXSHSIble fills the gap between the user and this emerging technology, assisting in the planning of horizontal characterization projects and providing a systematic methodology for evaluating the benefits obtained from a given level of dollar investment in terms of a quantified degree of risk reduction.

The concept presented in this paper is rather simplistic as the cost of performing a remediation action (e.g., 911 shaft; equipment recovery) may vary significantly depending on the presence and nature of surface and subsurface obstacles. For example, sinking a shaft in green field conditions will involve a significantly lower costs than when performed in a highly urbanized area. Similarly, abandonment of the alignment shortly after the initiation of the drive, or halfway through the project will be associated with different costs. Finally, emergency situations that require excavation in urbanized areas may be associated with significant social costs that should be considered in the cost-benefit analysis. Future enhancement of the model will include the accommodation of these factors.

While still in its infancy, it is anticipated that an increased use of horizontal site characterization technologies will occur over the next few years as a growing number of specialized characterization tools geared towards this market become available and practising professionals become aware of the capabilities of this technology

CHAPTER 6

I.M.P.E.C.T: TECHNICAL EVALUATION AND PREFERENCE ATTRIBUTES

6.1 OVERVIEW

The Integrated Modular Procedure for Evaluation of Construction Technologies (I.M.P.E.C.T) is intended to serve as a comprehensive decision-support system for practitioners involved in the planning, design and construction of buried infrastructure projects. I.M.P.E.C.T uses a two-stage alternative-evaluation process. namely a technical evaluation and a preference evaluation, to compute the probability that a given candidate construction method will satisfy the user's performance requirements.

I.M.P.E.C.T utilizes an eight-step methodology, as shown in the flow chart presented in Figure 6.1. The first step is the soliciting of project-specific information from the user. Based on this information, and the information in the model's database (Tables 4-1 through 4-4), the model performs a comprehensive technical evaluation of the candidate construction methods during which the characteristics of each construction method are compared with the project qualifying attributes to ensure technical soundness of the method. Parameters considered at this stage include product diameter, maximum single drive length, installation depth, installation tolerances and other design parameters. Additionally, an elaborate procedure was developed to evaluate the compatibility of each candidate method with anticipated subsurface conditions.

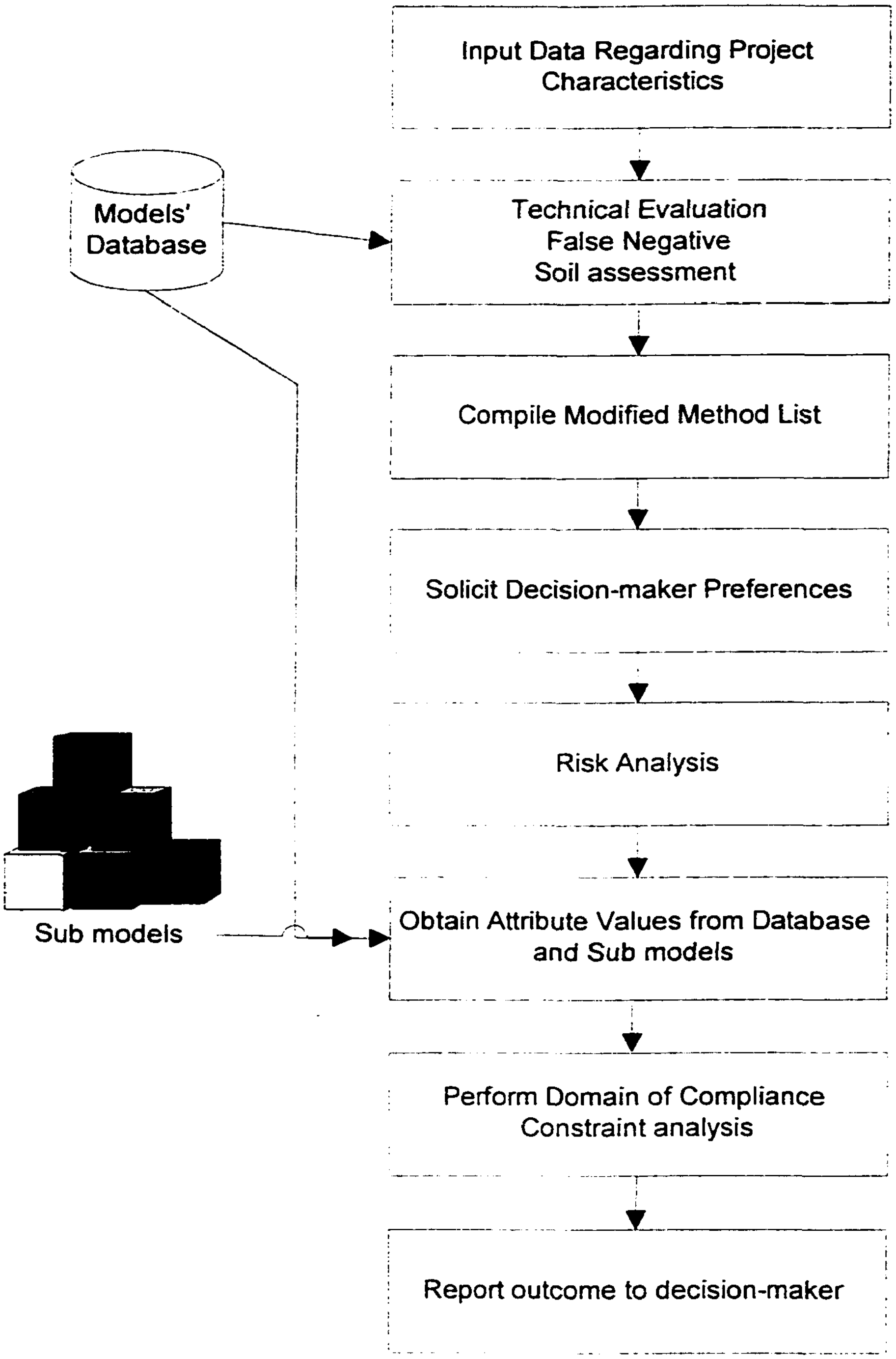

Figure 6.1 Flow Chart of Proposed Decision-Support System

Candidate methods found technically unsound are eliminated at the end of the technical evaluation, and a list of technically sound construction methods is compiled. This marks the end of Stage-One of the selection process.

The first step in Stage-Two of the selection process is the soliciting of the decision-maker's preferences. The model can currently account for the following eight preference attributes: cost, duration, environmental impact, loss of income, replacement of surface improvements, ground movement, traffic interference and business losses. For each preference attribute the user is asked to enter the maximum desirable value, maximum acceptable value and an importance value derived using the AHP or otherwise. At this point the user can also input any number of constraints he/she wishes to place on the acceptable values of the preference attributes (i.e., the sum of all direct and indirect costs should not exceed a maximum value, C). Next, a risk analysis is conducted focusing on the relative level of risk associated with the utilization of each technically sound construction method as a function of subsurface conditions, the method's capabilities, project parameters, confidence in the subsurface data, and the user's risk attitude. The results from the risk analysis together with range-estimate values obtained from the model's database and/or specialized sub-models are then used as the basis for developing a statistical distribution for each of the preference attributes. The information obtained from the user as well as the range estimates (or parameters of the statistical functions) are than input into the Domain-of-Compliance-Utility Model (DCUM), an innovative multi-objective evaluation technique that utilizes concepts from artificial intelligence, linear algebra and applied statistics to determine the likelihood that a particular alternative (e.g. construction method) will satisfy one or more set(s) of performance requirements (i.e., constraints). The model, implemented using MATLAB Version 5.3 computer language, calculates four parameters for each competitive construction method, namely:

1. The likelihood that the utilization of a construction method will result in an outcome that lies within the desired solution space (domain-of-compliance).
2. The likelihood that the utilization of a construction method will result in an outcome that lies within the tolerable solution space.
3. The likelihood that the utilization of a construction method will result in an outcome that lies outside the tolerable solution space.
4. The overall utility score (OUS) for each candidate construction method is equal to the Euclidean distance between the 'centre-of-gravity' of the method solution subspace and the origin of the Domain-of-Compliance.

The current chapter covers in detail Stage-One of I.M.P.E.C.T, namely the input of the project-specific data, the technical evaluation of the competing construction methods and the compilation of the list of technically sound candidate methods. Additionally, the various preference attributes accommodated by the model, and the format used to input the decision-maker's preferences into the model are also discussed. Stage-Two of I.M.P.E.C.T, including the risk analysis, the derivation of the underlying statistical distributions for the various preference attributes and the Domain-of-Compliance Methodology are considered in Chapter 7. The MATLAB codification of the Domain-of-Compliance Utility Model is given in Appendix 'D'.

6.2 DECISION-MAKER INPUT FOR QUALIFYING ATTRIBUTES AND RISK ANALYSIS

The first step in the execution of the model is the collection of information regarding the project's specific characteristics. For some entries, the decision-maker is asked to select the most suitable option, while in others a numerical value is required. The information gathered concerns the following parameters:

- Purpose of Installation:
  - New line.
  - In-line replacement.

Pipe material:

- Polyethylene (PE).
- High Density Polyethylene (HDPE).
- Polyethylene Vinyl Chloride (PVC).
- Ductile Steel.
- Cast Iron.
- Corrugated Metal.
- Reinforced Concrete (RC).
- Vitrified Clay (VC).
- Fiberglass.
- Asbestos-Cement.
- Brick.

Installation Parameters:

- Diameter.
- Length of instalation.
- Depth to invert.
- Required accuracy for profile / alignment (as per Table 4-2).
- Alignment (straight versus curved).

Site Conditions

- Staging areas (entry / exit).
- Degree of access from surface along proposed alignment (i.e., unlimited, - partially restricted; very restricted; no access).

Geological Conditions

- Anticipated geological formations (up to four different types) and the estimated likelihood of encountering each of these formations.
- Depth to groundwater table (GWT).
- Allowance for a dewatering operation (Yes / No).
- Anticipated diameter of cobble/boulder size (if applicable).
- Estimated unconfined compression strength of bedrock, (if applicable).

The information collected is stored in two-dimensional arrays for easy comparison with the technical specifications of the various methods stored in the Method Database. An example of one such array is presented in Table 6-1.

Table 6-1 Sample Input Attribute Matrix

Attribute	*Value*
Purpose of Installation	*String*
Pipe Material	*String*
Product Diameter	X_1
Maximum single drive length	X_2
Maximum invert depth	X_3
Accuracy (length)*	Low, Low-Medium, Medium, Medium-High or High
Accuracy (profile)*	Low, Low-Medium, Medium, Medium-High or High
Straight alignment	Yes / No

- See Table 4-2, Definitions and Acronyms

6.3 METHOD DATABASE

Based on the information collected in Chapter 4, a set of matrices was developed to capture the technical capabilities and requirements of the various construction methods. The format of the matrices was chosen to accommodate the comparison algorithms used in the technical evaluation stage (Section 6.4). A sample size of four such matrices is given in Tables 6-2 through 6-5. Tables 6-2 and 6-3 list the maximum and minimum values respectively, associated with the performance characteristics of the construction methods. The ability of these methods to handle different pipe materials is presented in Table 6-4 in a Boolean format, where '1' indicates 'suitable' and '0' indicates 'not suitable'. Table 6-5 contains the minimum dimensions of the staging area at the entry and exit locations in terms of length and width.

Table 6-2 Method Capability Matrix (maximum operating values)

Method	Length, m	Diameter, mm	Depth m	Accuracy (Alignment)	Accuracy (Depth)
Directional Drilling (maxi)	1500	1200	50	Medium-High	Medium-High
Micro-tunneling (Auger Method)	120	1800	30	High	High
Auger Boring (Track Type)	100	1200	30	Medium	Medium
Pipe Jacking	300	1060	30	High	High

Table 6-3 Method Capability Matrix (minimum operating values)

Method	Installation Length, m	Product Diameter, mm	Depth of Cover, m
Directional Drilling (maxi)	100	100	2.5m or cover/dia ≥ 5
Micro-tunneling (Auger Method)	25	250	1.5m or cover/dia ≥ 3
Auger Boring (Track Type)	12	200	1.5m or cover/dia ≥ 3
Pipe Jacking	25	3050	1.5m or cover/dia ≥ 3

Table 6-4 Method Capability Matrix - Pipe Material

Method	HDPE	PVC	Steel	Clay	Concrete	Corrugated Metal	Fiber-glass
Directional Drilling (maxi)	1	0	1	0	0	0	0
Micro-tunneling (Auger Method)	0	1	1	1	1	0	1
Auger Boring (Track Type)	0	0	1	0	0	0	0
Pipe Jacking	0	0	1	0	1	0	1

Table 6-5 Method Capability - Staging Areas

Method	*Entry*		*Exit*	
	Length, m	Width, m	Length, m	Width, m
Directional Drilling (maxi)	30	10	Length of bore	2
Micro-tunneling (Auger Method)	5	5	4	3
Auger Boring (Track Type)	10	3	8	3
Pipe Jacking	10	3	6	2
Tunnelling (TBM)	10	3	6	2

6.4 TECHNICAL EVALUATION

The technical evaluation stage comes to serve as a 'screening' mechanism intended to determine the technical suitability of a specific construction method given a particular set of project parameters. In other words, the operating parameters of the various methods, designated as 'qualifying attributes', are compared against the decision-maker's input (Section 6.2) to confirm that the latter lies within the range of the former. Qualifying attributes are defined as attributes that are deterministic in the method selection process and are typically independent of the decision-maker's preferences. Depending on its value, a qualifying attribute will either allow the use of a particular method or prohibit it. Failure to satisfy any of the qualifying attributes will disqualify the construction method for the purpose of the project under consideration. The evaluation is performed in three stages, namely: project parameter range evaluation; project option assessment; and geological assessment. A detailed description of the methodologies employed and the parameters assessed at each stage of the screening process is given below.

6.4.1 Project Parameter Range Evaluation

The model checks if the value associated with a particular project parameter is within the permissible range for the respective attribute. If the project parameter is found to be larger than or smaller than the maximum and minimum values of the method operating range, respectively, the method is eliminated. Otherwise, the method proceeds to the next evaluation stage. Parameters evaluated at this stage are listed in Table 6-6. A schematic algorithm developed for the project parameter range evaluation is shown in Algorithm 1.

Table 6-6 Parameters Evaluated Using the Range Evaluation Algorithm

False Negative (or below minimum)	*False Positive (or above maximum)*
Single Drive Length	Single Drive Length
Product Diameter	Product Diameter
Depth of Invert	Depth of Invert
Size of Entry Zone	Accuracy of Alignment
Size of Exit Zone	Accuracy of Profile

Algorithm 1 – Parameter Range Evaluation

Begin
Initialized "Status" for all methods = 1
For all construction methods in database, i = 1 to m
    For all qualifying range attributes, j = 1 to n
    If "Max. value" of(Attribute j, Method i) < Input
      Value for j
    Then "Status" for method i = 0 **And** Exit Loop
    Else
    If "Min. value" (Attribute j, Method i) > Input
      Value for j
    Then "Method Status" *i* = 0 **And** Exit Loop
    Else J = J +1
    End If
    End Loop
    i = i +1
End Loop

6.4.2 Project Range Assessment

The model checks if the options selected by the decision-maker (e.g., pipe material = steel) are supported by each of the construction methods in the database. The information in the database is stored in a Boolean format (see Table 6.4). The inclusion or exclusion of the method as a potential candidate for the project at hand involves a check of the value corresponding to the selected option, where '0' and '1' infer exclusion and inclusion, respectively (Algorithm 2).

Parameters evaluated at this stage are the type of installation (in-line replacement versus a new installation), pipe material and the ability to accommodate a curved alignment (if applicable).

Algorithm 2 – Check of Option Support

```
Begin
Initialized values of exclusion attributes as equal to
value of the corresponding option selected
For all construction methods in database, i = 1 to m
        For all qualifying option attributes, j = 1 to n
        If "Value" of (Method I, Value(Attribute j)) = 0
        Then "Status" for method i = 0 And Exit Loop
        Else J = J +1
        End If
        End Loop
        i = i +1
End Loop
```

6.4.3 Geological Assessment

Planning, design and estimating decisions for underground construction are strongly influenced by the uncertainty associated with underground conditions. As discussed in Chapter 4, the quality and quantity of geologic information available during the bidding phase can significantly impacts the selection of construction methods, prediction of productivity values, and the amounts of contingencies included in the bid. This is particularly true in the case of trenchless technologies that are significantly more complex than open-cut trenching, and as a result more likely to encounter difficulties due to adverse subsurface conditions (Mathy and Nielson, 1999). Failure to properly address subsurface conditions during the design phase may result in lengthy and costly delays (Allouche and MacAulay, 1999) or even a failure to complete the project. Thus, it is not surprising that the 49 contractors who were asked to rank information requirements for horizontal directional drilling projects singled out accurate descriptions of subsurface conditions as the overall number one factor (Allouche et al., 2000). This section describes a methodology developed to convert the decision-maker's input regarding expected subsurface conditions into a measure of estimated construction difficulty.

It is desirable in the decision-making process to capture the information gathered from all sources (e.g., vertical bore logs, geological maps, natural exposures) together with the degree of reliability the decision-maker assigns to each piece of information. The model focuses on the probability of encountering a given category of geological formation, but does not consider the formation's extent. The reason for this is twofold:

1. Even a relatively short section of adverse ground conditions can have a negative impact on a trenchless construction project.
2. Current site characterization practices do not lend themselves to the accurate prediction of the extent of geological formations.

Iseley and Gokhale (1997) and Allouche et al. (2000) classified geological conditions that may be encountered during a trenchless project using the following categories:

- Soft cohesive soils,
- Firm cohesive soils,
- Stiff-hard cohesive soils,
- Loose cohesionless soils,
- Medium cohesionless soils,
- Dense cohesionless soils,
- Gravel,

- Cobble / Boulders,
- Sandstone / Shale, and
- Bedrock.

Cohesive and cohesionless soils were assigned a range of 'N' values (standard blow count - ASTM 1452) to ensure consistency in the way field data is used in the model.

The decision-maker is asked to identify up to four categories and specify the likelihood (D_i) of encountering these types of geological formations along the proposed alignment. The model then computes the complement likelihood (i.e., likelihood that the formation will not be encountered = 1 - D_i), as well as the probability (P) of encountering all possible combinations of these four classes. For example, the probability of encountering only formation 'A' ($=P_a$) is given by:

$$(P_a)=(D_a)\cdot(1-D_b)\cdot(1-D_c)\cdot(1-D_d) \qquad \text{(Eq. 6.1)}$$

Table 6-7a shows sample input values. Four possible types of formations were identified, soft cohesive, firm cohesive, loose cohesionless and gravel, each with its own likelihood of being encountered. The probabilities associated with encountering each possible combination of the four types of formations are given in Table 6-7b.

Table 4-3 identifies each construction method as suitable, not suitable or possibly suitable (additional effort may be necessary) for various types of geological formations. For automation purposes each suitability category is assigned a numerical value:

- Suitable $= C_1$

- Possibly suitable = C_2, and

- Not suitable = C_3

For demonstration purposes the following suitability values were assigned:

- Suitable = 0.0
- Possibly suitable = 1.0, and
- Not suitable = 2.04

The method/formation suitability matrix for the geological categories selected in Table 6-7b is shown in Table 6-8.

Table 6-7a Sample Computation for Geological Assessment - User Input

Formation	Likelihood of Encounter	Complement
Soft Cohesive	0.8	0.2
Firm Cohesive	0.2	0.8
Stiff-Hard Cohesive	0.0	1.0
Loose Cohesiveless	0.3	0.7
Medium Cohesiveless	0.0	1.0
Dense Cohesiveless	0.0	1.0
Gravel	0.4	0.6
Cobble	0.0	1.0
Sandstone/Shale	0.0	1.0
Bedrock	0.0	1.0

Table 6-7b Sample Computation for Geological Assessment Valid Combinations

Combination	Soft Cohesive	Firm Cohesive	Loose Cohesiveless	Gravel	Likelihood
1	X				0.269
2		X			0.017
3			X		0.030
4				X	0.045
5	X	X			0.067
6	X		X		0.115
7	X			X	0.180
8		X	X		0.007
9		X		X	0.011
10			X	X	0.020
11	X	X	X		0.030
12	X		X	X	0.077
13		X	X	X	0.005
14	X	X		X	0.045
All	X	X	X	X	0.019
None					0.063
Total					**1.00**

Table 6-8: Sample of a Method/Formation Suitability Matrix

Method	Soft Cohesive	Firm Cohesive	Loose Cohesionless	Gravel
Microtunneling (Slurry system)	0	0	1	1
Auger Boring	1	0	1	1
Horizontal Drilling (Mini/Micro)	0	0	1	2.04
Tunneling (TBM)	1	0	1	0
Pipe Jacking (Hand)	1	0	1	1

Next, the suitability values (SV) for each category in the combination are added for each possible combination of formation categories. The sum is then divided by the number of categories in the combination to give the "SUitability Index", SUI:

$$SUI = \frac{\sum_{1}^{n} (SV)}{n} \qquad \text{(Eq. 6.2)}$$

The higher the overall compatibility of the construction method with the anticipated subsurface conditions, the lower is the SUI. Brackets can then be set to indicate the expected level of construction difficulty associated with a given SUI value:

$0 <$ Suitability Index $<= a_1 \Rightarrow$ Construction Difficulty = Low

$a_1 <$ Suitability Index $<= a_2 \Rightarrow$ Construction Difficulty = Medium

$a_2 <$ Suitability Index $<= a_3 \Rightarrow$ Construction Difficulty = High

$a_3 <$ Suitability Index $<= a_4 \Rightarrow$ Construction Difficulty = Very High

where $a_1 < a_2 < a_3 < a_4$.

A possible logic for developing threshold values is that if all types of formations anticipated to be encountered are compatible with the method under consideration, construction difficulty associated with subsurface conditions can be considered to be low. If at least half of the anticipated formations are considered compatible, and the remaining anticipated formations are considered possibly suitable, the construction difficulty level assigned to the combination is medium. If most of the anticipated formation categories are considered possibly suitable the construction difficulty is considered high. This is also the case when two or more of the categories are considered suitable and one is considered not suitable. For all other cases, the assigned level of construction difficulty is 'very high'. Based on the above logic and the previously assumed 'SUitability Values' the following figures were derived for a_1 through a_4 to demonstrate the proposed approach:

Suitability Index = 0.0 $\Rightarrow$ Construction Difficulty = Low

Suitability Index = 0.01 to 0.5 $\Rightarrow$ Construction Difficulty = Medium

Suitability Index = 0.51 to 1.0 $\Rightarrow$ Construction Difficulty = High

Suitability Index > 1.01 $\Rightarrow$ Construction Difficulty = Very High

Further investigation is needed to confirm the general applicability of the above stated logic. Table 6-9 shows the suitability index values and construction difficulty level assignment for the five construction methods listed in Table 6-8. based on the geological data presented in Tables 6-7a and 6-7b.

Table 6-9: Suitability Index Computations and Assignment of a Construction Difficulty Level

Combination*	Micro-Tunneling	Auger Boring	Directional Drilling	Tunneling (TBM)	Pipe Jacking (Hand)	Probability
1	0** [L]†	1 [H]	0 [L]	1 [H]	1 [H]	0.269
2	0 [L]	0 [L]	0 [L]	0 [L]	0 [L]	0.0168
3	1 [H]	1 [H]	1 [H]	1 [H]	1 [H]	0.03
4	1 [H]	1 [H]	2.04 [VH]	0 [L]	0 [L]	0.045
5	0 [L]	0.5 [M]	0 [L]	0.5 [M]	0.5 [M]	0.067
6	0.5 [M]	1 [H]	0.5 [M]	1 [H]	1 [H]	0.115
7	0.5 [M]	1 [H]	1.02 [VH]	0.5 [M]	0.5 [M]	0.18
8	0.5 [M]	0.5 [M]	0.5 [M]	0.5 [M]	0.5 [M]	0.007
9	0.5 [M]	0.5 [M]	1.02 [VH]	0 [L]	0 [L]	0.011
10	1 [H]	1 [H]	1.52 [VH]	0.5 [M]	0.5 [M]	0.02
11	0.33 [M]	0.66 [H]	0.33 [M]	0.66 [H]	0.66 [H]	0.03
12	0.66 [H]	1 [H]	1.01 [VH]	0.66 [H]	0.66 [H]	0.077
13	0.66 [H]	0.66 [H]	1.01 [VH]	0.33 [M]	0.33 [M]	0.005
14	0.33 [M]	0.66 [H]	0.68 [H]	0.33 [M]	0.33 [M]	0.045
15	0.5 [M]	0.75 [H]	0.76 [H]	0.5 [M]	0.5 [M]	0.019

* See Table 6-7b, Column 1; ** Suitability Index Value; † Level of construction difficulty; L = Low; M = Medium; H = High; VH = Very High

The probability of each of the four construction difficulty levels can now be calculated for each construction method. This is achieved by summing the individual probability values associated with all of the combinations belonging to a particular level of construction difficulty for each construction method, as demonstrated in Table 6-10. For example, based on the soil types listed in Table 6-7a and their respective likelihoods of encounter, the probability that a microtunneling unit will experience significant difficulties during the construction process due to ground conditions is 0.24 (= 0.177+0.063).

Table 6-10 Probability Values for Levels of Construction Difficulties

Level of Construction Difficulty	*Micro-Tunneling*	*Auger Boring*	*Directional Drilling*	*Tunneling (TBM)*	*Pipe Jacking (Hand)*
Low	0.353	0.0168	0.353	0.073	0.073
Medium	0.407	0.085	0.152	0.343	0.343
High	0.177	0.835	0.094	0.521	0.521
Very High	0.063	0.063	0.401	0.063	0.063
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

A concern may arise if a high probability value is assigned to one of the elevated levels of construction difficulty (i.e., High or Very High). It is proposed to establish threshold values above which the construction method will be considered not viable for the project. These thresholds can be either specified by the decision-maker or be hard coded (i.e., Algorithm 3).

Algorithm 3 - Anticipated Construction Difficulty Due to Subsurface Conditions

Begin
For all construction methods in database, i = 1 to m
If
"Value" of (Probability of anticipated Construction Difficulty = Very High) > α
Or
"Value" of (Probability of anticipated Construction Difficulty = Very High)+ "Value" of (Probability of anticipated Construction Difficulty = High) > β
Then "Status" for method i = 0 **And** Exit Loop
End If
End Loop

While there are sixteen possible combinations in Table 6-8, only fifteen are considered in Table 6-9. The last combination, which represents the probability that none of the geological formations under consideration will be encountered, is not considered as it is impractical to assign a construction level of difficulty to unknown types of formations. A possible solution is to adopt a conservative approach and assign a high suitability index value (e.g., 1) that infers a high level of construction difficulty. It is also worth noting that the probability associated with the combination "none of the formations is encountered" (=P_{None}) provides a direct measure of the confidence the decision-maker has in his geological data. A high value for P_{None} might serve as an indication that the reliability of the geological data is unsatisfactory.

6.4.4 Hydro-Geological Conditions and Boulder Size

Another area that needs to be addressed in the assessment is local hydro-geological conditions. The presence of perched aquifers, artesian aquifers or underground channels may result in significant difficulties for many underground construction methods or even render them technically unfeasible. The impact of these features on construction greatly depends on their characteristics (e.g., how many gallons per minute the formation yields) and the expected effectiveness of a dewatering operation. For the most part, little if any information is available regarding the presence and characteristics of such features. Furthermore, if it is known that an artesian aquifer or an underground channel is to be encountered, it is likely that a new alignment or profile will be selected, as these hydro-geological conditions may have an adverse effect on most underground construction methods. For these reasons, the only hydro-geological parameter considered by the model is the depth to the groundwater table. The higher the hydrostatic pressure, the more difficult it is to stabilize a cavity in the formation even when sealants and high-viscosity drilling fluids are utilized. Increased friction due to the collapse of the formation around the advancing casing or drilling string, or ahead of the cutting head, preclude the use of auger-type methods and low-thrust displacement/compaction methods under hydrostatic pressure conditions. As for open-cut methods, the presence of a high groundwater table requires dewatering to be performed, particularly in the case of deep excavation or when cohesionless soils are present.

For the purpose of simplicity, it was decided to define 'high groundwater table' as a minimum vertical distance of 3m between the pipe product invert and the location of the groundwater table for all auger-type methods (Uki et al., 1999), and 1m for compaction/displacment and open-cut methods. In Table 4-3, the various construction methods in the database were designated as either:

- *Class 1*: suitable or possibly suitable for construction at an invert depth of 3m or more under the groundwater table.

- *Class 2*: suitable or possibly suitable for construction at an invert depth of up to 3m below the groundwater table.
- *Class 3*: suitable or possibly suitable for construction at an invert depth of up to 1m below the groundwater table.

In the case where the distance between the elevations of the groundwater table and the pipe's invert exceeds the maximum allowable value for this method, the method is considered technically unfeasible for the project at hand. The user may deactivate this screening step by specifying 'Yes' for a dewatering operation allowance (Section 6.2). The algorithm used in the evaluation is presented as Algorithm 4.

Algorithm 4 - Check of Anticipated Construction Difficulty Due to Hydro-geological Conditions

```
Begin
If "Value"(Depth to invert)-"Value"(Depth to GWT)≤1.0
   Then Status_GWT = '0'
   Else if "Value"(Depth to invert)-"Value"
                  (Depth to GWT)≤3.0
   Then Status_GWT = '1'
   Else Status_GWT = '2'
End If
For all construction methods in database, i = 1 to m
If
  Class of Method  = 1 Then Exit Loop
  Else If
    Class of Method  = 2 and Status_GWT='0'
      or Status_GWT='1'
    Then Exit Loop
  Else If
    Class of Method  = 3 and Status_GWT='0'
      Then Exit Loop
   Else "Status" for method i = 0
        End If
        End Loop
```

Additional information is required for the case where it is anticipated that boulders or bedrock conditions will be encountered during construction. For boulders, the maximum boulder's diameter is critical as many of the tunneling type methods (either auger-type; slurry type or hand excavation) can only handle boulders with diameters smaller than a percentage of the cutting head diameter (e.g., 33%). However, using traditional site characterization techniques it is difficult to determine with any degree of confidence what will be the diameter of the largest boulder that may be encountered along the alignment. Also, the risk associated with encountering a boulder too large to be handled by the cutting head is proportional to the technical difficulty (e.g., accessibility) and cost (e.g., depth) associated with sinking an emergency shaft to remove that boulder (Rasmussen, 1999). For the purpose of the model prototype, the decision-maker is asked if, based on the geological investigation or past experience, there is a high likelihood of encountering boulders that are of a diameter equal to or larger than:

0.5*(Product Diameter)

1.0*(Product Diameter)

For cases where the answer is positive and access from the surface is very restrictive (Section 6.2), methods that cannot handle boulders with diameters equal to the pipe diameter (or half of it, whatever is the limitation specified in Table 4-3) are considered technically unfeasible and are assigned a Technical Feasibility Status of '0'.

As for bedrock conditions, if the bedrock is selected as one of the formations anticipated to be encountered, the decision-maker is asked to enter an estimated value for the bedrock compressive strength (MPa). If the compressive strength exceeds the method's penetration capacity as specified in Table 4-3, the method is considered technically unfeasible and assigned a Technical Feasibility Status of '0'.

6.5 COMPILATION OF A LIST OF TECHNICALLY SOUND METHODS

Prior to the initiation of the technical evaluation, a default value of '1' is assigned to the status of each of the methods. If the method fails to pass any of the three evaluation categories: 1) Project parameters range evaluation; 2) Project options assessment; or, 3) Surface conditions assessment; the status value is changed to '0' (see Algorithms 1 to 4). After the technical evaluation stage is completed, the model checks the status of each construction method. If the method's status is active (Status = '1') the method identification number is added to the list of technically viable construction methods. This list is used as the starting point for Stage Two of the selection process - the domain of compliance utility model (DCUM). The procedure used to sort the original list and construct the list of the technically sound construction methods is given as Algorithm 5.

Algorithm 5 - Check of Method Status and Construct the Modified List of Methods

```
Begin
Initialized a new 1-D array named Modified_Method_List
Initialized an Integer, j = 1
For all construction methods in database, i = 1 to m
        If
   "Value" of (Method_Status)= 1
Then Modified_Method_List(j) = Method_ID And
   j = j+1
        End If
End Loop
```

6.6 SOLICITING DECISION-MAKER INPUT FOR PREFERENCE ATTRIBUTES

Preference attributes can be defined as "any criterion that can be used to rank the applicable methods according to how well they suit the decision-maker's needs" (Moselhi and Sigurdardottir, 1998). Preference attributes in DCUM describe the decision-maker's objectives using domains of allowable values, maximum acceptable values and 'objective achievement' importance factors. Based on this information, the model computes the likelihood the performance attributes of a given construction method would satisfy the allowable domains considering the project's characteristics, site conditions, anticipated geological conditions and perceived level of risk.

6.6.1 Preference Attributes

A review of the literature, and in particular Ariartnam et al. (1999), Moselhi and Sigurdardottir (1998), and Iseley and Tarnwani (1990) the following eight performance factors were identified:

- *Project costs:* these include direct costs (e.g., labour, materials, equipment), indirect costs (supervision, on-site facilities), markup (overhead, profit) and contingency (sum of money to cover unforeseen expenses).
- *Project Duration:* including mobilization, construction and cleanup.
- *Environmental Impact:* including the removal of vegetation/trees; erosion and damage to local ecological systems.
- *Loss of income:* including productivity loss due to construction activities, loss of parking revenues and loss of tax revenues (i.e., municipal, provincial or federal).

- *Surface Improvements:* cost of restoring or reduction in the value of surface improvements including pavement, brick paving, landscaping and sidewalks. It also includes the cost associated with relocation of adjacent utilities.
- *Ground Movement:* including the cost of repairing damage caused to paved surfaces and foundations due to settlement. This category includes both short-term as well as long-term (maintenance) costs.
- *Traffic Interference:* including the costs associated with detours, traffic delays, delay to emergency vehicles, higher potential of accidents and damage to the detour roadways due to heavier traffic loads and volume.
- *Business Losses:* these losses include revenue losses of businesses in the vicinity of the construction site due to lack of convenient access, noise and dust.

Not all of the above mentioned factors are necessarily applicable for every project considered by the decision-maker. Furthermore, the decision-maker may want to see the effect on the model's outcome when considering different combinations of parameters. Therefore, the model enables the decision-maker to choose these preference attributes from the above-mentioned list that he desires to include in the analysis. The following six values are required for each of the selected attributes:

- **Minimum Allowable Value (MAV)** - the lower bound of the range of acceptable values. If the expected project performance parameter is less than the MAV, the method is considered to be non-compliant and therefore unable to meet the decision-maker's specifications. For the current application, a default value equal to '0.0' is used for all MAV values. However, this may not be the case for other applications of the Domain of Compliance methodology (i.e., outcome of an investment).

- **Minimum Desirable Value (MIDV)** - the minimum-value the decision-maker would like to accept in return for completing the project according to specifications. If the expected project performance parameter is less than the MIDV but higher than the Minimum Allowable Value, the method score for this parameter is penalized based on the value of the Lower Bound Importance Factor (defined below). Similar to MAV, in the current application all MIDVs are assigned a default value equal to '0.0'.

- **Maximum Desirable Value (MADV)** - the maximum value the decision-maker would like to accept in return for completion of the project according to specifications. For example, this value may correspond to the project budget as approved by the city council. If the expected project performance parameter is higher than MADV but less than the Maximum Allowable Value (MAAV), the method score for this parameter is penalized based on the value of the Upper Bound Importance Factor (defined below).

- **Maximum Allowable Value (MAAV)** - the upper bound of the range of acceptable values to the user. If this upper bound cannot be satisfied, the decision-maker will be forced to reconsider the project's design, scope or even viability. For example, a sewer forcemain across a river must be completed with no disturbance to the channel beds or else a longer route via a bridge located downstream will be selected.

- **Lower Bound Importance Factor (LBIF)** - this value represents the importance of adhering to the minimum desirable value. LBIF is used to compute the penalty for performance values below MIDV. For the application at hand, all LBIF values are assigned a default value of 1.0.

- **Upper Bound Importance Factor (UBIF)** - this value represents the importance of adhering to the maximum desirable value, MADV. UBIF is used to compute the penalty for a performance parameter that exceeds the attribute's MADV.

6.6.2 Preference Attributes - Units of Measurement and Constraints

Similar to traditional utility models, the Domain of Compliance Utility Method (DCUM) gives the decision-maker the freedom to mix various scales and units of measurement, including monetary terms, unit measures of time and linguistic terms. However, classical two-dimensional utility models require adding together the degrees of satisfaction of the decision-maker from the achievement level attained for each of the attributes to obtain the method's overall utility value. This approach assumes independence among the various attributes. This means the value of a given attribute must be independent of the value of all other attributes (Fishburn, 1970). Avoidance of the need to combine the individual levels of satisfaction to obtain an overall performance order makes it possible for DCUM to specify dependencies in the form of mathematical relationships (i.e., constraints) among the various attributes, giving the decision-maker greater flexibility in specifying goals and needs.

For example, in the case of an industrial site the decision-maker may be ready to pay up to $500,000, plus a $5000 per day premium for every day the project is completed prior to the maximum allowable duration of 45 days, to a maximum of $50,000. The maximum desirable value for the project cost is now a function of the project duration as given in Equation 6.3:

$$MADV = \$500{,}000 + 5000 * \{(45 - \text{Duration (Days)}\} \leq \$550{,}000 \qquad \text{(Eq. 6.3)}$$

In general, relationships need not be linear, as it is possible to use higher order polynomials, exponential or log-base mathematical relationships. Constraints that involve three or more attributes are termed 'global constraints', and are used to restrict the combined value of multiple attributes. For example, the decision-maker wants to limit his total direct costs due to the construction project from all foreseen sources to \$1,000,000. Thus, the following 'global constraint' could be imposed:

$$\text{(Project Costs)} + \text{(Loss of Income)} + \text{(Surface Improvement)} \leq \$1{,}000{,}000 \quad \text{(Eq. 6.4)}$$

There is no theoretical limit to the number of 'global constraints' that might be applied to the problem, although the level of computation tends to increase in a quadratic manner with the number of constraints (Bessiere et al., 1999).

Another advantage of the non-additive nature of DCUM is the fact that the values obtained for the more elusive parameters can be compared against an empirically derived limit, rather than be combined with values of deterministic attributes. For example, the incorporation of social costs (e.g., traffic disruption, lost revenue) into cost estimating models is in many cases problematic, since these costs tend to be greater than the cost of performing the project (McKim, 1997; Ariaratnam et al., 1996). When using DCUM, it is no longer necessary to add the social costs to the actual construction costs as these two types of costs are compared against different threshold values. For example, a municipality using a particular social cost model determined that negative public and business reaction (in terms of project related complaints) to infrastructure projects in the downtown area exhibited a substantial increase when the estimated value of social costs exceeded two million dollars. The engineer can now set a global constraint for all social costs equal to two millions dollars, regardless of the project's direct costs. This approach will enable the decision-maker to consider the potentially more economical open-trenching methods with a level of confidence that the public can tolerate the associated social costs.

For the application at hand, the selection of an underground construction method, the preference attributes are specified using the following units of measurement:

- *Project Cost*: any monetary value.

- *Project Duration*: any unit of time measurement (e.g., days, weeks, months).

- *Loss of Income:* any monetary value.

- *Business Loss:* any monetary value.

- *Surface Improvements*: any monetary value.

- *Ground Movements:* a predefined scale, e.g., Low - no damage; Low/Moderate-minor repairs to roadway and nearby paved surfaces; Moderate - minor repairs to roadway and nearby paved surfaces, requiring relocation of nearby utilities; Moderate/High - moderate damage to paved surfaces due to significant settlement, requiring relocation of nearby utilities, damage to nearby foundations possible; High - substantial short and long-term settlement causing damage to nearby paved surfaces, requiring relocation of nearby utilities, some damage to nearby foundations is likely.

- *Traffic Interference:* any monetary value derived from an established approach such as the 'lane-rental' method (Budhu and Iseley, 1994; Boyce and Bried, 1998). Alternatively, any measure of traffic delay can be used, e.g., (Annual Average Daily Traffic)*(Percent of roadway blocked)*(Expected project duration, days).

- *Environmental Impact:* a predefined scale, e.g., Low - no access to personnel or equipment between entry and exit points; Low/Moderate - on-foot access only, no clearance or excavations allowed; Moderate - access to light equipment (e.g., light trucks, small backhoes), limited clearing and excavation allowed (e.g., 911 shafts); High - access to all types of equipment, some limitations on clearing and excavation; Very High - unlimited access, clearing and excavation.

Table 6-11 summarizes the input data required from the decision-maker for the purpose of evaluating construction methods using the Domain of Compliance Utility methodology.

Table 6-11 Input Data for the Domain of Compliance Utility Model

Attribute	**MAV**	**MIDV**	**MADV**	**MAAV**	**LBIF**	**UBIF**
Cost	$*	$	$	$	Constant / Function	Constant / Function
Duration	⌚**	⌚	⌚	⌚	Constant / Function	Constant / Function
Environmental Impact	Lingu†	Lingu	Lingu	Lingu	Constant / Function	Constant / Function
Loss of Income	$	$	$	$	Constant / Function	Constant / Function
Surface Improvements	$	$	$	$	Constant / Function	Constant / Function
Ground Movement	Lingu†	Lingu	Lingu	Lingu	Constant / Function	Constant / Function
Traffic Interferences	$ or CS	$ or CS	$ or CS	$ or CS	Constant / Function	Constant / Function
Business Losses	$	$	$	$	Constant / Function	Constant / Function

* Monetary value **Units of time †Linguistic scale CS – Custom Scale

All input data to the DCUM is normalized. The boundary values MAV, MADV, MIAV and MIDV are divided by the value of MADV for each respective attribute. Thus, the maximum desirable value for each attribute is equal to 1.0. Similarly, the values of the performance parameters for the various construction methods are also divided by the MADV of the relevant attribute. Linguistic terms are converted to a relative scale (e.g., environmental impact, 1-5). Consequently, the domain of compliance is a multi-dimensional space where the maximum value of each of the domain axes is 1.0. For the specific application at hand the minimum domain value is 0.0. The model in its current configuration cannot handle negative input values but can be expanded to accommodate such input.

The lower and upper bound Importance Factors for each attribute represent the level of importance the decision-maker gives to adhering to the maximum desirable value of this attribute. Since decision-making can be viewed as an optimization exercise where one attempts to maximize the benefits obtained, it is reasonable to use the pair-wise comparison method adopted from the Analytical Hierarchy Process (AHP) to derive the bound importance factors. Values are assigned to each pair of attributes representing the relative importance of the attributes with respect to one another. A sample comparison matrix is presented in Table 6-12. Next, the pairwise comparison matrix is raised to a squared power using standard matrix multiplication methodology (Anton, 1987). The sum of each row of the resulting matrix is computed and then normalized by dividing the sum of each row by the total of the sums. The resulting *1xn* eigenvector reflects the relative importance of each criterion with respect to all other criteria. The relative importance values are divided by the lower value to obtain a minimum Importance Factor value of 1.0 and a maximum Importance Factor equal to the ratio of the maximum to minimum values in the vector WA (Table 6-12).

Table 6-12 Sample Comparison Matrix

		A1	A2	A3	A4	A5	A6	A7	A8
	A1	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
$A = (a_{ij}) =$	A2	$1/a_{12}$	a_{22}	a_{23}	a_{24}	a_{25}	a_{26}	a_{27}	a_{28}
	A3	$1/a_{13}$	$1/a_{23}$	a_{33}	a_{34}	a_{35}	a_{36}	a_{37}	a_{38}
	A4	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	a_{44}	a_{45}	a_{46}	a_{47}	a_{48}
	A5	$1/a_{15}$	$1/a_{25}$	$1/a_{35}$	$1/a_{45}$	a_{55}	a_{56}	a_{57}	a_{58}
	A6	$1/a_{16}$	$1/a_{26}$	$1/a_{36}$	$1/a_{46}$	$1/a_{56}$	a_{66}	a_{67}	a_{68}
	A7	$1/a_{17}$	$1/a_{27}$	$1/a_{37}$	$1/a_{47}$	$1/a_{57}$	$1/a_{67}$	a_{77}	a_{78}
	A8	$1/a_{18}$	$1/a_{28}$	$1/a_{38}$	$1/a_{48}$	$1/a_{58}$	$1/a_{68}$	$1/a_{78}$	a_{88}

$$WA = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix}$$

Where :
A1 = Project Cost
A2 = Project Duration
A3 = Environmental Impact
A4 = Surface Improvements
A5 = Loss of Income
A6 = Business Loss
A7 = Traffic Interference
A8 = Ground Movement
WA = Eigen vector containing the eigen values x_1 to x_8 corresponding to A1 to A8.

For the purpose of demonstrating the DCUM model, a scale was adopted from Saaty (1982) and is presented in Table 6-13. Additional details regarding the AHP method are given in Section 2.2.1 and Saaty (1978).

Table 6-13 Comparison Scale (after Saaty, 1982)

Degree of importance	*Definition*
1	Equal importance of attributes
3	Weak importance of one attribute over another
5	Strong importance of one attribute over another
7	Very strong importance of one attribute over another
9	Absolute importance of one attribute over another
2,4,6,8	Intermediate values between two adjacent degrees of importance

In the general case of DCUM, the AHP pairwise comparison needs to be performed twice, once for the Lower Bound Importance Factors and once for the Upper Bound Importance Factors. However, for the specific application at hand, all lower boundary importance factors are assigned a default value = 1.0, and thus no pairwise comparison is necessary.

CHAPTER 7

I.M.P.E.C.T : RISK ANALYSIS AND DOMAIN-OF–COMPLIANCE UTILITY MODEL COMPUTATIONS

7.1 RISK ANALYSIS

7.1.1 Overview: Definition of Risk, Risk Analysis and Risk Management

Risk is a part of nearly every action one takes, as it is the outcome of our inability to see into the future or to know the current and/or future status of each and every parameter that might affect the outcome of a given action. Risk can be defined as the "potential impact of all threats (and opportunities) which can affect the achievement of an objective for an investment" (RAMP, 1998). Risk may be objective or subjective (Palisade, 1992). For an objective risk, possible outcomes and their associated probabilities can be described precisely based on theory, while a subjective risk is open-ended and probabilities may change as more information becomes available.

The first step in risk analysis is recognizing the need for it. In other words, is there a significant risk involved in the action under consideration? The term 'significant risk' can be said to have two components - the decision-maker's utility level and the degree of uncertainty. The term 'utility level' refers to the significance the decision-maker attributes to the potential losses associated with a particular risk, while uncertainty can be described as the gap between the information required to determine the outcome and the information possessed by the decision-maker. The lower the decision-maker's utility level and the larger is the uncertainty, the greater is the risk.

In the case where the presence of a 'significant risk' is determined, two additional steps are performed. The identification and listing of all sources of risk (risk factors) involved, and the determination of all foreseeable happenings that can influence the success of an investment (risk events). With the risk analysis completed, a risk assessment can be performed. The term risk assessment refers to the quantification of the various risk events; in other words, determining all possible outcomes (e.g., magnitude of loss) of each risk event and the likeiihood of this outcome to occur. The third and final stage is risk mitigation; measures undertaken to reduce the likelihood of occurrence and/or impact of the various risk events. Based on the likelihood and the potential impact of a given risk event, the decision-maker may opt to accept, reject or mitigate this event. For example, the risk of encountering adverse subsurface conditions during tunnel construction may be dealt with, at least partially, by performing a more detailed site characterization program.

The three steps, identifying, analyzing, and responding to potential risk events are commonly termed risk management. This work is concerned mainly with identifying potential risks associated with underground construction of linear excavation projects, estimating their likelihood of occurrence and evaluating their potential effect on parameters such as expected project cost, project duration and ground movements.

To accomplish this, a new algorithm was developed, utilizing concepts from fuzzy set theory, matrix manipulation and classical risk analysis theory. The proposed paradigm is general in nature and can be applied to a range of risk analysis phenomena that are based on subjective information. The proposed approach evaluates the likelihood of a given action to breach a predetermined risk threshold established by the decision-maker. A series of matrix manipulations are used to dreate a link between the various risk parameters and the foreseen risk events to arrive at a single risk value for the project designated the 'Overall Risk Index' (ORI). In computing ORI, consideration is given to the likelihood of triggering a given risk event by the aggregate action of all risk factors, the anticipated magnitude of loss associated with the risk event and the decision-maker's utility level (termed 'risk threshold').

7.1.2 Construction Risks

Construction risk can be described as the possible consequences of a decision that was made based on incomplete knowledge regarding site conditions, weather conditions, equipment capabilities, crew experience and other factors that may have an effect on project execution. As discussed in Chapter 5, this is particularly true in the case of underground construction, where planning, design and estimating decisions are strongly influenced by the uncertainty associated with underground conditions. A statistical analysis designed to evaluate the probability of encountering various combinations of geological and hydro-geological formations was developed in Section 6.4.3. Other factors that may present potential risk during the installation of pipeline or conduit include (Ariaratnam et al., 1998):

1. Exceeding the equipment operation capabilities.
2. The need to meet pre-specified grade or alignment tolerances.
3. An encounter with existing utilities and other buried objects.
4. Inappropriate selection of line product.
5. Insufficient crew experience.

6. Adverse weather conditions, and
7. Unfavorable contract provisions.

Risks associated with unfavouable contract provisions in relation to trenchless technologies are discussed in depth by Hinze and DCCA (1991) and McClelland (1997). The risk associated with an inexperienced crew can be mitigated by a contractor pre-qualification process (Allouche, 2000; Ariaratnam et al., 1998), while risks associated with inadequate selection of line product and failure to identify manmade obstructions along the alignment are reviewed by Ariaratnam et al. (1998) and Allouche et. al (1999), respectively. The effect of weather on construction was discussed by Mosheli et al. (1997). While all of these factors may affect project cost and/or contractor productivity, the only risk factors directly related to the selection of a construction method are subsurface conditions, difficulties due to operating near or beyond the equipment operating capabilities and failure to meet grade or alignment specifications. The only additional risk factor considered in this analysis is the viability of sinking a shaft from the surface in order to expose the drilling/cutting head, the most common method of salvage in the case of a troubled trenchless installation. The less accessible the alignment to excavation equipment, the greater the risk of abandoning the alignment or even the drilling/boring equipment in the case when difficulties arise.

7.1.3 Risk Assessment Algorithm

For each technically viable method a risk assessment procedure is performed based on the following factors:

1. The degree of compatibility between the anticipated geological and hydro-geological conditions and the method characteristics.

2. The ratio between the four project installation parameters - length (l), diameter (d), depth (h) and accuracy (δ), and corresponding the operation limits of the construction method (represented by *L, D, H,* and Δ, respectively). The closer the project requirements are to the operation limit of the constructions method the smaller the probability of a successful installation.
3. Degree of accessibility to the alignment. The greater the accessibility, the smaller the risk.

The risks associated with each factor are assumed to be independent of each other. For the purpose of demonstrating the proposed paradigm four possible undesirable outcomes (risk events) were identified, namely:

1. Completion of installation not to specifications.
2. Delays and/or reduced productivity.
3. Jamming the boring/drilling assembly in the borehole.
4. Failure of the boring/drilling unit to complete the installation due to lack of capacity.

It can be argued that the likelihood of occurrence of the four risk events listed above is related to the 'Level of Construction Difficulty', which is a function of the degree of compatibility between the construction method and anticipated subsurface conditions (Section 6.4.3). The Level of 'Construction Difficulty' is introduced later in the calculations. As for the operating parameters, the likelihood of occurance of a given risk event is considered to be proportional to the ratio between the project-specified value and the maximum theoretical value for the method under consideration (obtained from Table 4-4). Take for example the situation where

Microtunneling is the method under consideration, and the project specifications calls for a diameter d = 1000mm. The maximum theoretical value for this method is D = 3000mm, therefore the value of the risk parameter is equal to the ratio d/D = 1000/3000 = 0.333. The increased level of risk associated with a decrease in surface access to the alignment is accounted for through the user's risk adversion factor, γ.

The determination of the likelihood of a risk event to occur given a specific combination of project characteristics may be difficult to quantify in a precise manner, and might be best-assessed using subjective evaluation, such as the expert opinions of practising professionals. These expert opinions can then be represented using fuzzy set theory, developed by Zadeh (1965). Fuzzy set theory enables one to assign a numerical value to linguistic terms such as 'unlikely' and 'probably' using membership functions, which represent numerically the degree to which an element belongs to a given set. This is in contrast to conventional set theory where objects either belong or do not belong to a set. Fuzzy membership functions are mathematical expressions that map objects in the domain of concern to the membership value in a set. The degree of membership in the set is expressed by a value between 0 and 1, representing 'entirely-not' and 'completely-in' the set, respectively. Intermediate values indicate partial membership in the set. Membership functions are usually denoted by the Greek symbol, μ. The relation representing a link between two sets of data through their relations to a third set of data is named a fuzzy binary relationship. Binary relationships can be portrayed by a matrix, the elements of which represent the degree of membership of each link between the two data sets (Fayek, 1998).

Additional information regarding fuzzy set theory can be found in Yen and Langari (1999) and Schmucker (1984).

Figure 7.1 show a schematic algorithm of the module used for the computation of the level of risk for a given construction method. It can be seen that the various risk parameters are linked to the risk events via a third, common set of data named the 'residual risk level', defined as the likelihood of a particular risk event to occur given a set of risk parameters. The values computed for the individual risk events are then aggregated to form the Overall Risk Index for the candidate method under consideration. The following paragraphs explain the proposed algorithm. Additionally, a validation example is given in Section 7.1.4.

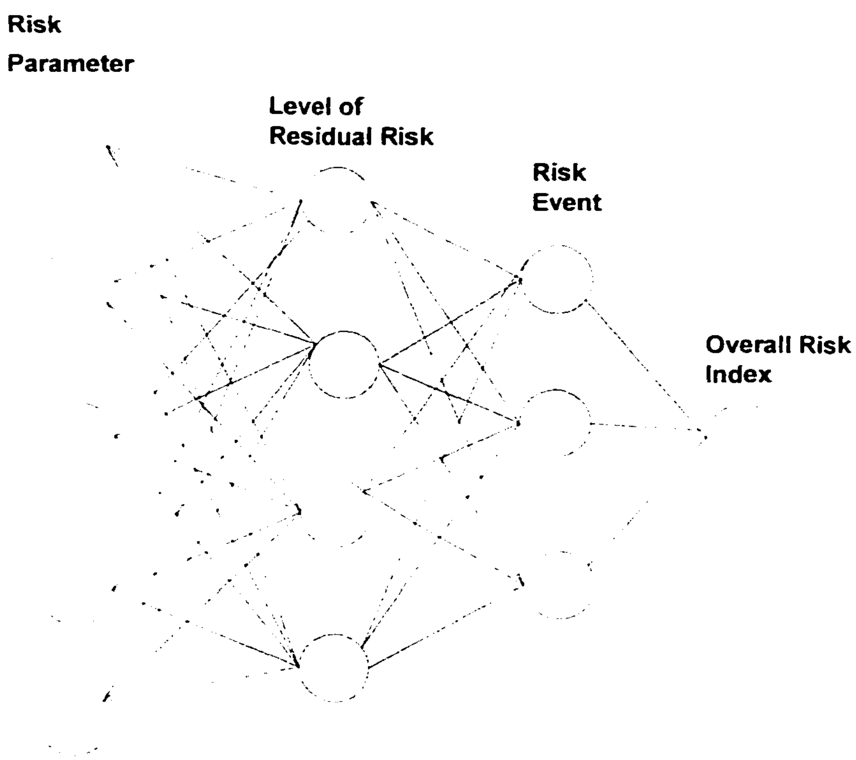

Figure 7.1 Schematic Layout of Risk Analysis Paradigm

Fuzzy functions that map the relevant level of residual risk for each risk event can be developed for the following four risk parameters – length ratio (l/L), diameter ratio (d/D), depth ratio (h/H) and accuracy ratio (δ/Δ). In order for the membership functions to be independent of the construction method considered, the ratio for each operating parameter is determined using the following relationship:

$$RFR = \frac{(X - Y_{MIN})}{(Y_{MAX} - Y_{MIN})} \qquad \text{(Eq. 7.1)}$$

Where *RFR* = Risk Factor Ratio; X = user's specified value (l, d, h, or δ); and Y_{MAX} and Y_{MIN} are the upper and lower limits of the construction method operating range, respectively. The domain of membership function (also called 'the universe of discourse') for each of the RFR's lies between 0.0 and1.0.

When developing fuzzy set functions the literature on the subject strongly recommends the use of continuous functions rather than defining the membership function point by point. Also it is suggested that triangular or trapezoidial membership functions be used unless the data indicate otherwise (Yen and Langary, 1999). Finally, in designing membership functions two conditions need to be satisfied: 1) a maximum of two membership functions may overlap at any point along the universe of discourse; 2) for any possible input data the membership value in all relevant fuzzy sets should add to 1, or nearly so. These conditions are expressed mathematically below as Equations 7.2 and 7.3, respectively:

$$A_i \cap A_j = \emptyset \qquad \forall j \neq i, i+1, i-1 \qquad \text{(Eq. 7.2)}$$

$$\sum_i \mu_{A_i}(X) \cong 1 \qquad \text{(Eq. 7.3)}$$

An example of a set of membership functions for the 'Product Diameter' ratio in relation to the four risk events, namely 1) completion not to specifications; 2) reduced productivity; 3) jamming of the boring assembly; and, 4) failure to complete installation, is given in Figures 7.2a through 7.2d. These membership function were developed based on the author's limited knowledge in the field. Similar membership functions can be derived for the other three risk parameters, namely, length of drive, maximum invert depth and specified accuracy. As for geological conditions, it is assumed that the level of residual risk for each of the risk events stated above, is directly related to the 'Level of Construction Difficulty', as defined in Section 6.4.3. Given this assumption, the membership values can be approximated by the probability values associated with each Construction Difficulty Level, given in Table 6-10. For example, based on the anticipated geological conditions, listed in Table 6-7a, the probability that the microtunneling method will encounter little difficulty due to subsurface conditions is 0.353. Similarly, the probability of encountering a very high level of construction difficulty due to the subsurface conditions is 0.063.

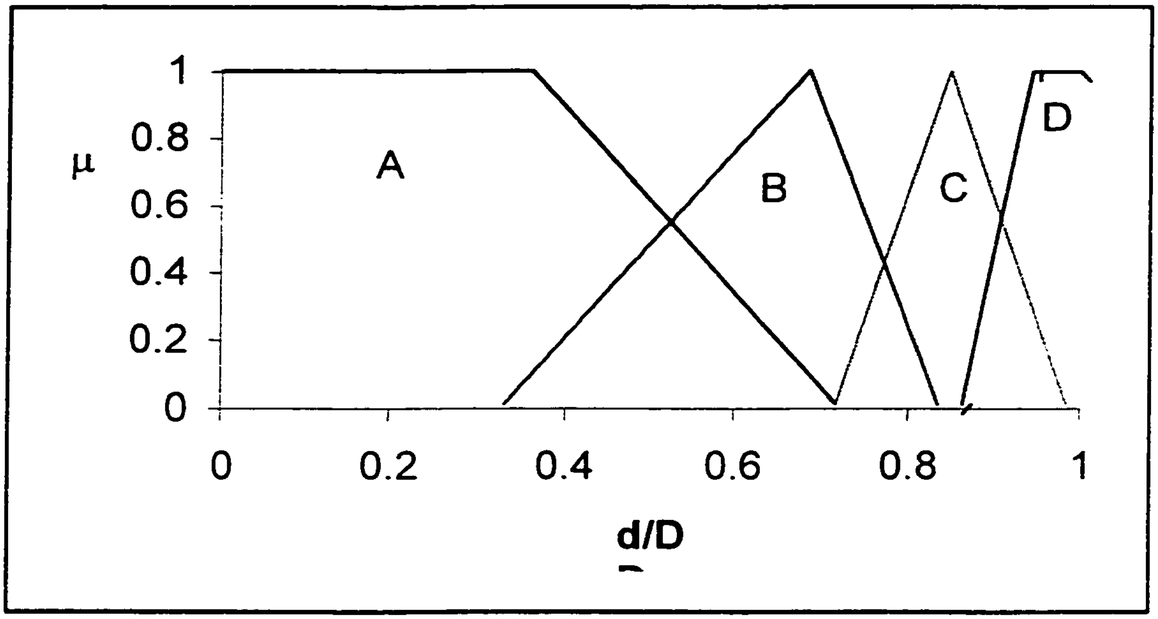

Figure 7.2a Fuzzy membership functions for risk factor 'Product Diameter' with respect to risk event 'Completion not according to specifications'.A = 'Unlikely'; B = 'Somewhat Likely'; C = 'Likely'; D = 'Very Likely'

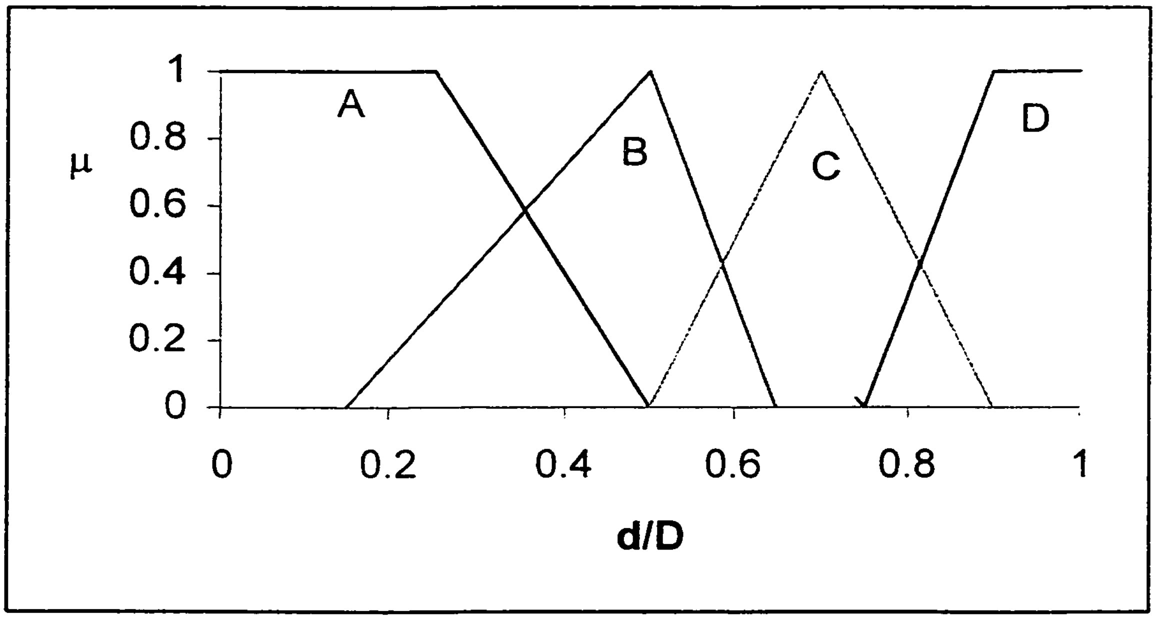

Figure 7.2b Fuzzy membership functions for risk factor 'Product Diameter'with respect to risk event 'Productivity delays'. A = 'Unlikely'; B = 'Somewhat Likely'; C = 'Likely'; D = 'Very Likely'

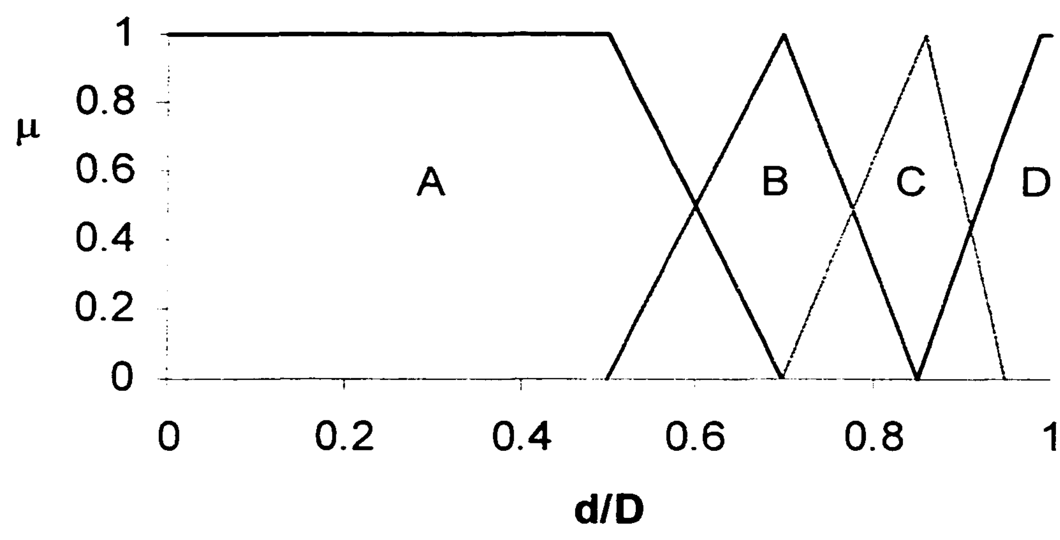

Figure 7.2c Fuzzy membership functions for risk factor 'Product Diameter' with respect to risk event 'Jamming of boring assembly in borehole'. A = 'Unlikely'; B = 'Somewhat Likely'; C = 'Likely'; D = 'Very Likely'

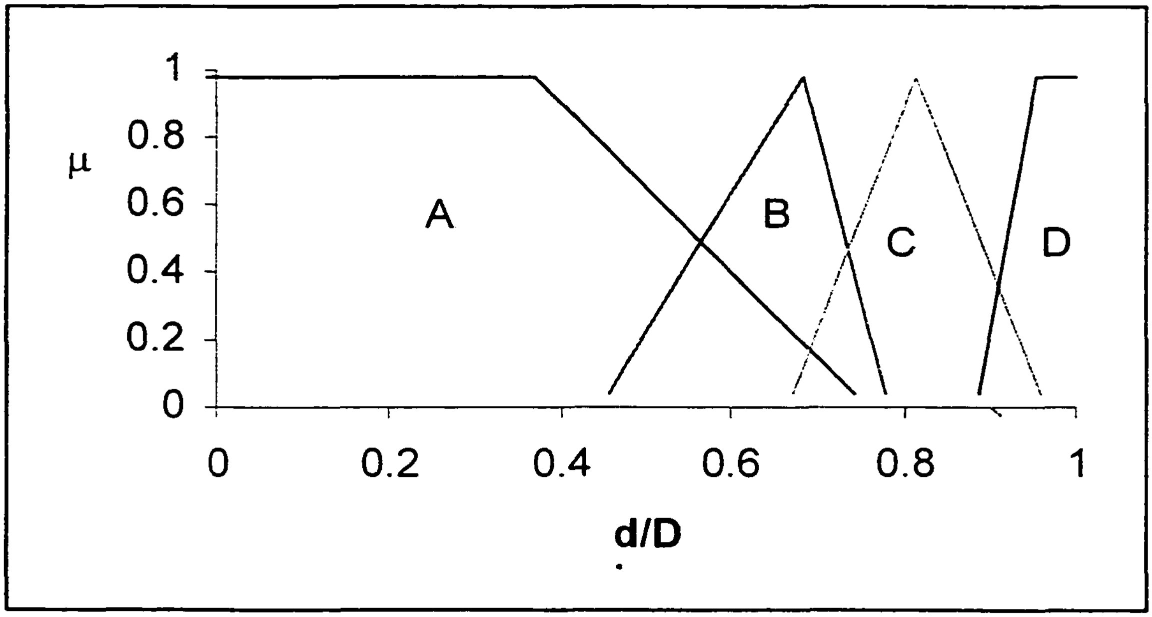

Figure 7.2d Fuzzy membership functions for risk factor 'Product Diameter' with respect to risk event 'Failure to complete installation'. A = 'Unlikely'; B = 'Somewhat Likely'; C = 'Likely'; D = 'Very Likely'

The risk analysis begins with the determination of the fuzzy set membership values for each residual risk associated with a given risk parameter. In other words, for a given risk parameter *i* the membership values for *n* residual risk levels (e.g., unlikely, somewhat likely, likely and very likely) associated with risk event *j*, are $R1_{ij}$, $R2_{ij}$ $R3_{ij}...Rn_{ij}$. The residual risk matrix for risk parameter *i*, $[A_{ri}]$, is obtained by assembling the residual risk levels (i.e., membership values) for each of the risk events, $j = \{1...m\}$. Thus, for *m* risk events, each with *n* levels of residual risk, the matrix $[A_{ri}]$ for risk parameter *i* is an *m* x *n* matrix, as shown below:

$$[A_{ri}] = \begin{bmatrix} R1_{i1} & R2_{i1} & \cdots & Rn_{i1} \\ R1_{i2} & R2_{i2} & \cdots & R2_{i2} \\ \vdots & \vdots & \cdots & R3_{im} \\ R1_{im} & R2_{im} & R3_{im} & Rn_{im} \end{bmatrix}$$

Next, $[A_{ri}]$ is defuzzified by multiplying the membership values for each residual risk level by its corresponding weight to calculate the weighted average likelihood (Kickert, 1978):

$$\bar{R}_{ij} = \sum_{x=1}^{n} w_x R_{xj} \qquad \text{(Eq. 7.4)}$$

Where $\bar{R}_{ij}$ is the weighted average likelihood that risk factor *i* will result in risk event *j*; R_{jx} is the membership value for residual risk level *x* for risk event *j*; and w_{jx} is the relative importance of residual risk level *x*.

The values of w_{jx} $\{x = 1...n\}$, the relative importance of the various residual risk levels, represent the risk attitude of the decision-maker and serve as a benchmark against which the project Overall Risk Index (ORI) is compared. As discussed above, the perception of risk is relative, and a situation deemed risky to one individual may seem acceptable to another, depending on their relative utility. Risk attitude curves are computed using the following exponential risk function (Moselhi and Sigurdardottir, 1998):

$$W_x(Y) = \frac{1 - e^{-\gamma Y}}{1 - e^{-\gamma}} \Big| \gamma \neq 0 \quad \text{and} \qquad Y = \{a_1 \ldots a_n\} \qquad \text{(Eq. 7.5)}$$

where:

$W_x(Y)$ = exponential function for computing weights w_1 to w_n, that takes values from 0 to 1 ; γ = risk aversion factor, the higher its value the greater the risk aversion of the user; and, Y = a set of predetemined likelihood percentiles $\{a_1 \ldots a_n\}$ associated with weights $\{w_1 \ldots w_n\}$.

Figure 7.3 shows several examples of risk attitude curves for selected values of γ . For $\gamma = 0$ a linear relationship exists between the percentile likelihood (Y) and the weights (w). Convex forms of the Eq. 7.5 ($\gamma < 0$), which represent risk prone attitude, are also allowed (French, 1986). However, risk prone attitude is not commonly encountred in the field of underground construction.

The decision-maker is asked to select a risk aversion factor, γ, from a predetermined range $\{\alpha_1 \ldots \alpha_k\}$. The greater the value of γ , the more conservative is the analysis, and the higher the weights assigned to the lower levels of residual risk. By the same token, the lower the value of γ the less conservative is the analysis. A value of $\gamma = 0$ represents a risk indifference attitude - a 50/50 percent likelihod of exceeding the decision-maker's risk threshold. The values $\gamma = \infty$ and $\gamma = -\infty$ represent a 0% and a 100% likelihood of exceeding the decision-maker's risk threshold, respectively.

The chosen value for γ is subtituted into Equation 7.5, and for each predetermined percentile value (Y_x) a weight, w_x, is computed. Additional insight can be gained by constructing the complete project risk profile. This is done by calculating the ORI for each risk aversion factor, $\gamma = \{\alpha_1 \ldots \alpha_k\}$, and plotting the results to construct the ORI curve. A detailed example of the use of Equation 7.5 and the relationshp between ORI and γ is given in Section 7.1.4.

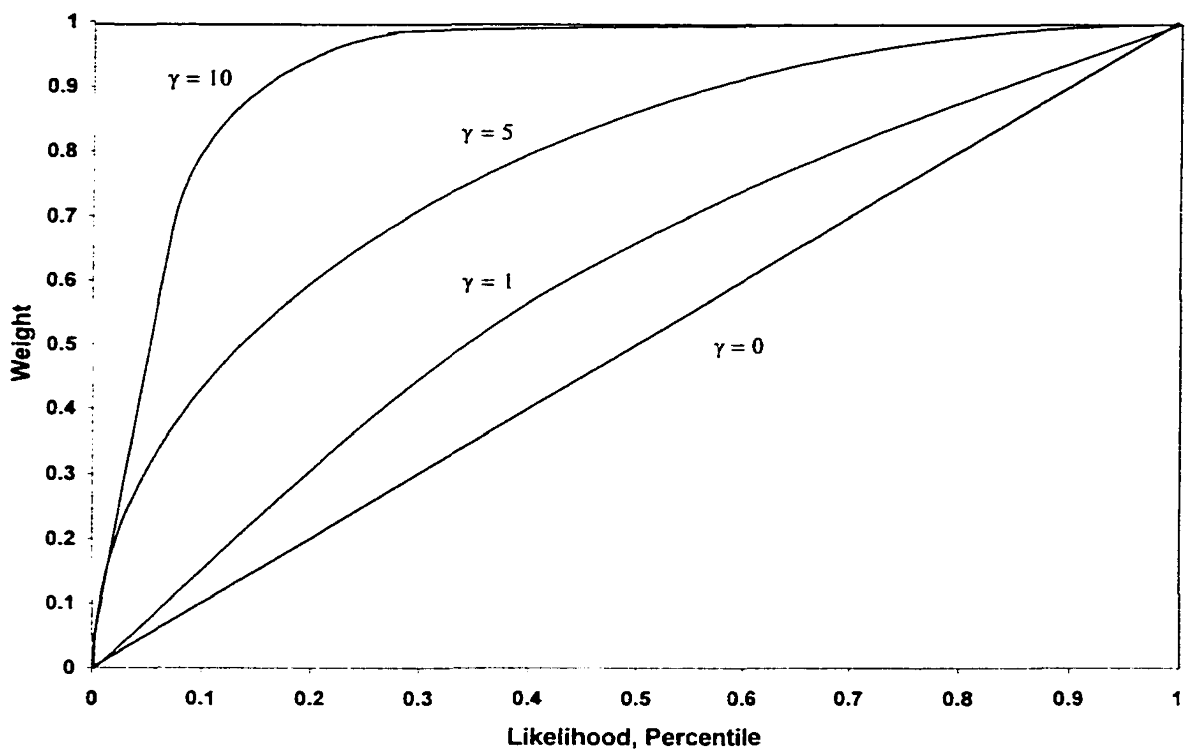

Figure 7.3 Examples of risk behavior curves

The residual risk levels $\{1 \ldots n\}$ associated with a given risk event j are multiplied by the weights vector [W_{RR}], which consists of the importance factors w_1 to w_n, using a standard matrix multiplication procedure and Equation 7.4. The first entry in the first row of $[A_{ri}]$ is multiplied by the first entry in the first column of $[W_{RR}]$, next, the second entry in the first row of $[A_{ri}]$ is multiplied by the second entry in the first column of $[W_{RR}]$ and so on. The sum of the multiplication product is equal to $\bar{R}_{ij}$, the weighted average likelihood that risk factor i will cause risk event j. The product of the multipication of $[A_{ri}]$ by $[W_{RR}]$ is a vector named the Weighted Impact Factor [WIF], representing the average likelihood that risk events $\{1...m\}$ will take place as a result of the presence of risk parameter i. The above procedure is described mathematically by Equation 7.6

$$[A_{ri}] \bullet [W_{RR}] = [WIF_i] \qquad \text{(Eq. 7.6)}$$

$$n\text{x}m \quad \bullet \quad m\text{x}1 \quad = \quad n\text{x}1$$

Using the above-described process, a residual risk matrix is calculated for each of the risk parameters $\{1...i\}$, using the relevant membership functions, and then it is multiplied by the weight factor vector $[W_{RR}]$ to obtain the respective weighted impact vector. Next, the weighted impact vectors from all risk factors, 1 to i, are assembled to form a new matrix designated the Weighted Impact Matrix, [WIM]:

$$[WIM] = \begin{bmatrix} RE_{11} & RE_{21} & \cdots & RE_{k1} \\ RE_{12} & RE_{22} & \cdots & RE_{k2} \\ \vdots & \vdots & \cdots & RE_{k3} \\ RE_{1m} & RE_{2m} & \cdots & RE_{km} \end{bmatrix}$$

The rows in the resulting matrix represent risk events $\{1...m\}$ while the columns represent risk factors $\{1...k\}$. The entries are the weighted likelihood that risk factor i will trigger risk event j, and are designated as RE_{ij}. The weighted impact matrix is then multiplied by a second set of weights named the Risk Factor Importance (RFI) vector. The purpose of this operation is to aggregate into a single value the contributions from each of the risk parameters to obtain the combined likelihood that a given risk event takes place.

Two approaches can be used to derive the aggregated likelihood values for a given risk event. The first approach reasons that the only risk parameter requiring consideration is the one with the highest likelihood of triggering risk event j. A fuzzy computational rule termed max-product composition can then be used to identify the critical value:

$$\prod (AI_m) = \underset{i=1..k}{Max}\left(\prod (RE_m) \times W_i\right) \qquad \text{(Eq. 7.7)}$$

where $\Pi(AI_m)$ is the highest likelihood of risk event j occurring due to risk factor i; $\Pi(RE_m)$ is the rated average residual risk of risk factor i; and, W_i is the importance weight factor associated with risk factor i.

The difficulty with the above approach is that in some scenarios the residual risk contributions from the various risk factors may be considered cumulative. In other words, the combined impact of several risk factors might be greater than the impact of the factor with the highest potential level of risk alone. Under such circumstances, an alternative computational method can be used. This method sums the product of the weighted average impact from all of the risk factors $\{1...i\}$ and their respective importance factors $\{W_1 \ldots W_i\}$ for a given risk event j. This is accomplished simply by using a standard matrix multiplication operation. The resulting vector is called the weighted combined impact vector, which represents the relative likelihood that risk event j will take place due to the aggregated impact of risk factors $\{1 \ldots i\}$. The weights of the various risk factors are introduced in order to assign the appropriate significance to each of the residual contributions from each of the risk factors (i.e., suitability of geological conditions may be considered to have a more significant overall impact on project success than the relative depth of operation). The sum of the weights in the Risk Factor Importance vector, $[W_{RF}]$, is 1.0. Since they represent the relative importance of one risk factor in comparison to the others, these values can be derived using the Analytical Hierarchy Process (Section 6.6.2) or otherwise.

The product of the weight impact matrix and the risk factor importance vector is the Aggregated Impact vector, [AI]. Equation 7.8 provides a mathematical description of the above procedure:

$$\begin{bmatrix} RE_{11} & RE_{21} & \cdots & RE_{k1} \\ RE_{12} & RE_{22} & \cdots & RE_{k2} \\ \vdots & \vdots & \cdots & RE_{k3} \\ RE_{1m} & RE_{2m} & \cdots & RE_{km} \end{bmatrix} \bullet \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_k \end{bmatrix} = \begin{bmatrix} AI_{RE_1} \\ AI_{RE_2} \\ \vdots \\ AI_{RE_m} \end{bmatrix} \qquad \text{(Eq. 7.8)}$$

The entries in [AI] represent the aggregated weighted impact from all foreseen risk factors that contribute toward the occurrence of a risk event j. The final step in computing the project overall risk factor is the multiplication of the aggregated impact vector by an additional set of weights, named the Risk Event Importance vector [REI]. [REI] represents the relative impact (e.g., magnitude of loss) of each of the risk events on the project's final outcome. For example, failure to meet profile requirements may be considered to result in more severe consequences then reduced productivity, but may not be as severe as the boring head getting jammed in the bore. An additional consideration in determining the weights is the degree of accessibility of excavation equipment to the borehole alignment. Having the boring head jammed in the borehole in a 'green-field' situation may not be as severe as getting it jammed beneath a busy freeway. Individual weight values can be developed using AHP and should be normalized. The product of [AI] and the [REI] is the project's Overall Risk Index (ORI), as shown in Equation 7.9:

$$\begin{bmatrix} AI_{RE_1} \\ AI_{RE_2} \\ \vdots \\ AI_{RE_m} \end{bmatrix} \bullet \begin{bmatrix} W_{RE_1} & W_{RE_2} & \cdots & W_{RE_J} \end{bmatrix} = \begin{bmatrix} ORI \end{bmatrix} \qquad \text{(Eq. 7.9)}$$

The value of the overall project's risk factor lies in the domain $\{0\ldots1\}$. The closer the index is to '0.0' the less risky is the project from the construction point of view, and the closer the index is to '1.0' the riskier the project. The value of ORI is directly related to the decision-maker's risk attitude as reflected in the value of γ. A linguistic interpretation of ORI can be obtained through Figure 7.3, by entering the chart at the Y-axis at the ORI value and moving horizontally to intersect the diagonal ($\gamma = 0$), and then going down vertically to read the corresponding percentile of likelihood off the 'X'-axis. This value represents the average likelihood that the decision-maker's risk threshold will be breached. Mathematically this is the equivalent of direct mapping of ORI into the likelihood domain:

If $0.0 \le ORI < b_1 \Rightarrow$ the likelihood of breaching risk threshold = unlikely

If $b_1 \le ORI < b_2 \Rightarrow$ the likelihood of breaching risk threshold = somewhat likely.

If $b_2 \le ORI < b_3 \Rightarrow$ the likelihood of breaching risk threshold = likely

If $b_3 \le ORI \le 1.0 \Rightarrow$ the likelihood of breaching risk threshold = very likely

where $0.0 \le b_1 < b_2 < b_3 \le 1.0$, are to be specified by the user, with a default value equal to:

$$b_i = b_{i-1} + \frac{1}{n} \qquad \text{(Eq. 7.10)}$$

where n is the number of residual risk levels. The domain $Y = \{a_1 \ldots a_n\}$ used in equation 7.5 is computed from the values of b_i using the following relationship:

$$a_i = \frac{b_i + b_{i-1}}{2} \Big| i = \{1 \ldots n\} \qquad \text{(Eq. 7.11)}$$

The following section presents an example that demonstrates the viability, logic and generality of the proposed paradigm. An inherent advantage in the proposed approach is that it lends itself to full automation, in contrast to many of risk analysis algorithms found in the literature that require extensive interaction with the user (Jeljeli and Russell, 1995). The model can accommodate any number of risk parameters and risk events.

7.1.4 Working Example - Risk Assessment

In order to demonstrate the viability of the proposed methodology and its generality, an obvious risk analysis situation was selected from everyday life - crossing of an intersection at a red light. Three risk factors were identified:

1. Crossing vehicular traffic,
2. Crossing pedestrian traffic, and
3. Presence of law enforcement (e.g., police car, hidden camera).

The following risk events are associated with the above risk factors:

1. Collision resulting in collateral damage only (i.e., insurance increase; fines).
2. Collision resulting in bodily injuries with or without collateral damage (i.e., insurance increase; fines; demerits; possible criminal charges), and
3. Traffic violation ticket/demerits.

For the purpose of illustration the following residual risk domains and percentiles were established:

Unlikely: 0 to 25%; $b_1 = 0.25$; $a_1 = 0.125$

Somewhat Likely: 25.1 to 50%; $b_2 = 0.50$; $a_2 = 0.375$

Likely: 50.1 to 75%; $b_3 = 0.75$; $a_3 = 0.625$

Very Likely: 75.1 to 100%; $b_4 = 1.00$; $a_4 = 0.875$

The range below and above a given '*a*' value is described by the linguistic terms 'less than' and 'more than', e.g., - less than unlikely. The value of 'b' represents the upper threshold for the corresponding level of risk in term of the ORI value. Table 7-1 gives the fuzzy membership values for the residual levels of risk from each of the risk factors in relation to the three risk events listed above. Based on Table 7-1 the residual risk matrices $[A_{r1}]$ to $[A_{r3}]$ are assembled for risk factors 1 to 3, respectively.

Table 7-1 Membership Values for Levels of Residual Risk

Risk Event	Unlikely	Somewhat likely	Likely	Very Likely
Risk factor 1: Crossing vehicular traffic				
collateral damage	0.0	0.0	0.2	0.8
body injuries	0.0	0.3	0.5	0.2
ticket/demerits	0.0	0.0	0.0	1.0
Risk factor 2: Crossing pedestrian traffic				
collateral damage	0.8	0.2	0.0	0.0
body injuries	0.0	0.0	0.1	0.9
ticket/demerits	0.0	0.0	0.0	1.0
Risk factor 3: Law enforcement presence				
collateral damage	1.0	0.0	0.0	0.0
body injuries	1.0	0.0	0.0	0.0
ticket/demerits	0.0	0.0	0.0	1.0

$$[A_{r1}]=\begin{bmatrix}0.0 & 0.0 & 0.2 & 0.8\\ 0.0 & 0.3 & 0.5 & 0.2\\ 0.0 & 0.0 & 0.0 & 1.0\end{bmatrix} \qquad [A_{r2}]=\begin{bmatrix}0.8 & 0.2 & 0.0 & 0.0\\ 0.0 & 0.0 & 0.1 & 0.9\\ 0.0 & 0.0 & 0.0 & 1.0\end{bmatrix}$$

$$[A_{r3}]=\begin{bmatrix}1.0 & 0.0 & 0.0 & 0.0\\ 1.0 & 0.0 & 0.0 & 0.0\\ 0.0 & 0.0 & 0.0 & 1.0\end{bmatrix}$$

The domain of γ includes the real numbers between $\lim_{\gamma\to 0}$ and 10.0, where $\lim_{\gamma\to 0}$ indicates indifference in risk attitude - neither risk prone nor risk averse, 10.0 indicates extreme caution, and intermediate values represent equal increments of the degree of conservatism. Risk prone attitude, represented by values of $\gamma<0.0$, is considered to be uncommon in construction in general and municipal engineering in particular (Moselhi and Sigurdardottir, 1998). For the sake of demonstration a value of $\gamma = 5$ was selected. Using Equation 7.5 the following weights were derived for the four levels of residual risks using the values of a_1 to a_4 listed above:

$$W_{RR} = \begin{bmatrix} 0.469 \\ 0.852 \\ 0.963 \\ 0.994 \end{bmatrix}$$

Using Equations 7.4 and 7.6 a weighted impact factor [WIF] is derived for each of the risk factors 1 to 3, and the weighted impact matrix [WIM] is assembled:

$$[WIM] = [WIF_1, WIF_2, WIF_3] = \begin{bmatrix} 0.988 & 0.545 & 0.468 \\ 0.936 & 0.991 & 0.468 \\ 0.994 & 0.994 & 0.994 \end{bmatrix}$$

The risk factor importance vector represents the relative importance of one risk factor in comparison to the others. For the current example, this is represented by the probability of presence in the intersection during the crossing, which is assumed to be:

- crossing traffic - 80%,
- crossing pedestrians - 50%, and
- law enforcement 20%.

The above weights are normalized and substituted into Equation 7.8 to compute the Aggregated Impact vector, [AI]:

$$[AI] = \begin{bmatrix} 0.988 & 0.545 & 0.468 \\ 0.936 & 0.991 & 0.468 \\ 0.994 & 0.994 & 0.994 \end{bmatrix} \begin{bmatrix} 0.533 \\ 0.333 \\ 0.133 \end{bmatrix} = \begin{bmatrix} 0.770 \\ 0.891 \\ 0.993 \end{bmatrix}$$

The final step involves the computation of the Overall Risk Index (ORI), which is equal to the product of [AI] and the Risk Event Importance factor [REI]. [REI] represents the relative impact (i.e., magnitude of loss) of each of the risk events on the action's outcome. For demonstration purposes, it is assumed that body injury is three and a half times more severe than collateral damage and seven times more severe than a fine. Also, collateral damage is twice as severe as a fine. Using Equation 7.9:

$$\begin{bmatrix} 0.770 \\ 0.891 \\ 0.993 \end{bmatrix} \bullet \begin{bmatrix} 0.2 & 0.7 & 0.1 \end{bmatrix} = \begin{bmatrix} 0.877 \end{bmatrix}$$

The meaning of the ORI value (= 0.877) is that it is very likely (=0.875) that the outcome of the proposed action (crossing the intersection on a red light) will breach the decision-maker risk threshold. The risk profile for $\gamma = \{0.001 \ldots 10.0\}$ is shown in Figure 7.4. The zones designated as 'A' to 'D' represent levels of likelihood of breaching the decision-maker risk threshold: 'A' – Very Likely; 'B' - Likely; 'C' – Somewhat Likely; and, 'D' - Unlikely. It can be seen that over the entire domain of γ it is likely to very likely that the decision-maker's risk threshold will be breached by the action under consideration, thus this action should be avoided.

Figure 7.5 demonstrates the risk profile over the domain $\gamma = \{-50 \ldots 50\}$. The function is discontinuous at $\gamma = 0$. Values smaller than 0 represent a risk prone attitude, for example a fugitive involved in a vehicle chase.

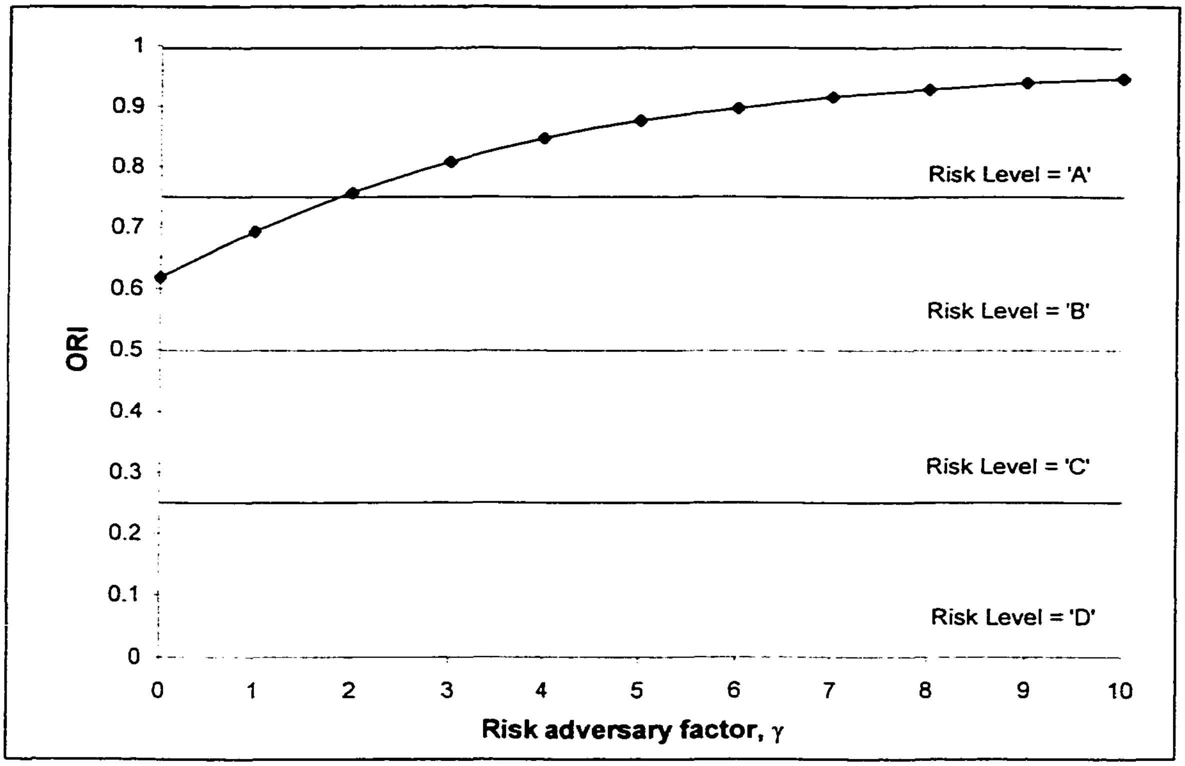

Figure 7.4 The risk profile for γ = 0.001 to 10.0

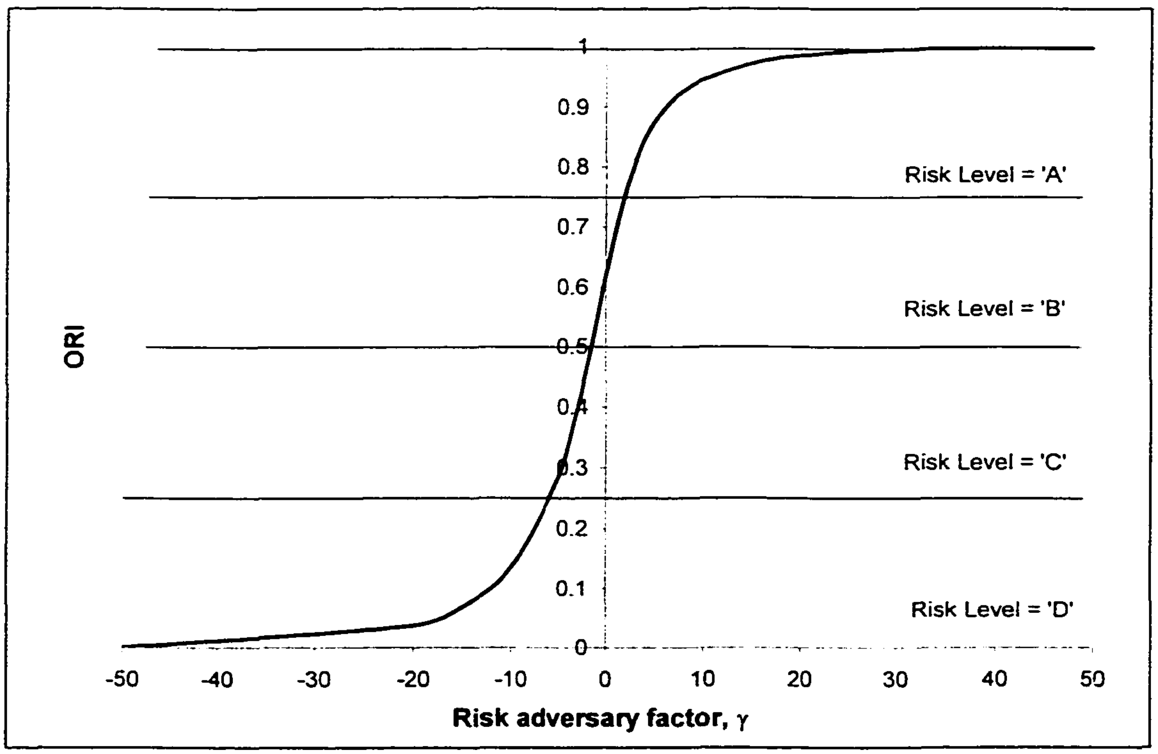

Figure 7.5 The risk profile for γ = -50 to 50

7.2 DEVELOPMENT OF DISTRIBUTIONS FOR PREFERENCE ATTRIBUTES

7.2.1 Overview

The preference evaluation process includes parameters not associated with the technical soundness of the method, and therefore considered to be controlled by the decision-maker. In other words, the model computes the likelihood for each technically sound method to satisfy the decision-maker's objectives. Eight preference attributes associated with trenchless projects were identified in Section 6.6.1, namely:

- *Project Costs:* direct costs, indirect costs, markup and contingency. Specified in monetary values. Range of values can be obtained from prediction models, historical records or industry surveys.
- *Project Duration:* duration is specified in any type of time unit such as days, weeks or months. Project duration can be estimated by dividing the length of the installation (L) by the estimated productivity. Productivity values may be obtained from historical records or industry surveys.
- *Environmental Impact:* a predetermined scale with a detailed description of environmental impact associated with each value (e.g., 5 - unlimited clearing and excavation).
- *Loss of Income:* including productivity loss due to construction activities, loss of parking revenues and loss of tax revenues. Specified in monetary terms. Range of values can be obtained from historical records or experience.
- *Surface Improvements:* Restoration costs or reduction in the value of surface improvements. It also includes the cost associated with relocation of adjacent

utilities. Specified in monetary terms. Range of values can be obtained from historical records, personal experience and the project's specific parameters.

- *Ground Movement:* including the cost of repairing damage caused to paved surfaces and foundations due to settlement. Specified in linguistic terms. Assignment of values can be based on historical records, experience and the project's specific parameters.
- *Traffic Interferences:* including the costs associated with detours, traffic delays and damage to roadways on the detour route due to heavier traffic loads and volume. Specified in monetary terms or a measure of traffic delay. Range of values can be obtained from social cost estimating models (e.g., McKim, 1997).
- *Business Loss:* these losses include revenue losses of businesses in the vicinity of the construction site due to lack of convenient access, noise and clutter. Specified in monetary terms. Range of values can be obtained from social cost estimating models and surveys.

A general range of values for each of the preference attributes can be derived from historical data, prediction models or can be specified by the user in the form of a set of statistical parameters (e.g., low, high and mean). Alternatively, values of attributes can be represented using a constant or in the form of a constraint (i.e., as a function of the value of one or more variables).

In the case where a historical database exists a curve-fitting technique can be used to determine the underlying distribution using a curve-fitting program such as BetaFit (AbouRizk et. al., 1994b). This process is demonstrated in the next section for horizontal directional drilling. Alternatively, if only the minimum and maximum values of the range of expected values are available, software such as VIBES (AbouRizk et. al., 1991) can be used to determine the most likely values of the distribution's shape parameters. An example application for Microtunneling is shown in Section 7.2.3. The user may also select to account for a particular attribute in an implicit manner (e.g., Business Loss = $3000*Duration). The model treats such relationships as constraints. Constraints are discussed later in the text.

7.2.2 Construction of Underlying Distribution Using Statistical Analysis

Fitting statistical distributions to sample data can be found in many construction applications including simulation, risk analysis, quality control, costing and scheduling. To obtain the underlying probability distribution for a set of sample data one can utilize the conventional approach of fitting a probability distribution from a standard family of continuous distributions. One such distribution is the normal distribution, the shape and location of its probability density function can be completely described by the sample Mean (μ) and Variance (σ^2), as computed by equations 7.12 to 7.14, respectively.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad \text{(Eq. 7.12)}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n} (X_i - \mu)^2 \qquad \text{(Eq. 7.13)}$$

where n is the number of entries in the sample and X_i is the value of the *i*th entry. The probability associated with a given value, X, along the permissible range is then computed by the functional form:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \qquad \text{(Eq. 7.14)}$$

Other common continuous distributions include exponential, Lognormal, triangular, Weibull and Gamma. The difficulty arises from the need to fit the field data to several types of distributions and then evaluate the one which best represents the sample data based on goodness-of-fit tests such as the Chi-square test, the Kolmgrov-Simrov test or a Cumulative Density Function (CDF) comparison. Aside from the tedious fitting and evaluation process, the outcome may not always be clear as to which standard distribution best fits the test data.

An alternative method is the application of a flexible family of distributions that is capable of exhibiting a variety of shapes (AbouRizk et al., 1994b). This class includes, among others, the generalized beta family of distribution that can be described by four parameters, namely, the lower limit [L], the upper limit [U], and the shape parameters *a* and *b*. For a random variable X the mean and variance for the generalized beta distribution are computed using the following expressions:

$$\mu = L + (U - L)\frac{a}{a+b} \qquad \text{(Eq. 7.15)}$$

$$\sigma^2 = (U - L)^2 \frac{ab}{(a+b)^2(a+b+1))} \qquad \text{(Eq. 7.16)}$$

and the functional form:

$$f(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \cdot \frac{(x-L)^{a-1}(U-x)^{b-1}}{(U-L)^{a=b-1}} \qquad \text{if } L \le X \le U$$

$$f(x) = 0 \qquad \text{otherwise} \qquad \text{(Eq. 7.17)}$$

Betafit, a software application program that fits sample field data into a general Beta distribution, was developed and described by AbouRizk (1990) and (AbouRizk et al., 1994b). For demonstration purposes Betafit was used to fit cost data collected from 49 directional drilling contractors from across North America (Allouche, 1999). The contractors were asked to indicate the cost of installation associated with a particular product diameter. The data was normalized by dividing the cost of installation by the product diameter, to obtain the cost of installation per millimeter of product diameter per meter length. Similarly, data was collected regarding productivity values in various types of geological formations. Installation cost data as well as data concerning productivity values in clay, silt and sand formations was imported into Betafit, where it was fitted to a generalized beta distribution using the matching mean, variance, and sample end points method. The resulting values are shown in Tables 7-2 and 7-3, respectively. The number of data points for installation rates in gravel/cobble and stiff clay for a product diameter greater than 100mm was insufficient for a statistical analysis. The data in both, raw and published forms, can be found in Appendix 'E'.

Table 7-2 Fitted Beta Distributions for Installation Costs for HDD

Installation costs in Canadian dollars/millimeter diameter per meter length						
Diameter, mm	Upper limit	Lower limit	a	b	μ	σ^2
50	5.89	0.95	0.073	0.383	1.74	2.26
100	4.75	0.48	0.407	1.548	1.37	1.02
150	4.75	0.32	0.741	2.687	1.28	0.75
200	3.56	0.24	1.173	2.372	1.34	0.54
250	2.85	0.38	0.709	0.868	1.49	0.58
300	3.14	0.32	0.489	0.694	1.57	0.85

Table 7-3 Fitted Beta Distributions for Productivity Rates for HDD

Type of formation	Upper limit	Lower limit	*a*	*b*	μ	σ2
Product diameter 50-100mm						
Soft-medium Clay	350	70	0.889	1.465	175.2	5493.6
Sand	300	70	0.358	0.989	131.2	4398.6
Stiff clay	140	25	0.484	0.431	85.8	1720.1
Cobble/gravel	70	25	0.46	0.56	47.5	306.3
Product diameter 150-200mm						
Soft-medium Clay	300	25	0.745	1.242	128.1	5931.3
Sand	300	25	0.452	1.193	100.6	5699.1
Product diameter 250-300mm						
Soft-medium Clay	300	25	0.355	0.905	102.5	6771.2
Sand	300	25	0.294	0.937	90.6	6158.9

7.2.3 Construction of Underlying Distribution Without Statistical Analysis

Apart from horizontal directional drilling and microtunneling, where data regarding installation costs was collected and published by several investigators (Allouche et. al, 1999; Sangster and Kramer, 1998), little published data were found in the literature regarding installation costs of other trenchless methods. More commonly, upper and lower limits are quoted (e.g., Iseley and Gokhale, 1997). Thus, it is useful to have a method that enables one to construct the statistical distribution from only a few data points that are supplemented by the knowledge and experience of the user.

The simplest approach is to assume that the most likely estimate (MLE) for a particular attribute is the mean/mode of a particular continuous distribution, the parameters of which are known from historical data. The assumed distribution is typically simple in nature as it is based on a relatively small quantity of sample observations combined with subjective information. Commonly employed distributions include triangular, normal and exponential.

An alternate, and somewhat more refined approach, was adopted by AbouRizk et al., 1991 who developed a visual interactive procedure called VIBES (visual interactive beta estimation system). VIBES requires the user to specify the attribute's minimum and maximum values, together with two of the following characteristics: mode, mean, variance, or selected percentiles. VIBES then generates the PDF of the distribution. If desired, the user can manipulate the fitted distribution by either revising the specified characteristics of the distribution or by interactive modification of the displayed PDF on the screen.

7.2.4 Development of a Site Specific Distribution Range

In many cases, the sample data set (lower and upper limits) used to derive the underlying distributions may be based on a large number of projects performed in a wide range of geographical areas, geological conditions and site characteristics. It can be seen in Table 7-2 that installation costs may range up to 1000% depending on project specific characteristics. Table 7-3 shows that productivity values in similar formations may vary significantly depending on installation tolerances, product type and length of installation, to mention just a few of the parameters. In general, it is reasonable to assume that construction costs and average productivity values will vary primarily as a function of the overall level of construction risk associated with the project, as computed in Section 7.1. Thus, it might be more suitable to account for this by constructing a secondary, bias distribution from the general underlying distribution. Depending on the value of the risk index, certain areas of the general distribution are 'blacked-out' using predetermined percentile boundaries established from industry surveys. For example, for a risk level = 'High', the percentile boundaries are 50% to 95%. The Monte Carlo simulation technique is then used to randomly sample the general distribution. A random number is generated using the Linear Congruential Scheme (LCS), which is based on the following equations:

$$Z_n = a * Z_{n-1} MODm \quad \text{(Eq. 7.18)}$$

$$R_n = \frac{Z_n}{m} \quad \text{(Eq. 7.19)}$$

Where Z_n is the starting integer value and a (the multiplier) and m (the modulus) are constants. Typical values for a and m are 7^5 (=16,807) and (2^{16}-1) respectively (taha, 1997). The LCS method generates fairly uniform numbers on the range [0,1] that are reproducible.

The random number is then 'mapped' into the assumed distribution using the distribution inverse function, a mathematical expression that gives the value from a particular distribution that corresponds to a particular probability, represented by the random number. In a more formal form, it can be said that the distribution probability density function *f(x)* is integrated to yield the distribution's cumulative density function *F(x:)* :

$$F(x) = \int f(x)dx \quad \text{(Eq. 7.20)}$$

The cumulative density function is then equaled to the random number deviate, R, and solved for the variable x:

$$F(x)_x = R \quad \text{(Eq. 7.21a)}$$

$$x = F^{-1}(R) \quad \text{(Eq. 7.21b)}$$

Equation 7-21b is called the inverse function. The inverse functions for normal, exponential and triangular distributions are shown in Equations 7.22 to 7.24, respectively.

$$F^{-1}(x) = M + \cos 2\pi R_1 \sqrt{-2SD * \log(R_2)} \text{ (Normal distribution)} \qquad \text{(Eq. 7.22)}$$

$$F^{-1} = -M * \ln(R) \text{ (Exponential distribution)} \qquad \text{(Eq. 7.23)}$$

$$F^{-1}(x) = \begin{cases} L + \sqrt{(M-L)(U-L)R} & \text{for} \quad 0 \le R \le (M-L)/(U-L) \\ U - \sqrt{(U-M)(U-L)(1-R)} & \quad (M-L)/(U-L) < R \le 1 \end{cases}$$

(Triangular) (Eq. 7.24)

where M is the mode/mean, L is the lower limit, U is the upper limit, SD is the standard deviation and R is a random number.

Mapping the random number into the distribution yields a single value for the attribute. The entire process is repeated a large number of times in order to construct the modified distribution. Values sampled outside the boundaries are ignored. The sample data set is then fitted to generate a bias distribution that better represents the range of values for a particular project given the anticipated level of risk. The characteristics of the modified distribution (e.g., mean, variance) are computed, and serve as input data for the Domain-of-Compliance Utility model.

The procedure described in this section is particularly useful when the parameters of a high-risk project (river-crossing) are estimated using a general data set. For example, a 200mm-diameter HDPE product is to be installed across the North Saskatchewan River (approximately 350m long). The risk analysis indicates that completing the project with a midi-size directional drilling rig is associated with a high level of construction risk. From Table 7-2 the upper and lower limits of the appropriate distribution are \$3.56 and \$0.24 per millimeter diameter, respectively. The shape parameters *a* and *b* are 1.173 and 2.372, respectively. The percentile boundaries for the sake of demonstration were assumed to be 50% and 95%. Using MS Excel fifty random values were generated and mapped into the underlying Beta distribution. Values below the 50 percentile or above the 95 percentile were eliminated. The bias sample data was re-fitted into a new Beta distribution. The parameters of the general and modified distributions are compared in Table 7-4.

Table 7-4 Comparison of General and Modified Beta Distributions

Installation costs in Canadian dollars/millimeter diameter per meter length						
Distribution	**Upper limit**	**Lower limit**	***a***	***b***	μ	σ^2
General	3.56	0.24	1.173	2.372	1.34	0.54
Modified	2.63	1.23	0.796	1.457	1.73	0.135

The values from the modified distribution are more likely to represent the expected average bid price (\$300-\$500 per meter of product installed, based on historical records) in comparison to the general distribution.

The step described in this section is optional, and can be skipped if the user feels that it is more suitable to use the entire underlying distribution as input data for the Domain-of-Compliance Utility model.

7.3 DOMAIN-OF-COMPLIANCE UTILITY MODEL

7.3.1 Overview – Constraint Satisfaction Techniques

Sets of constraints and variables together with their affordable domains are called constraint satisfaction problems (CSPs). Constraint satisfaction problems provide frameworks in which it is possible to express, in a natural way, computational problems encountered in many fields including artificial intelligence (e.g., pattern recognition), molecular biology (DNA sequencing), business (option trading) and electrical engineering (to locate faults). A constraint satisfaction problem consists of a domain (D), a number of variables ($V_1, V_2, \ldots V_n$) and a number of constraints ($C_1, C_2, \ldots C_q$) that restrict the allowable combination of the values of the variables. A solution to a constraint satisfaction problem is an assignment of a domain value to each variable that satisfies all the constraints simultaneously. CSP can be represented using graphs called constraint satisfaction networks. In such graphs nodes are used to represent variables (i.e., A, B and C, in Figure 7.6) while arcs are used to show the constraints among them (the lines between the boxes in Figure 7.6 and the mathematical expressions associated with them).

In engineering, constraints are typically numerical relationships (equalities or inequalities) that dictate the acceptable values for continuous or discrete variables. However, as a general rule constraints may assume analytical forms. A solution for a constraint satisfaction problem is a set of values that satisfies the constraints and is within the allowable range. In other words, D is the allowable domain if and only if each set of values for variables for V_1 through V_m satisfies the constraints C_1 through C_n, simultaneously.

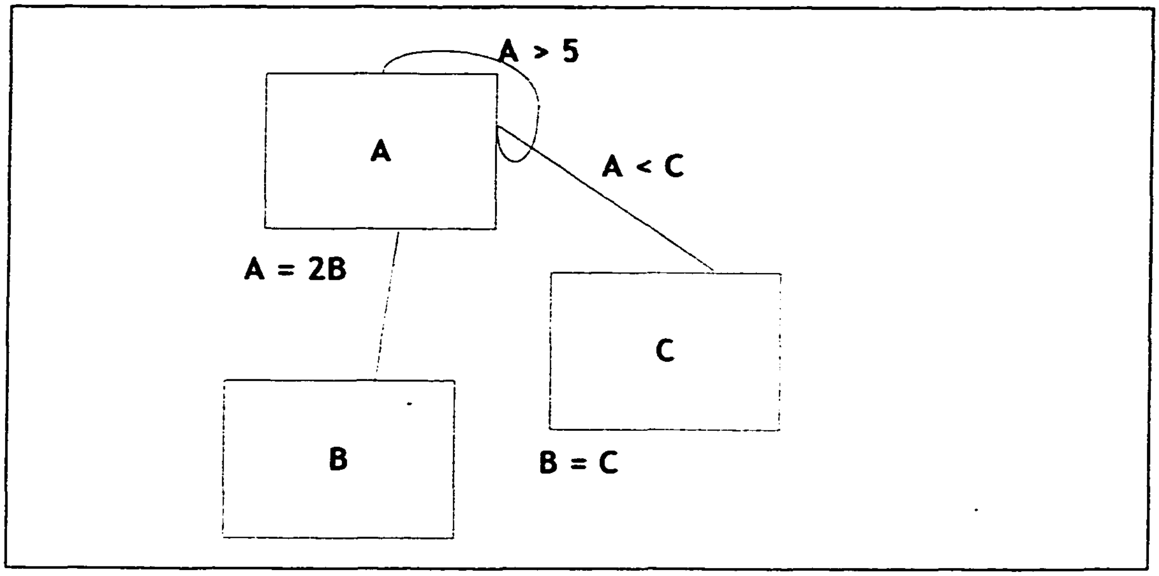

Figure 7.6 Sample of a Constraint Satisfaction Network

Solutions to CSPs are found using constraint satisfaction techniques, which compute an approximation of the solution spaces. Many of these search techniques use the concept of *consistency*. The term consistency is a measure of the success in carrying out the task of identifying those variables that satisfy the constraints and are within allowable variable domains. In contrast to search techniques of discrete intervals (e.g., Newton-Raphson) that commonly attempt to identify the optimal solution, consistency algorithms approximate the solution space. As a general rule, the degree of consistency achieved by a given search technique is inversely related to the complexity of the required computational effort. CSP algorithms that have a low degree of consistency tend to overestimate the solution space, but have a low degree of computational complexity. On the other hand, CSP algorithms that ensure a high degree of consistency provide a tight estimate of the solution spaces, but require a high degree of computational complexity. Computational complexity is defined as the sensitivity of the execution time to the amount of input data in terms of both the number of variables involved and the maximum number of variables associated with each constraint.

As a general rule CSPs require an enormous number of computations even if constraints are represented in a form that permits quick computation (i.e., explicit), because constraint algorithms often seek to establish support for a value of $a \in D$. In other words, the algorithm checks every possible combination of allowable values for all other variables in the constraint to ensure that 'a' belong to the solution space. As a result much of the work on constraint reasoning has focused on ways to reduce the number of constraint checks required. CSPs that involve discrete domains can be typically dealt with effectively using search techniques such as splitting and backtracking. Such brute-force search techniques are suitable for problems where variables have finite domains, such as resource allocation. However, for problems that employ variables that have continuous domains, and hence infinite number of values, more efficient and sophisticated methods are required. Consistency techniques use a variety of rules to identify these parts of the solution space that do not contain any solution, and prune the search space to discard those intervals. Common consistency algorithms include arc-consistency, path-consistency and 2-relational consistency.

While the nature of problems solved using arc-consistency checks is different from that of problems solved by the domain of compliance method, the underlying concept of manipulating large domains of numbers in R^n dimensions is the same, enabling parallels to be drawn between the two methodologies.

7.3.2 Applications of CSPs in Construction

In civil engineering in general, and project management in particular, the modeling of complete project knowledge is rarely feasible, thus optimization is an unattainable goal. However, using solution spaces it is possible to identify solutions that are better according to selected criteria. In other words, solution spaces improve the efficiency of optimally directed decision-making processes by defining the possible point solutions.

In recent years constraint satisfaction techniques were adopted by several investigators for solving problems in construction management, particularly negotiations and conflict resolutions (Bahler, 1995; Bowen and Bahler, 1993; Khedro and Genesereth, 1994). A more recent application of constraint satisfaction was reported by Ivezic and Gasiett (1998), in the context of a simulation-based decision support system capable of assisting early collaborative design processes. Simulated data are used to train neural networks. The trained networks are then sampled using Monte-Carlo simulation to approximate the likelihood of design variable values. Constraint-satisfaction techniques are consequently used to narrow the valid range for the various variables. Another recent research initiative in this area, designated SpaceSolver, was reported by Lottaz et al. (1999). SpaceSolver is a constraint-satisfaction framework developed at the University of Zurich as part of a project for the development of a tool set for virtual Architect Engineering Construction (AEC) companies. Collaborating users define constraints on possible shared variables. All constraints are then collected into one constraint-satisfaction problem (CSP), which is transmitted to a centralized solver, where an array of constraint satisfaction techniques is utilized to identify the solution domains. The program is implemented on the Internet, and a visualization of the constraints and solution spaces is performed using VRML 2.0.

Other potential applications of CSP in construction management include site layout (e.g., location of a tower crane), resource allocation and scheduling. The latter topic has been studied extensively over the past decade by several researchers in the context of industrial engineering and manufacturing (Davis, 1994).

Much of the knowledge in civil engineering, such as codes, behaviour models and planning strategies, employ explicit forms of constraints. Thus, the direct use of constraint-based systems is a logical step, and it is anticipated that a growing number of applications for CSPs will be developed across the civil engineering discipline in the near future.

7.3.3 Domain of Compliance Utility Model – Underlying Concepts and Terminology

The concept behind the Domain of Compliance Utility Model (DCUM) was developed in order to overcome several limitations associated with the decision support models described in Sections 2.2 and 2.3, particularly those that are based on the two-dimensional additive utility theory and the Analytical Hierarchy Process (AHP). These limitations include:

1. Failure to explicitly account for the uncertainty in the input data including anticipated geological conditions, productivity values and cost estimates. It is desirable to reflect this uncertainty in the model and to carry it through the calculations, thus enabling a more realistic presentation of real-life decision-making.
2. Insufficient flexibility. The underlying assumption behind the additive utility theory is that the elements of each subcriteria set are independent, which

enables the decision-maker to combine the performance order for each factor into an overall performance order (Fishburn, 1970). Greater flexibility may be achieved if dependency among parameters is allowed in the model (e.g., payment of a premium for early completion).

3. Pairwise comparisons, the basis for AHP models, are highly subjective, may promote arbitrary input and require the translation of goals that are deterministic in nature to an abstract level of priority. DCUM presents a less subjective way of capturing the preferences of the decision-maker, where the score for each method is calculated based on the probability that it would satisfy a set of pre-specified objectives. This rational approach is expected to improve the consistency of the predictions and reduce sensitivity to personal interpretations.

4. Many of the evaluation models for construction methods covered in Chapter 2 simply identify the most suitable method by computing a single score for each alternative, a score that in most cases is meaningful only with respect to scores assigned to the other alternatives. It is desired that a decision-support system will provide the decision-maker with the opportunity to gain an insight into the potential difficulties associated with the project, the quality of the input data, as well as his/her own priorities in case not all objectives can be fully satisfied.

While constraint satisfaction techniques are intended to identify the subset of values that will simultaneously satisfy a particular set of constraints, the domain-of-compliance utility model (DCUM) is concerned primarily with the likelihood that a given outcome lies within a predetermined solution space. While their primary goals are rather different, some similarities can be drawn between the two approaches. Thus, several concepts and some terminology used in CSP were adopted in developing DCUM in order to take advantage of the well-established state-of-the-art in CSP research. DCUM and its various components are described in the following sections. The terms 'attribute' and 'variable' are used interchangeably throughout the discussion.

Several terms need to be defined before the Domain-of-Compliance methodology can be discussed in detail: *domain of compliance; compliance envelope; solution value;* and, *solution subspace. Domain of compliance* refers to a subset of coordinates ($\{X_1, Y_1, Z_1,\ldots\}\ldots\{X_n, Y_n, Z_n,\ldots\}$) that satisfies the decision-maker's requirements. For example, if three preference attributes are considered in the evaluation, the entire solution domain (R^n) can be visualized as a three-dimensional space (Figure 7.7). Values along each of the three axes are expressed in the same units as the measure they represent (e.g., dollars for cost; days for duration). The decision-maker then specifies the highest acceptable value for each of the measures. In the case of a three-dimensional space, the boundary for each variable will be presented in the form of a plane. The space confined by the six planes may then be defined as the *domain of compliance. Solution value* is every point (represented by coordinates x, y and z) within the domain or on its boundaries, named the *compliance envelope*. Each *solution value* can then be said to fully satisfy the decision-maker's requirements and therefore represents an acceptable solution.

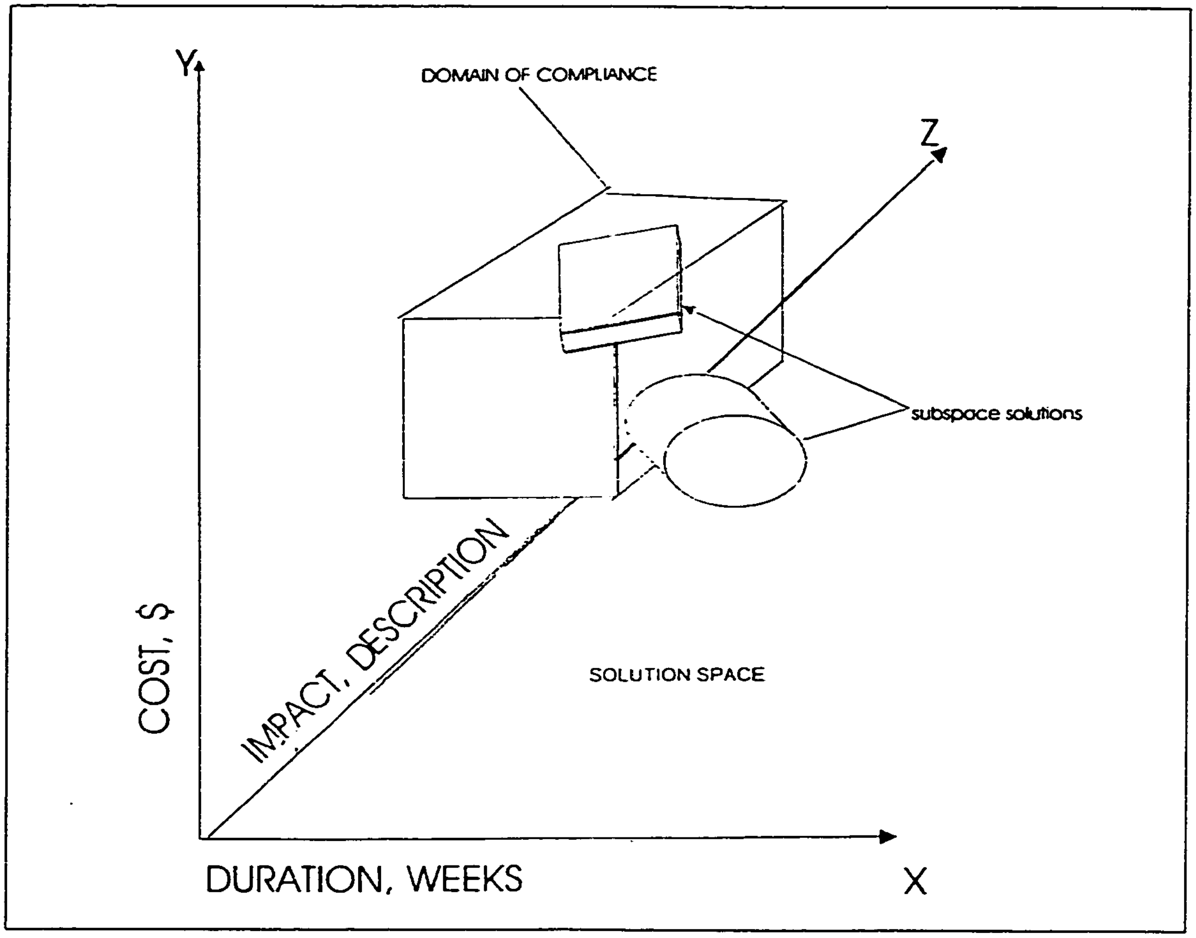

Figure 7.7 Domain of Compliance and Solution Subspace for a 3D Solution Space

As mentioned previously, in providing a unique *solution value* for a particular construction method one ignores the fact that the measures represented by this value are only estimates. The uncertainty in the estimates of the various attributes (e.g. cost, duration, social costs) can be conveyed into the *solution value* by specifying a range rather than a single value for each attribute. The method is represented in this case by a finite set of *solution values* or a *solution subspace*. The *solution subspace* for a given method may lie within, partially within, or outside the *compliance envelope*. Methods of construction represented by *solution subspaces* that lie fully within the compliance envelope are considered viable (likely to satisfy the decision-maker's requirements). Methods of construction represented by *solution subspaces* that lie outside the envelope are considered non-viable (unlikely to satisfy the decision-maker's requirements). Construction methods for which the *solution subspace* lies partially within the *compliance envelope* are considered to have the potential to satisfy the decision-maker's requirements. By computing the compliance status of a sufficient number of discrete values in the *solution subspace,* it is possible to obtain an approximation of the extent to which the solution space lies within the compliance envelope, i.e., the likelihood that the method's performance parameters satisfy the decision-maker's requirements.

The *solution subspace* is constructed by computing the Cartesian product for all real numbers within the preference attributes domains to obtain the probability of each particular outcome. As there is an infinite number of solution points within each *solution subspace*, it is necessary to either discretize or randomly sample the domains of the preference attributes in order to estimate the boundaries of the *solution* *subspace.* The attribute domains are represented in the form of a statistical distribution in the first approach. Values from each distribution are computed at predetermined percentiles (e.g., 5%, 25%, 50%, 75%, and 95%), and all possible combinations of these values are then computed to create a grid in n dimensions representing the *solution subspace.* The number of computations required for each alternative is X^n, where X is the number of discrete points that represent the solution and n is the number of dimensions (i.e., attributes). For example, if there are eight preference attributes in the model, and five percentile values are used to represent each of the distributions, the total number of *solution values* (i.e., number of possible outcome combinations) in each *solution subset* (i.e., alternative) will be equal to 5^8 (= 390,625). The second approach involves random sampling of each of the attributes' statistical distributions using Monte-Carlo simulation to obtain a single *solution point.* The model then checks if the *solution point* is within the compliance envelope. After a predetermined number of iterations (e.g., 50,000), the probability of the *solution subspace* to lie within the compliance envelope is evaluated. A fixed number of additional iterations are initiated and the likelihood that the *solution subspace* lies within the compliance envelope is re-evaluated. If the difference between the likelihood at iteration m and the likelihood at iteration $m-1$ is within a pre-specified tolerance, δ, then convergence is assumed to occur. The random sampling approach was automated in the form of a computer program using MATLAB 5.3 (see Appendix 'D').

For the purpose of the proposed decision support system it is desirable to determine the extent to which a given *solution space* lies within the *domain of* *compliance*, the boundaries of which are specified as either constants or mathematical relationships among two or more attributes (i.e., constraints).

In order to check if a given point '*i*' in method subspace '*D*' lies within the *compliance envelope* (i.e. satisfies constraints R_1 to R_n), a Modified Arc-Consistency (MAC) algorithm was developed. Arc-consistency computations are widely used in the area of artificial intelligence to compute solution domains that satisfy a set of pre-determined constraints. Similar to CSP solution methods, an effort was made to explore various approaches in order to minimize the problem's computational complexity by investigating the mathematical properties of the algorithm and the class of problems considered in this investigation (i.e., selection of a construction method). The MAC algorithm is described in detail in Section 7.3.5.

The utility value of each alternative is calculated using a scoring function that accounts for the degree of discrepancy between the desired and achievable levels of performance as well as the relative importance of meeting a given objective in comparison to meeting others. The final score is a function of the Euclidean distance between the solution subspace 'centre-of-gravity' and the origin of the Domain-of-Compliance solution space.

There is no theoretical limit on the number of dimensions that can be handled by the model, although practical limitations associated with the available computing power may be applied. Also, DCUM may be used in a range of decision-making applications since the theoretical development presented here applies to decision-making in any area in which alternatives can be represented as a set of outcomes, each with a determinable probability of occurrence. The model developed for the evaluation of underground construction technologies allows the decision-maker to specify as many as eight attributes (i.e., eight-dimension solution space). The model is flexible, as the decision-maker may choose to ignore non-relevant attributes thus reducing computation time. An added benefit of the proposed approach is the ability to evaluate the impact of the quality of the information that forms the basis for the decision-making process. For example, if a particular construction method was found to lie partially within the *compliance envelope*, the decision-maker may want to reassess his/her input or gather more data to better evaluate the expected performance parameters. Data collection should continue as long as there are opportunities to profitably reduce uncertainty. The potentially large number of mathematical computations merits the development of a computer-based application for increased user friendliness.

7.3.4 User Input

In order to define the domain of compliance and enable the computation of the utility value for each of the alternatives, the user is asked to define six values for each attribute:

- Minimum Allowable Value (MAV): the lower bound of the range of acceptable values to the owner. The decision-maker will be forced to reconsider the proposed project's design, scope or even viability below this value.

- Minimum Desirable Value (MIDV): the lower limit of the range of values the decision-maker would like to accept in return for completion of the project according to specifications.

- Maximum Allowable Value (MAAV): the upper bound of the range of acceptable values to the owner. The decision-maker will be forced to reconsider the project's design, scope or viability above this value.

- Maximum Desirable Value (MADV): the upper limit of the range of values the decision-maker would like to accept in return for completion of the project according to specifications.

- Lower Bound Importance Factor (LBIF) - this value represents the importance of adhering to the minimum desirable value. LIBF is used to compute the penalty for a performance parameter that lies between the attribute's minimum desirable and allowable values.

- Upper Bound Importance Factor (UBIF) - this value represents the importance of adhering to the maximum desirable value. UBIF is used to compute the penalty for a performance parameter that lies between the attribute's maximum desirable and allowable values.

The minimum and maximum desirable values for each of the attributes form the boundaries of the domain of compliance. Assignment of these values requires careful consideration by the user, as the model's goal is to find the solution that best satisfies these criteria. The upper and lower allowable values indicate the allowable 'objective overrun' for each of the desirable values. The concept of objective overrun was introduced to increase the flexibility of the model and reduce the number of iterations required to arrive at an acceptable solution (i.e., the number of times the decision-maker needs to modify the boundaries of the Domain-of-Compliance). The desirable and allowable limits can be specified as either constants (e.g., Desirable Duration = 90 days) or as a function of other variables:

(Cost) = (\$2,000,000)- (\$25,000)*(90-Duration) where 75$\leq$ (Duration) $\geq$ 90m (Eq. 7.25)

or

(Environmental impact)= 2+(250,000-Proj. Cost)/(50,000) ≤ 4 (Eq. 7.26)

Additionally, the tolerance value can be specified as a percentage of the desirable value (e.g., $MAAV_{cost} = 1.26 \times MADV_{cost}$).

Outcomes that do not lie within the solution space defined by the allowable limits are labeled as non-compliant. A detailed discussion of the input format required by DCUM for each preference attribute can be found in Section 6.6.2.

The importance factors reflect how essential it is to satisfy a given desirable value. The final score for each method is a function of the distance between the origin and the solution point. The smaller the distance the more closely the *solution point* (e.g., a potential project outcome) is to satisfying the user's requirements. The importance factors are multipliers that artificially increase the value of the portion of the vector length located between the *solution point* and the 'Maximum Desirable Value' for a given attribute, thus making the utility value of the *solution point* less desirable. The importance factors can be viewed as a comparison scale among the desirable values of the various attributes, e.g., 'highly desirable' versus 'not critical'. The scale assigned to the importance factors can be either predetermined ('highly desirable'=2.0; 'not critical'=1.2) or may be generated using a procedure similar to

Saaty's AHP (see Table 6-12). In either case, the multiplier is applied to the percentage of the objective overrun, expressed as:

(Outcome Value–Desirable Value) /(Allowable Value–Desirable Value) (Eq. 7.27)

An alternate approach is to view the importance factor as a mapping function for a given attribute. This approach allows greater flexibility in the sense that instead of a constant the importance factor can be represented by a mathematical expression such as:

$$UBIF(x) = Exp.^{\left(\frac{X-MTV}{MAV-MTV}\right)} \quad \text{(Eq. 7.28)}$$

The assignment of a hard coded or user's predetermined constant value for a given degree of importance factor (e.g., highly desired) will be satisfactory for most applications. However, the more involved approach of assigning mathematical expressions should be kept in mind in cases where greater flexibility is required.

Constraints are mathematical relationships between two or more attributes, and are classified as either local or global constraints. Local constraints include up to *n-1* variables, where *n* is the total number of variables in the domain-of-compliance problem (DCP). The physical interpretation of local constraints is a surface that constrains the maximum allowable values of the variables involved. Global constraints, on the other hand, include all *n* variables considered in the DCP. They are subspaces that lie, at least partially, within the domain-of-compliance. Constraints must be expressed as inequalities, either as "greater than/equal to" or "less than/equal to". Examples of possible constraints are given in Equations 7.29 and 7.30.

(Project Costs) + (Loss of Income) + (Surface Improvement) ≤ \$3,000,000 (Eq. 7.29)

$$\frac{\sum_{i}^{I}(Activity_i)\cdot(Employees/Activity_i)}{(Area)} \leq 0.2 \qquad \text{(Eq. 7.30)}$$

There is no theoretical limit to the number of 'local' or 'global' constraints that may be applied to a given problem.

The origin for a DCP is the optimum *solution point* for the problem, e.g. in the case of a construction problem the optimum outcome will be completion of the project to specifications at zero costs, zero duration, with zero environmental impact, etc. Where more than one optimum solution is present for a given DCP, a separate analysis is currently required for each optimum solution. Upon completion of the current research program, further research into DCPs with multiple focal points is recommended.

Domain of Compliance Problems (DCPs) can be represented using domain of compliance networks. The different variables are listed along the vertical axis and are represented by nodes. The constraints are listed along the horizontal axis and are represented using arcs. The ability to visualize the problem at hand in a simple fashion helps to avoid oversight of potential dependencies among the variables. It also enables future automation of the model's input using a graphical interface. An example of a domain of compliance network is given in Figure 7.8. The network presented contains eight variables (represented by A to H) and five constraints (represented by α to ε).

Another important concept related to the user's input and input processing is that of an 'over-constraint problem' that refers to a problem defined in such a way that it is mathematically impossible to satisfy all constraints simultaneously (e.g., D =

{}). Consistency tests are required to identify such conflict prior to the initiation of subspace computations. One approach to ensure that the conditions expressed by the constraints are consistent with the desirable values of the variables involved is the utilization of a standard CSP consistency methodology such as backtracking. In other words, $D \neq \{\}$ if and only if a subset of the domain-of-compliance domain satisfies all of the constraints simultaneously. Another important test is to verify that the solution subspace for a given constraint intersects the solution space of all other constraints. In other words, if $X_1+Y_1=C$ and $X_2+Y_2=C$, then $X_1 \neq X_2$ or $Y_1 \neq Y_2$.

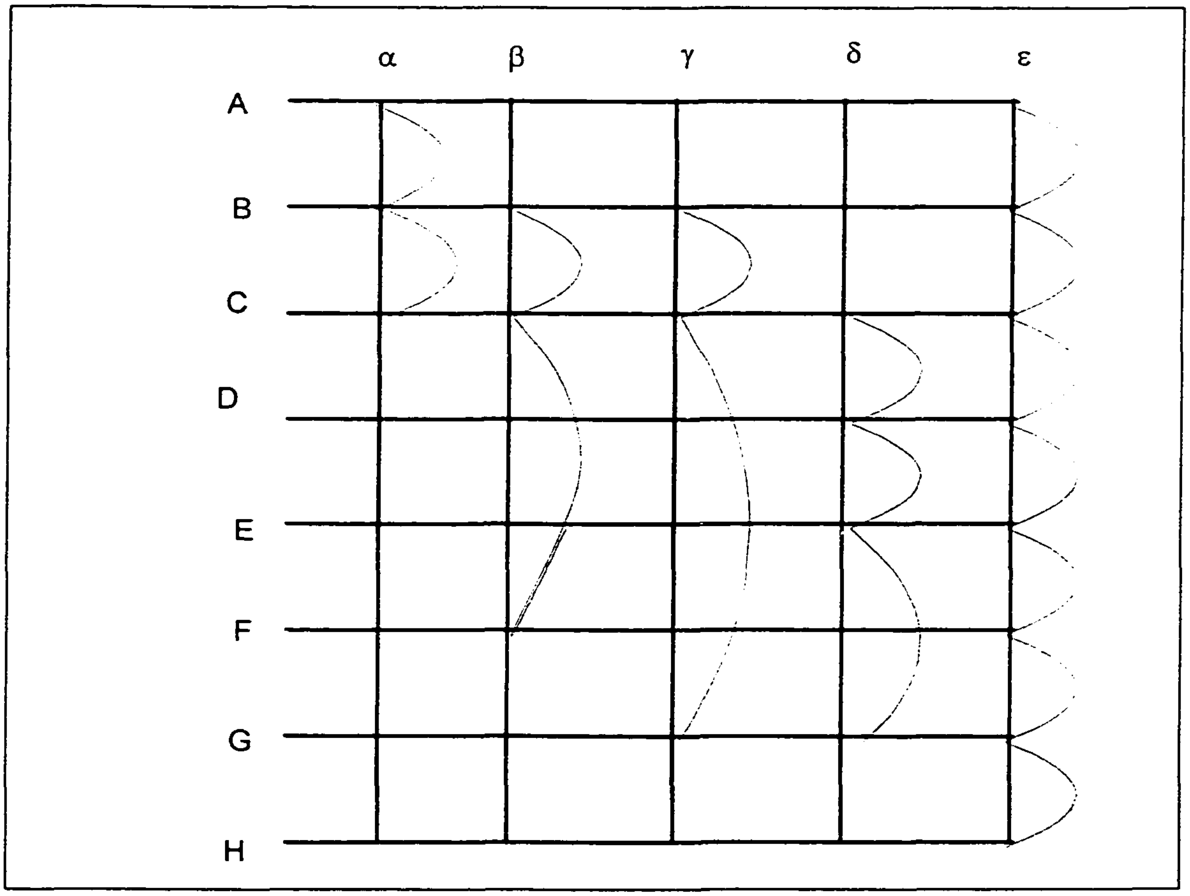

Figure 7.8 Example of a Domain-of-Compliance Network

7.3.5 Algorithm and Numerical Computations

This section deals with the mechanics of assessing the status of a given solution point and computing the overall utility score for each alternative. In general, a solution point is a set of coordinates (e.g., x, y, z) that is associated with a probability value, *p*. The coordinates indicate the predicted values for the various attributes. The probability value is the Cartesian product, p_i, of the probabilities associated with *m* individual attribute values, as given by the following expression:

$$P_i = (P_1) \cdot (P_2) \ldots \cdot (P_m) \qquad \text{(Eq. 7.31)}$$

Table 7-5 Sample Solution Point

Attribute	Value	Probability
Project Costs, $	1,200,987	0.17
Duration, days	61.3	0.43
Environmental Impact (scale of 1 to 5)	3.4	0.52
Loss of Revenue, $	362,466	0.32
Surface Improvement, $	57,904	0.46
Ground Movement (scale of 1 to 5)	2	0.81

The coordinates for the sample point presented in Table 7.5 are {1,200,987; 61.3; 3.4; 302,466; 57,904; 6,956}, and the combined probability of this outcome as given by Equation 7.31 is 0.004532.

Each value in the set must first be checked against the boundaries of the desirable and allowable solution spaces to determine the zone in which the value is located (i.e., within the domain-of-compliance; within the allowable solution space; or, outside the allowable solution space). The following four checks are performed to evaluate the status of a given coordinate X:

X ≤ Maximum Allowable Value (Eq. 7.32a)

$X \geq$ Minimum Allowable Value (Eq. 7.32b)

$X \leq$ Maximum Desirable Value (Eq. 7.32c)

$X \geq$ Minimum Desirable Value (Eq. 7.32d)

The answers to these checks are recorded in a binary format where '1' represents a positive answer and '0' a negative answer. If the checks are performed in the order shown in Equations 7.32a to 7.32d, one of the following six combinations listed in Table 7-6 will be obtained.

Table 7-6 Possible Binary Status Positions

Location	Binary Code	Status
Outside Allowable Limits	0101 (above upper limit) 1010 (below lower limit)	Unacceptable Unacceptable
Between Desirable and Allowable Limits	1101 (between upper limits) 1110 (between lower limits)	Acceptable Acceptable
In Domain of Compliance	1111 (between origin and upper desirable) 1111 (between origin and lower desirable)	Acceptable Acceptable

If any of the attribute values are determined to be unacceptable, the solution point is classified as non-compliant and no further checks are performed. Alternatively, if all values are determined to be acceptable the solution point is classified as 'compliant', and a second round of checks is initiated to confirm that all local and global constraints are satisfied. The values for the appropriate attributes are substituted into the constraints and each expression is then evaluated separately. If any of the constraints are not satisfied, the status of the solution point is changed to 'non-compliant', and no further checks take place. Where all of the constraints are found to be satisfied, the solution point is confirmed to be in compliance.

The utility value for each solution point is computed using a scoring function based on the Euclidean distance between each solution point and the origin of the solution space. The general equation for computing the Euclidean distance ('length') between two points u = $(u_1, u_2, \ldots, u_n)$ and v = $(v_1, v_1, \ldots, v_n)$ in R^n is defined by:

$$d(u,v) = \|u - v\| = \sqrt{(u_1 - v_1)^2 + (u_2 - v_2)^2 + \ldots + (u_n - v_n)^2} \qquad \text{(Eq. 7.33)}$$

In DCUM, u represents the solution point while v represents the origin. MAC uses a modified Euclidean distance (Equation 7.32) to account for the discrepancy between the user's specified desirable value and the solution value in cases where the anticipated attribute value lies outside the domain of compliance:

$$\mathrm{d(u,v)} = \sqrt{\{(\mathrm{T}_1 - v_1) + \mathrm{IF}_1(\mathrm{u}_1 - T_1)\}^2 + \ldots + \{(\mathrm{T}_n - v_n) + \mathrm{IF}_n(\mathrm{u}_n - T_n)\}^2} \qquad \text{(Eq. 7.34)}$$

where T_i and IF_i are the desirable values (either upper or lower) and importance factors (either LBIF or UBIF) associated with attribute i, respectively. Also, to avoid bias of the Euclidean distance due to the different magnitudes of the various attribute values, all attribute values are normalized with respect to their respective desirable value prior to computing the Euclidean distance. Normalization of the solution point described in Table 7-5 is given in Table 7-7.

Table 7-7 Normalization of Sample Solution Point

Attribute	Attribute's Value	Desirable Value	Normalized Attribute's Value
Project Costs, $	1,200,987	1,250,000	0.96
Duration, days	61.3	75	0.82
Environmental Impact (scale of 1 to 5)	3.4	3	1.13
Loss of Revenue, $	362,466	300,000	1.21
Surface Improvement, $	57,904	50,000	1.16
Ground Movement (scale of 1 to 5)	2	2	1.0

Based on the status and the modified Euclidean distance value for each solution point, four indicators have been calculated for each alternative (e.g., construction method). The underlying assumption beyond these measures is that the data sample used in the analysis provides a reasonable representation of the general data population. The four indicators are:

1. The likelihood that an alternative will lie within the domain-of-compliance. This measure is a function of the number of solution points that were found to be within the domain of compliance (DoC) solution space and their associated probabilities. This measure is given by the following expression:

$$\frac{\Sigma(\text{Probabilities of solution points for alternative 'i' within DoC})}{\Sigma(\text{Probabilities of all solution points for alternative 'i'})} \quad \text{(Eq. 7.35)}$$

2. The likelihood that an alternative will lie within the allowable solution space. This measure is a function of the number of solution points that were found to be within the allowable solution space and their associated probabilities. This measure is given by the following expression:

$$\frac{\Sigma(\text{Probabilities of solution points for alternative 'i' within allowable space})}{\Sigma(\text{Probabilities of all solution points for alternative 'i'})} \quad \text{(Eq. 7.36)}$$

The upper term in Equation 7.36 includes the probabilities of those outcomes that lie within the Domain-of-Compliance as well as outcomes that lie between the compliance envelope and the allowable solution space boundaries.

3. The likelihood that an alternative will lie outside the allowable solution space. It is a function of the difference between the sum of probabilities of all generated outcomes for alternative '*i*' and the sum of probabilities of those outcomes found to be within the allowable solution space, as expressed by Equation. 7.37:

$$\frac{\Sigma(\text{Prob. of all solution points}) - \Sigma(\text{Prob. of solution points within allow. solut. space})}{\Sigma(\text{Prob. of all solution points})}$$

4. The overall utility score (OUS) represents the solution subspace's likelihood to minimize the overall utility value associated with the project. The overall utility score is equal to the sum of the product of the modified Euclidean distance and the probability for each solution point divided by the sum of the probabilities of the data sample. The value obtained is the Euclidean distance for the 'centre-of-gravity' of the solution subspace (i.e., the median of the solution point probability density function).

$$OUS_i = \frac{\sum_{1}^{m}\{(Modified\_Euclidean\_Distance)_i \cdot (Probability)_i\}}{\sum_{1}^{m}(Probability)} \qquad \text{(Eq. 7.38)}$$

where m is the number of solution points in the data sample.

The above methodology was implemented in the form of a computer program using MATLAB version 5.3 and MATLAB statistical toolbox. The program randomly samples the underlying distributions to obtain a given solution set for each particular alternative (e.g., construction method). A user manual as well as a sample input file and the output window are given in Appendix 'D'. In addition, two working examples that demonstrate the practical application of the proposed models are also presented.

CHAPTER 8

CONCLUSIONS & RECOMMENDATIONS

8.1 CONCLUSIONS

This thesis describes a decision-support model for the selection of a construction method for the installation or replacement of buried pipelines and conduits. First, a detailed literature review of decision support systems for selection of construction methods was presented, establishing the need for the current study. A review of the state-of-the-practice of trenchless construction in Canadian municipalities further demonstrated the need for the current work. It set the stage for the introduction of twenty construction methods and their subclasses that can be used for the installation or in-line replacement of buried infrastructure. The administrative, operating and constructability characteristics of the various construction methods were summarized in a table format, thus providing the population of the model's database. One of the most important factors in the selection of an underground construction method is the nature of the subsurface conditions. A state-of-the-art review of emerging horizontal site characterization technologies that have the potential to provide detailed continuous information regarding subsurface conditions in an economical manner was presented. A methodology, named EXSHSIble, for integration of subsurface information obtained from various site characterization technologies was also introduced. EXSHSIble is intended to assist in the processing of geotechnical data for the main decisions-support model.

Next, an evaluation process for underground construction methods named I.M.P.E.C.T was described. I.M.P.E.C.T utilizes a two-stage selection process, namely, a technical evaluation and a preference evaluation. To enhance the flexibility and comprehensiveness of I.M.P.E.C.T several unique mechanisms were developed including an innovative risk analysis module and a unique algorithm for comparison of the overall anticipated performance of various multi-attribute alternatives. In particular, the algorithm, named the Domain-of-Compliance Utility Model, computes the likelihood of each construction method satisfying the user's preference attributes and constraints by estimating the fraction of all possible outcomes that are deemed by the user as desirable, acceptable and not acceptable. The model was implemented in MATLAB Version 5.3 computer language and sample applications were presented.

Based on the findings of the study, the following conclusions can be drawn:

1. The utilization of trenchless technologies in Canada is driven by the need to replace/expand many infrastructure networks in highly urbanized areas, increasing environmental legislation, growing competition for limited underground space and an increased awareness of social costs. This trend is expected to continue. However, only limited amount of data is currently available regarding the performance characteristics of many trenchless construction methods.
2. The evaluation of competing construction methods for installation and replacement of buried infrastructure systems should not be limited to direct costs and technical capabilities, but must also account for social and indirect costs as well as the inherent risks associated with underground construction.

3. Accounting for the factors listed in (2) requires a systematic evaluation of the unique characteristics of each method in an unbiased manner. The development of automated decision-support systems is needed to assist the decision-maker in performing this immense task by breaking it into manageable subtasks that can then be automated.
4. Many well-established and widely accepted decision-making methodologies such as rule-based expert systems, utility theory and the Analytical Hierarchy Process, suffer from some inherent shortcomings when employed in the development of construction method evaluation models, thus posing limitations on the models' performance. Therefore, there is a need for the development of an alternate decision-making algorithm.
5. To gain acceptance among researchers as well as practicioners the proposed algorithm must be generic, flexible, mathematically and logically sound, simple to use, and realistic. Realisim include explicitly accounting for the uncertainty associated with the project parameters and the method performance as well as by permiting dependencies among the various attributes to be expressed in a quantitative manner.
6. The risk analysis algorithm developed in Chapter 7 is an effective way to assimilate subjective and objective data from various sources into a single quantifiable risk value. The risk assessment value is interpreted based on the user's own risk aversion preference. The proposed algorithm lends itself to nearly full automation.

7. The Domain-of-Compliance Utility Model (DCUM) is a generic, flexible decision-making algorithm that provides a way to overcome some of the inherent shortcomings of well-established decision-making methodologies by utilizing solution domains to describe both, the user requirements and the anticipated performance of the various alternatives. In particular, it is capable of simultaneous evaluation of several multi-attribute alternatives, the consideration of tangible as well as intangible attributes, and the incorporation of dependencies among the attributes.
8. The ability to specify a large number of complex relationships among the various attributes enable to model complex problems with minimum amount data manipulation. The attributes can be constants, functions or standalone models.
9. The domain-of-compliance model determine two characteristics of each solution subset, namely the union set between the domain-of-compliance and the solution subset and the distance between the solution subset center of gravity and the origin of the solution space. The first characteristic is a measure of the probability that the alternative will satisfy all of the user requirements. The second measure is an indication of the overall utility value associated with carrying out the project. Depending on the problem at hand, one of these measures will be the determining factor in identifying the most suitable alternative.
10. In contrast to 'black-box' decision support models, I.M.P.E.C.T provides the decision-maker with the opportunity to gain an insight into the potential

difficulties associated with the project and the quality of the available information. Additionally, the user is required to identify his or her priorities and constraints, particularly in the case where not all objectives can be fully satisfied.

11. Adequate subsurface information is invaluable for the informed selection of an underground construction method. However, in many cases site characterization programs are inadequate due to the difficulty in quantifying the benefits from a given level of investment as well as the technical limitations of current site investigation techniques.
12. Site investigation programs for horizontal linear underground projects can be enhanced by horizontal site characterization techniques capable of reaching otherwise inaccessible areas and having the capacity to provide continuous information regarding anticipated subsurface conditions.
13. The continuous and near-continuous nature of subsurface information obtained from horizontal site characterization techniques enables the utilization of a new approach for data analysis where the host medium is treated as a mesh and the likelihood of detecting a given hazard located in a given element in the mesh is computed numerically based on the number and characteristics of the investigation methods used, the number and configuration of the horizontal bores, and the anticipated geological properties of the medium.

8.2 RECOMMENDATIONS FOR FURTHER WORK

The work presented in this thesis is but one step towards the development of a comprehensive decision support system for engineers and other decision-makers responsible for the expansion and replacement of buried infrastructure networks. The following recommendations are made for further research in this area:

1. Further theoretical development of the Domain-of-Compliance methodology is required, particularly with respect to identification of over-constraint problems and the analysis of problems with multiple origins.
2. Further optimization of the Modified Arc-Consistency algorithm, particularly an investigation of the relationship between the number of data points used in the analysis and the accuracy in predicting the union set between the method subspace and the domain-of-compliance.
3. A full-fledged validation of I.M.P.E.C.T is warranted using information from several real-life projects. It is desirable to choose projects where several different construction methods were utilized at different segments along the alignment.
4. Further population of the model's database as well as the addition of selected submodels (e.g., to compute social costs) is warranted.
5. Prior to implementation further automation of I.M.P.E.C.T is required, in particular the technical evaluation stage and the risk analysis module.
6. In reality underground construction projects may involve the installation of different pipe sizes and materials, at different depths in different environemnts. In its current form I.M.P.E.C.T is designed to identify the most suitable construction method for a given set of project parameters. A possible

area of future research may include an optimization module that will evaluate the economic of utilizing a number of different construction methods in a single project by accounting for parameters not included in the current analyssis such as mobilization costs.

7. EXSHSIble should be expanded to better account for data provided by traditional horizontal site characterization techniques. Additional work is also needed in the area of determining the effective penetration range and the detection reliability values for various geophysical methods in different formations.

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APPENDIX 'A'

TESTING OF A NEW GENERATION HORIZONTAL SOIL SAMPLER

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BACKGROUND

The earliest sampler to be used in conjunction with HDD rigs to characterizing contaminated sites was developed in the early 1990's (Karlsson, 1993). The sampler, which operated on a principal similar to a Shelby Tube core sampler, is capable of collecting a 1 .5m long, 55mm diameter sample from soft to medium soils. Due to the large size of the sampler (nearly 6m) and awkward mechanism operation, usage of the tool was limited. In the mid-1990's, a second generation sampler, significantly smaller and lighter than its predecessor, was developed, capable of being used with medium and small sized drill rigs typically employed in the utility installation industry (Allouche et al., 1999). Leszkowicz (1999) indicated that the sampler suffered from several shortcomings, however, including possible contamination of the sample as it being retrieved and a lack of certainty of the exact location from which the sample was obtained. More information regarding these and other horizontal sampling devices can be found in Allouche et al., (1999).

Another drawback shared by both samplers is their operation methodology. Initially a horizontal borehole is drilled to a point just short of the desired sample. The drill string is then retrieved, and the drilling head is removed and replaced with the sampler. The sampler is then advanced through the pre-bored cavity to the target area

[1] after Ariaratnam S.T., Allouche E.N, and Biggar K.W., 2000. Can. Geotec. J., 37:259-263

where a mechanism is opened and the soil sample is taken. The sampler is then drawn back to the drilling rig. This process is repeated for each sample. The repetitive nature of the sampling process, which requires the assembly and disassembly of the entire drill string twice for each sample makes the process lengthy and therefore costly.

THE MULTIPLE-PORT SOIL SAMPLER

The sampling process differs conceptually from traditional HDD sampling methods described previously in that the samples are obtained during the pull back stage as opposed to being taken ahead of the drilling head. The drilling operation proceeds using normal HDD procedures. Once the target zone has been reached, a dry drilling procedure is initiated as the drilling string progresses horizontally across the target area. Finally, the drill resurfaces at an exit location using normal (wet) drilling procedures. The drill head is then removed and the multiple-port soil sampler is placed on the end of the drill string. This assembly is pulled back through the borehole, stopping at specified locations to obtain samples from the borehole wall. The multiple-port sampler can be then reloaded with empty sampling tubes and pulled through the pre-bored cavity again to collect additional samples. The process is repeated until sufficient samples are collected. The borehole can then be either grouted or used for the installation of a permanent horizontal well screen.

A schematic diagram of the multiple-port sampler is shown in **Figure 1.** It consists of a 190mm diameter, 1930mm long outer casing which houses the sampling mechanism. Six, 19mm diameter, 180mm long sampling tubes contained on a rotating carousel are used to collect individual samples. The sampling tubes are arranged so that they may be rotated into a position where they are pushed through a hole in the outer casing at an angle of 39°, and into the formation. A 2200N actuator pushes and withdraws the sample tubes, while a 100N motor connected to a gear mechanism rotates the carousel. A proximity probe is used to ensure that the alignment of the sampling tubes with the sampling window is within the specified tolerance of +0.5°. A second linear actuator powers a gate along the inside of the sampler body, covering and uncovering the sampling window, effectively preventing soil particles and water from entering the sampler interior between sampling locations. The "nerve center" of the device is a CPU board sealed in a compartment at the rear of the sampler. Information regarding the position and status of the various components is monitored and transmitted to the surface via a control cable. The sampler is operated using a laptop computer with custom designed software. The multiple-port soil sampler is capable of collecting multiple soil samples during a single pass along the borehole. It can also be operated by any HDD rig, and has the ability to retrieve high-quality samples.

The multi-port sampler presents several advantages in comparison to existing horizontal sampling methods. The ability to extract several samples in one sampling pass can reduce sampling time by up to 70%, resulting in significant productivity improvement. As soil samples are collected from the borehole wall they experience little disturbance. Also, as soon as the soil sample is retrieved it is stored in a closed chamber, preventing possible contamination during the withdrawal of the sampling device. Additionally, the reduction in effort to decontaminate sampling equipment results in improved safety levels and reduced costs (Allouche et. al 1998). Finally, the presence of a CPU board within the sampler itself makes it possible to replace the sampling tubes with various sensors and probes which can be pushed into the formation to take multiple in-situ readings. The information can be then be stored on a memory chip and later down loaded onto a computer for further analysis.

TESTING PROCEDURES

The testing program was divided into two phases. Phase I involved both bench scale and full-scale laboratory testing, while Phase II consisted of a field test. The laboratory tests were designed to evaluate the performance of the multiple-port soil sampler and identify functionality problems. Specifically, the following parameters were evaluated:

Load-displacement behavior as the sampling tube was pushed into the following soils:

stiff clay (Athabasca clay, moisture content = 18%),

soft clay (Athabasca clay, moisture content = 21%),

manufactured Lake Edmonton Till (sand, Athabasca clay and Devon silt mixed at a mass ratio 40:20:40; moisture content = 13%),

loose sand (γ = 12 kN/m^3), and

compacted sand (γ = 16.5 kN/m^3);

Percentage of sample retention within the sampling tube in the various soils;

Sample size, integrity and degree of compaction;

Performance of controls, mechanical, and electrical components under loaded conditions;

Ease of loading and unloading of sampling tubes and handling of the samples.

Bench Scale Laboratory Tests

The main objective of the bench scale testing was to evaluate the axial force required to push the sampling tube into various soil types. Additionally, the percentage sample recovery versus the actual penetration depth for each type of soil was evaluated. The soil was compacted in a standard proctor mold, which was then placed in a 10,000kg compression-loading machine. The tube was positioned perpendicular to the soil surface, directly below a load cell. A ball-type bearing was used to connect the sampling tube to the loading machine crossbar to minimize eccentric loading. Displacement was measured using a 150mm stroke Linear Variable Displacement Transducer (LVDT). The leading tip of the sampling tube was cut at an angle of 39^0 to simulate the angle of the tube with respect to the borehole wall as it is launched from the soil sampler. Readings from the load cell and displacement transducer were transmitted to a data acquisition system. The loading rate during all tests was maintained at 36 mm/min, which is significantly lower than the rate the sampling tubes are launched from the soil sampler (about 180 mm/min). This limitation was not expected to substantially influence the test results. The mold used for the cohesive soils (clay) was 100 mm in diameter and 100 mm high. A larger mold (150 mm in diameter and 150 mm high) was used for the cohesionless soils to reduce the effect of confinement.

The bench scale tests concluded that the axial pushing capacity of the sampler actuator was sufficient for fully extending the sampling tube into the following soil types: loose sand; dense sand; soft clay; and Lake Edmonton Till. However, the actuator was under-powered for collecting samples from stiff clay. Satisfactory performance in stiff clays will require doubling the thrust capacity of the actuator from 2200N to 4400N. The load-displacement behavior for sand appeared to follow an exponential curve, while the load-displacement behavior for cohesive soil follows a linear or near-linear relationship (**Figure 2**). Sample recovery rate for both cohesive and cohesionless soils during bench-scale testing was between 60 and 80%. Failure in achieving 100% recovery rate was attributed to high friction between the soil sample and the tube inner wall. To reduce friction, the sampling tube's diameter was reduced at the opening, reducing the cross-sectional area by approximately 8%. This modification increased the recovery rate but did not eliminate the problem.

The soil samples collected in the sampling tubes during the bench scale tests were found to be undisturbed and well intact. No indication of compaction during sampling was noticed in cohesionless soils. For cohesive soils, compaction up to 10% of initial density was observed. Sample size ranged between 50 and 100 grams. While this quantity may be sufficient for contaminant identification tests, the usefulness of the current sampling device for geotechnical investigations is limited to soil classification and identification of index properties (i.e. moisture content, grain size analysis). No mechanical behavior testing can be accomplished given the small size of sample obtained; however, the use of larger sampling tubes could be utilized to overcome this limitation.

Full Scale Laboratory Tests

A special loading frame to house the sampler was constructed and a special mold designed and built to simulate the borehole wall (**Figure 3**). Full-scale tests were performed on three type of soils; Athabasca Clay (M.C.=18% and M.C.=21%) and moist Dense Sand (γ = 16.5kN/m^3). The mold was positioned to accommodate extraction of two soil samples per test as the average value of the two results was taken. Results revealed that the sample recovery rates during full-scale testing ranged between 95-100% for cohesionless soils and 60-80% for cohesive soils. The sampler functioned properly in cohesionless soil, however, failed to withdraw the sampling tube from cohesive soils due to inadequate design of the retraction mechanism. As a result, the retraction mechanism was re-designed and the carousel rebuilt prior to the field tests.

Field Tests

Once modifications to the sampler were made, field tests were conducted at the University of Alberta test site. The soil profile at the site is essentially Lake Edmonton Clay to about 4 to 7m, overlying dense glacial till. The upper 4m is predominantly clay and below this depth the profile starts to become predominantly sandy-silty (Clementino et. al. 1998). A 3.5m x 3.5m x 3.75m deep pit was excavated along the proposed alignment and filled with sand end-dumped from a truck to create a mixed face condition test section. The first test was conducted above the groundwater table. A 46m long, 100mm diameter pilot bore was drilled along the profile at a depth of 2.8m. Upon arriving at the exit location the drilling head was replaced with a 200mm reamer to which the sampling device was connected as illustrated in **Figure 4**. The entire assembly was then pulled back towards the rig, with soil samples taken at predetermined locations along the path. During the sampling process the operator, sheltered inside the back of a van, continuously monitored the operation via a laptop computer. The sampling process lasted less than

30 minutes, during which all systems appeared to perform satisfactory. Inspection of the sampler upon retrieval from the borehole revealed that no drilling fluids, formation water or soil entered the sampler cavity. The samples collected were undisturbed and 90-100% recovery rate was achieved in both the clay and the sand.

The following day, a second test was performed along the same alignment at a depth of 4.6 m. The drilling of the pilot bore and the attachment of the reamer and sampler proceeded as described previously. The collection of the first sample took place as planned; however, during the collection of the second sample, difficulty arose as the carousal failed to index into its next position. The sampler was subsequently retrieved and inspected. The host formation was a silty-sand aquifer with a high hydrostatic pressure. It appeared that during the sampling operation, as the sampling port opened, some sand infiltrated into the sampler, jamming the rotation mechanism. Modifications to correct this problem are currently underway.

CONCLUSIONS

Horizontal sampling possesses the capability for a major breakthrough in site characterization of geoenvironmental and geo-construction sites. The idea of a borehole stretching over an extensive horizontal distance opens exciting opportunities as it is now feasible to collect multiple samples below buildings and other structures or to remotely sample environmentally sensitive or hazardous areas. Consequently, plumes can now be delineated using a few horizontal boreholes with potentially greater accuracy than that provided by numerous vertical wells. A new horizontal sampling tool is presented which attempts to overcome the main limitation of current horizontal sampling methodologies, namely a lengthy and expensive sampling process. The device was tested in both the laboratory and in the field. The laboratory and field tests demonstrated that the main limiting factors for the use of the multiple-port soil sampler are small sample size and possible infiltration of formation fluids into the interior cavity under a high hydrostatic pressure. Mechanical modifications are currently underway to improve the device water tightness and increase the robustness of the rotating mechanism. In terms of sample size, various mechanical mechanisms that will accommodate larger sampling tubes are being considered, including a new carousel that will carry 32mm diameter sampling tubes, thus increasing sample volume by approximately 250%.

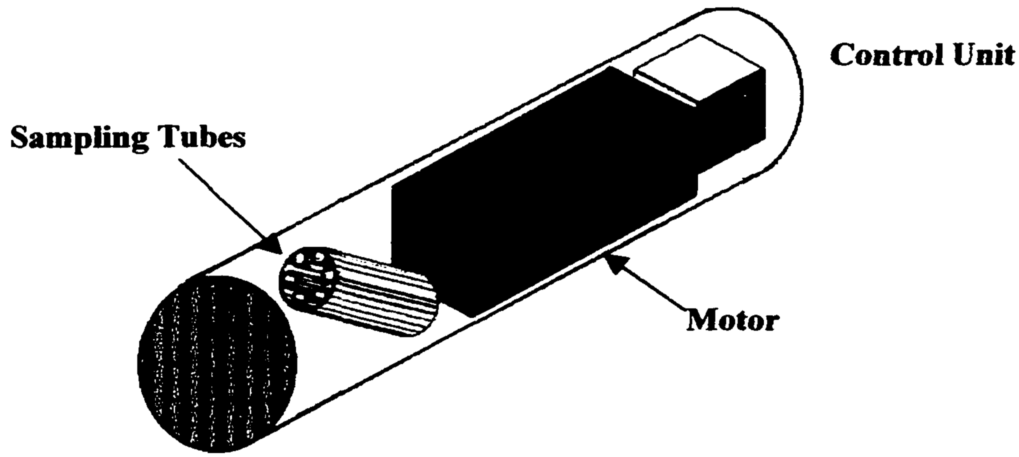


Figure 1. Schematic of the multiple-port soil sampler

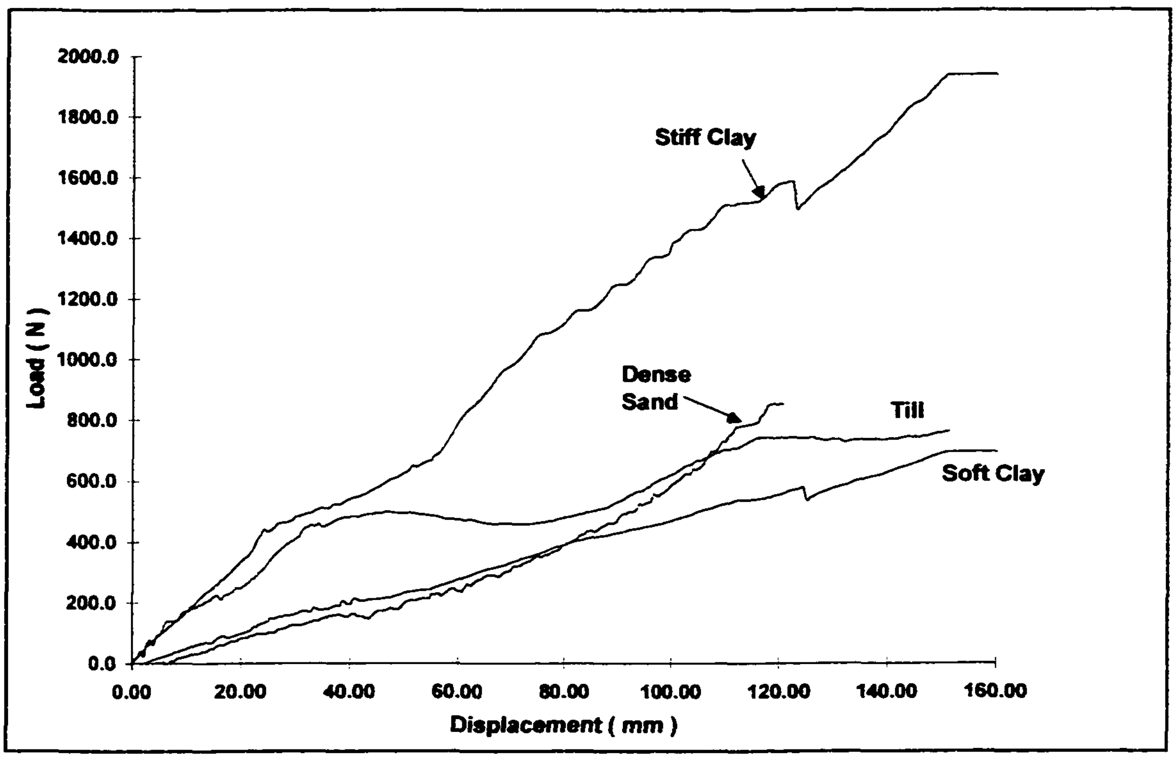


Figure 2. Typical load-displacement behavior of sampling tube

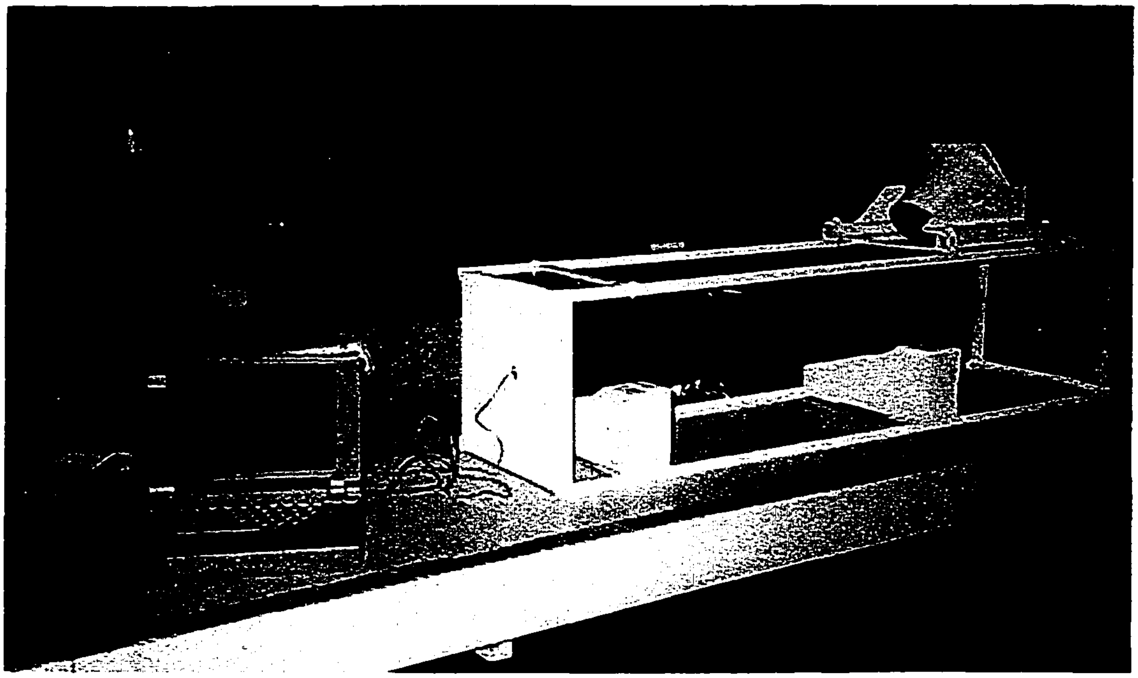


Figure 3. Special-purpose testing frame

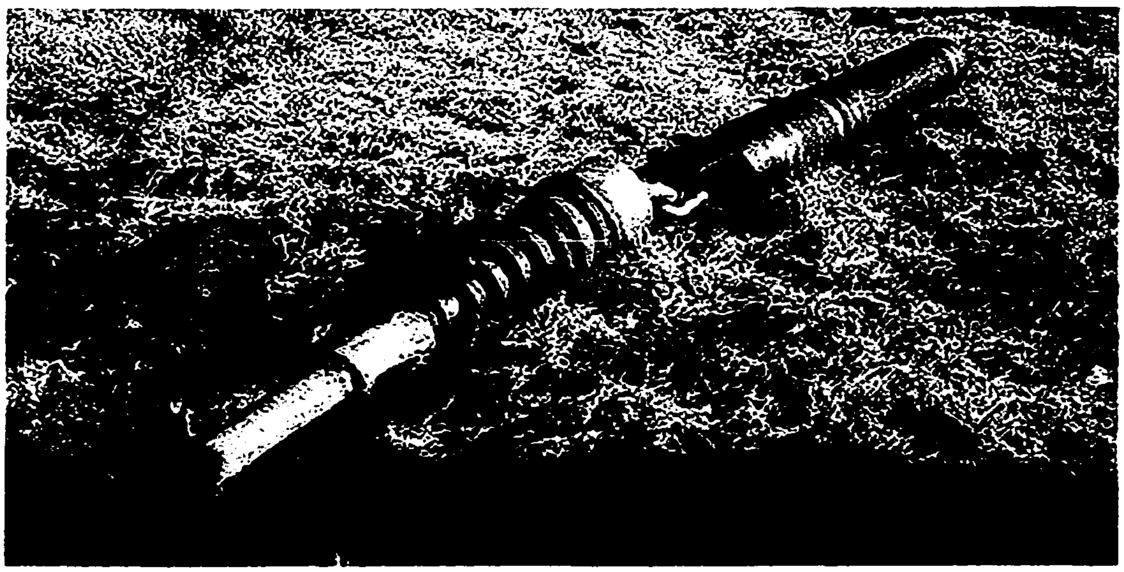


Figure 4. Prototype multiple-port sampling device

APPENDIX 'B'

‘EXESIble’ KNOWLEDGE BASE IN TABLE FORMAT

APPENDIX 'B'

'EXESIble' KNOWLEDGE BASE IN TABLE FORMAT

(After Allouche, 1999)

Table B1 - Information Provided by Geophysical Methods Regarding Geological Conditions in Soft Formations

Method	Lithology	Stratigraphy	Porosity	Formation Fluid Conductivity	Degree of Saturation	Grain Size Distribution
Induction	2	2	1	2	1	1
Magnetic Susceptibility	1	1	1	1	1	1
Deviation	0	0	0	0	0	0
Natural Gamma	3	3	2	0	1	2
Seismic	3	3	0	0	0	0
Neutron	3	3	1	0	1	1
Acoustic Televiewer	3	3	3	0	3	3
GPR	3	3	0	1	1	0
Resistivity	1	2	1	2	3	1
Sonic	3	3	3	0	0	0
Density	3	3	3	0	1	2

0 = Not Applicable, 1 = May be used to gather that data as a secondary source, 2 = Applicable under most conditions, 3 = Recommended

Table B2 - Information Provided by Geophysical Methods Regarding Geological Conditions in Rocky Formations

Method	Fractures Location	Fractures Orientation	Fractures Extent	Faults Location	Faults Features	Rock Type	Rock Composition	Bulk Density	Elastic Moduli	Clay Content	Formation Resistivity
Induction	1	0	0	0	0	1	0	0	0	3	3
Magnetic Susceptibility	0	0	0	0	0	2	2	0	0	2	0
Deviation	0	0	0	0	0	0	0	0	0	0	0
Natural Gamma	0	0	0	0	0	3	3	0	0	3	0
Seismic	3	0	2	3	3	2	0	0	3	0	0
Neutron	0	0	0	0	0	2	2	0	0	0	0
Acoustic Televiewer	3	3	3	3	3	3	3	1	1	1	0
GPR	3	3	3	3	2	2	0	0	0	2	1
Resistivity	0	0	0	0	0	1	1	0	0	3	3
Sonic	2	0	2	2	1	3	1	0	3	0	0
Density	1	0	0	0	0	3	3	3	1	1	0

0 = Not Applicable, 1 = May be used to gather that data as a secondary source, 2 = Applicable under most conditions, 3 = Recommended

Table B3 - Natural Hazards which can be Identified by Various Geophysical Methods (Assuming hazard within operating range)

Method	Boulders	Gravel Seams	Cobbles	Sand Pockets	Voids	Artesian Aquifer	Perched Aquifer	Flowing Sand	Tree Logs
Induction	1	2	1	2	0	0	1	0	0
Magnetic Susceptibility	1	0	0	0	0	0	0	0	0
Deviation	0	0	0	0	0	0	0	0	0
Natural Gamma	1	1	1	3	0	0	0	0	0
Seismic	3	2	2	2	3	0	0	0	0
Neutron	0	0	0	0	0	0	0	0	0
Acoustic Televiewer	3	3	3	3	1	0	1	1	1
GPR	3	2	2	1	3	1	1	2	3
Resistivity	1	1	1	1	0	0	1	1	1
Sonic	3	1	1	1	3	1	1	1	2
Density	3	2	2	2	2	0	0	1	1

0 = Not Applicable, 1 = May be used to gather that data as a secondary source, 2 = Applicable under most conditions, 3 = Recommended

Table B4 - Buried Manmade Obstacles which can be Identified by Geophysical Methods (Assuming obstacle within operating range)

Method	Utilities Metallic	Utilities Non-Metallic	Metallic Waste	Structures Metallic	Structures Non-Metallic
Induction	3	0	3	3	0
Magnetic Susceptibility	3	0	3	3	0
Deviation (magnetic)	2	1	0	1	0
Natural Gamma	0	0	0	0	0
Seismic	2	2	1	2	2
Neutron	0	0	0	0	0
Acoustic Televiewer	1	1	1	1	1
GPR	3	3	3	3	3
Resistivity	2	0	2	3	0
Sonic	0	0	0	0	0
Density	0	0	0	0	0

0 = Not Applicable, 1 = May be used to gather that data as a secondary source, 2 = Applicable under most conditions, 3 = Recommended

Table B5 - Range for Depth of Penetration in Various Formations (assuming typical resolution for method)

Method	Organic Soils	Clay	Silty-Clay	Silt	Tills	Sand	Sandstone	Rock	General
Induction	0.2m	0.2m	0.4m	0.4m	0.6m	0.8m	0.8m	1.0m	0.2-1.0m
Magnetic Susceptibility	0.2m	0.2m	0.4m	0.4m	0.6m	0.8m	0.8m	1.0m	0.2-1.0m
Deviation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Natural Gamma	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m
Seismic	0.3-5m	0.3-5m	0.3-5m	0.3-5m	0.3-5m	0.3-5m	0.3-5m	0.3-10m	0.3-10m
Neutron	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m	0.1-0.5m
Acoustic Televiewer	<0.1m	<0.1m	<0.1m	<0.1m	<0.1m	<0.1m	<0.1m	<0.1m	0.05-0.1m
GPR*	0.2-5m	0.2-5m	0.2-7m	0.2-7m	0.2-10m	0.2-20m	0.2-20m	0.2-20m	0.2-20m
Resistivity	0.5-2m	0.5-2m	0.5-2m	0.5-2m	0.5-2m	0.5-2m	0.5-2m	0.5-2m	0.5-2m
Sonic	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m
Density	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m	0.2m

* Low value - saturated conditions; High value – dry conditions.

Table B6 - Operating Conditions & Physical Properties

	Cased					Slim borehole tools			Approx. Cost
Method	Metallic	Non-metallic	Uncased	Water Filled	Air Filled	Typical Length of Tool (m)	Logging Speed (m/min)	Diameter of Tool – Typical (mm)	Logging + Analysis Per Linear Meter
Induction	0	1	1	1	1	1.3 to 1.8	1.6 to 6	40 to 45	$2.7-3.5
Magnetic Susceptibility	0	1	1	1	1	1.3 to 1.8	1.5 to 6	40	$1.8-3.0
Deviation	0	1	1	1	1	1.1	At stations	40	$1.8
Natural Gamma	1	1	1	1	1	1.1	0.6 to 1.5	40	$0.9
Seismic	1	1	1	1	1	0.9 to 1.8	At stations	40 to 65	$8.0-12.0
Neutron	1	1	1	1	1	1.1 to 1.8	5	40	$1.8
Acoustic Televiewer	0	0	1	1	0	3.0	1.8	40	$9.0
GPR	0	1	1	1	1	1.5	0.3 to 1	40	$5.0-9.0
Resistivity	0	0	1	1	0	1.8 to 2.4	4.5 to 6	40	$0.9
Sonic	1	1	1	1	0	2.1 to 2.7	3 to 4	40-55	$3.0
Density	1	1	1	1	1	2.1 to 2.7	3 to 4.5	40 to 50	$1.8

0 = Not Applicable
1 = Applicable

Table B7 - Ability to Identify Presence of Contaminants

Method	Organic	Inorganic	Metallic Waste
Induction	2	3	3
Magnetic Susceptibility	1	2	3
Deviation	0	0	0
Natural Gamma	1	1	0
Seismic	0	0	0
Neutron	0	0	0
Acoustic Televiewer	0	0	0
GPR	1	3	3
Resistivity	1	3	3
Sonic	0	0	0
Density	0	0	0

Table B8 - Type and Quality of Information Provided by Imaging Methods

	Resolution	Distance to Target		Size of Target		Location in Space	
Method		**Ability**	**Confidence Level**	**Ability**	**Confidence Level**	**Ability**	**Confidence Level**
Seismic (cross-borehole)	Medium	Y	Medium	Y	Medium	3D	Medium
Sonic (single borehole)	Medium	Y	High	Y	Medium	2D	High
Sonic (cross-borehole)	High	Y	High	Y	High	2D	High
GPR non-directional (single borehole)	Medium	Y	High	Y	Medium	2D	High
GPR non-directional (cross-borehole)	High	Y	High	Y	High	2D	High
GPR Directional (single borehole)	Medium	Y	High	Y	High	3D	High
GPR Directional (cross borehole)	High	Y	High	Y	High	3D	High

Y = Ability to provide an indication of relevant attribute (i.e., distance to target).

Table B9 – Geotechnical Information Collected By Various Sampling Methods

Geotechnical Factor	Vertical Drilling	Rock Coring	Vertical CPT	Ditch Witch Sampler	Punch Master 2000	MPSS	Devico Coring	Horizontal	
								CPT	SEAMIST
Groundwater	Y	N	Y	N	N	N	N	Y	Y
Soil Type	Y	N	Y	Y	Y	Y	N	Y	N
Contamination in Greenfield conditions	Y	N	Y*	Y	Y	Y	N	Y†	Y
Contamination beneath surface / subsurface structures	N	N	N	Y	Y	Y	N	Y†	Y
Soil gradation	Y	N	Y	Y	Y	Y	N	Y	N
Cobbles/boulders, size and distribution	N	N	N	N	N	N	N	N	N
Cobbles/boulders, compressive strength, abrasive	Y	N	N	N	N	N	N	N	N
Swelling clays and claystones	Y	N	Y	Y	Y	Y	N	N	N
Reaction wall bearing capacity	Y	N	Y	N	Y	N	N	N	N
Bedrock hardness/strength	N	Y	N	N	N	N	Y	N	N
Bedrock fracturing/jointing	N	Y	N	N	N	N	Y	N	N
Bedrock abrasive	N	Y	N	N	N	N	Y	N	N
Bedrock slake/durability	N	Y	N	N	N	N	Y	N	N
Changed-face condition	N	N	N	Y	Y	Y	Y	Y	N

* Selective contaminetns with additional sensors; † inorganics, utilizing a resistivity unit

Table B10 - Level of Risk from Potential Hazards to Trenchless Technology Methods

Method	Boulders	Cobbles	Sand Lenses	Flowing Sand	Coal Seam	High GWT	Buried Structures	Tree Logs	Perched Aquifers	Artesian Aquifers	Constr. Waste	Metallic Waste
Micro-Tunneling (slurry system)	> D/3	Medium	Medium	High	High	High	High	High	High	High	High	High
Micro-Tunneling (EPB)	> D/3	Medium	Medium	Low	High	Low	High	High	High	High	High	High
HDD	Medium	High	Low	Medium	Low	Medium	High	Low	High	High	Medium	Medium
Pipe Ramming	> 0.9D	Medium	Low	Low	Medium	Low	High	Low	Medium	Medium	Medium	Medium
Pipe Jacking	> 0.9D	Medium	Low	Low	Medium	Low	High	Low	Medium	Medium	Medium	Medium
TBM Tunneling	Medium	Low	Medium	Low	High	Low	High	Low	High	High	Medium	Medium
Hand Tunneling	Low	Low	Medium	Medium	High	Medium	High	Low	High	High	Low	Low

Appendix 'C'

GLOSSARY

APPENDIX 'C'

GLOSSARY

Acoustic Logging

Acoustic logging also known as sonic logging measures the travel time of compressional waves through the borehole fluid, the mud-cake, and the geologic formation. The device uses a transmitter located in the borehole which emits a pulse of mechanical energy which is recorded by one or more receivers located in the borehole some distance away from the transmitter. In full waveform acoustic logging, the complete acoustic wave at each receiver is recorded digitally. The character of the acoustic signal that is detected by the receivers is affected by the mechanical properties of the rock around the borehole.

The applications of full waveform acoustic logs include: 1) in-situ determination of compressional and shear wave velocities, which are useful in the interpretation of hole-to-hole seismic tomography and surface seismic data; 2) combined with a density logging tool, calculations can be made of elastic parameters such as Poisson's ratio, Young's modulus, the bulk modulus and shear modulus, which are important geotechnical parameters; 3) determination of porosity in porous rocks form the compressional wave velocity; 4) measurement of permeability in porous rocks; and, 5) detection of fractures and the measurement of fracture permeability.

Logs of compressional and shear wave velocity can be useful for hole-to-hole lithological correlation. The compressional wave amplitude is used to determine the presence of cement grout behind steel casing and to assess the degree of bonding betwen the casing and the formation, in 'the cement bond log'.

Core Barrel

Diamond drilled horizontal holes are performed on a regular basis in the mining industry. Boreholes 1000 to 3000ft long are not uncommon with holes up to 7000ft reported. The shortfall of these methods is the difficulty associated with steering the borehole to hit specific targets. Typically the industry utilised steel wedges to steer the drill string which greatly slowed advancement. The sampling tubes are available in single, double, and triple tubes. The single tubes are best applied to strong unified soil or rock. The double and triple tubes are meant for samples in soil or rock where the material is non-uniform, fractured or friable.

Density

Density logs, also known as gamma-gamma logs, use artificial source placed at the bottom end of the probe and the gamma detector is housed above, which must be shielded from each other with a lead column. The gamma radiation is absorbed into the surrounding geologic material, the degree to which is based on the density. The portion of radiation that isn't fully absorbed and reaches the detector is recorded and is a measure of the rock density. The density log can be applied to subsurface materials to determine their boundaries and to locate fractured seepage paths in consolidated rocks.

Deviation

The deviation method uses a dipmeter probe with its purpose to determine the deviation of the borehole axis from the vertical and its azimuth towards north. The dipmeter probe is usually a multishot instrument, which determines the dip and the orientation by taking photographs at every sequence of still measurements. Advanced dipmeter probes have continuous survey dipmeter capabilities, which record the spatial geometry of the borehole axis. Other dipmeter probes available have a magnetic compass which are restricted to open holes and do not work well in steel casing. The gyrocompass can be used to overcome difficulties with a magnetic compass, where it will be important to measure the deviation of the borehole as often as possible during the drilling operation.

Devico Rock Sampler

A system for horizontal steered core drilling developed by SINTEF (an industrial research foundation) in Trondheim, Norway, was launched by Devico in 1988. The system allows continuous sampling during steering using a special core barrel and diamond core bit. Normal rock drilling techniques are used to advance the drilling string to the target area. When at the target area the drilling string is retracted and the conventional drilling head replaced with the coring head. The system is advanced into the formation following the pre-bore hole. Next, coring is initiated. Up to 3 metre long cores are collected in any single sampling operation. When the coring barrel is full, it is pulled back to the surface using a trip wire and emptied. At this stage the core barrel is sent back down the drilling string and the coring operation resumed. Alternatively, the entire drilling string is withdrawn, the coring head is replaced with a traditional drilling head and the drill string is advanced to the next target area. The triple tube core-barrel is available in three diameters, 48mm, 56mm, 60mm, and 76mm. The core-barrel and the drilling bit are rotated inside a stationary outer tube, which has a bent-sub for steering purposes. At intervals during the coring operation a navigation tool is pumped down through the drilling string to a position ahead of the drilling head. The navigation tool provides information regarding the inclination and orientation of the drilling head, to ensure that drilling proceeds along the desired alignment. Corrections are done using a conventional bent-sub configuration.

Ditch-Witch Soil Sampler

In the mid 1990's Ditch Witch™ developed a sampler which can be used with medium and small sized drill rigs, typically employed in the utility installation industry. The Ditch Witch soil sampler is smaller and lighter than the Punch Master 2000. The sampling process is as follows. A drilling rig is located off-site and a drilling head is navigated, below ground, to a distance of 1 to 2 ft from the sampling area. The drill string is then retracted, the cutting head removed, and a soil sampler is connected to the end of the drill string. The sampler is pushed through the bore, then continues to be pushed through the undisturbed soil until target area is reached. The drill string is retracted approximately 18", and the sampler tube is automatically locked in open position. The sampler is pushed forward 1 to 2 ft, filling the tube with soil. The sampler and drill string are then removed from the bore. The sampling tube is removed and replaced with the drilling head, and the process is repeated. The sample is packed and prepared to be shipped for analysis. This device can be modified for use with most Jet-Trac and Vermeer horizontal boring units.

The sampler dimensions are:

Length of sampler (without tail piece): 20.5"

Sample tube length: 12 inches

Diameter: 2.5"

Diameter: 2"

Weight (without tail piece): 20.5 lbs.

Weight: 1.4lbs.

Ground Penetrating Radar (GPR)

A GPR system consists of four modules: 1) a transmitting unit: 2) a receiving unit; 3) a control unit; and, 4) a display unit. The transmitter generates a short pulse of electromagnetic energy that is radiated through an antenna into the ground as radio waves. The energy is reflected back to a receiving antenna, and its signal is amplified, formatted, stored and displayed. Applications of GPR include the mapping of soil stratigraphy, determining the depth to the ground water table and bedrock, locating buried metallic and non-metallic targets (e.g., drums or building foundations) and identifying certain contaminants in the groundwater. The penetration range of the radar pulse into the subsurface is governed by the conductivity of the ground. In low conductivity conditions penetration of more than 20 m is possible. On the other hand, conductive clay can restrict penetration to less than 1 m.

Horizontal Directional Cone Penetration (HD-CPT)

A modification of the vertical cone penetration technology. By measuring the soil friction and resistance on the cone's sleeve and tip, respectively, the probe can provide the information regarding the geo-technical parameters as well as delineate the lateral extent of a Dense Non-Aquatic Phase Liqiud (DNAPL) pool. An advantage of the technology is that the horizontal well offers the possibility of accessing a DNAPL pool without creating a vertical conduit that could spread the contamination to other more vulnerable stratas, hence minimizing risk. Boreholes can terminate in the subsurface (called blind holes) or the hole can be continuous where by the well is arced upwards terminating at the ground surface. The principle that will govern the soil response to the cone penetration is based on cavity expansion theory. The technique employed is one where the cone is pulled through a 4" pre-bore continuous bore while the data related to tip resistance and friction is transmitted to a laptop computer. The device is susceptible to a degree of disturbance of the formation caused by the drilling operation as well as the presence of drilling fluids. Currently it is in the experimental stage.

Electromagnetic Induction (EI)

Electromagnetic induction logs record electrical conductivity, which is the reciprocal of resistivity with depth. Induction logs can be collected in PVC cased or open boreholes that are air, water or mud filled. Induction logs are commonly used to determine formation conductivity or resistivity, calculate fluid conductivity or resistivity in the formation, and delineate lithology. The instrumentation measures formation conductivity in milli-siemens per metre (mS/m) which is converted to resistivity in the software. Electromagnetic waves of the frequency which is at about 20 kHz are transmitted by a coil on a probe. The frequency waves on the coil cause eddy currents in materials or rocks of different conductivity. The eddy currents are received by another coil which is located approximately 1m away. The rock conductivity is then calculated from amplitudes and phases of the received secondary field. The advantage of induction logs is that they are capable of calculating rock conductivities of very low resistivities. It is suitable for the exploration of rocks that are infiltrated by saline fluids or leachate.

Magnetic Susceptibility (MS)

Magnetic susceptibility is a measure of the ability of a material to become magnetized. Magnetic investigations are used primarily to locate buried metal objects. However magnetic survey can also be used to characterised the geological structure since, in general, unconsolidated sediments are non-magnetic while some bedrock (e.g., Basalet) have an appreciable magnetic susceptibility. In addition, faults and fracture zones that are potential migration channels for liquid waste can also be identified using this technique.

Multiple-Port Soil Sampler (MPSS)

The multiple-port soil sampler is designed to be pulled back through a continuous borehole, collecting samples from the borehole's wall at predetermined locations. A horizontal drilling rig may be used to drill down to the target area using normal drilling procedures. Then, the drilling fluid supply is shut down and a dry boring procedure is conducted across the target area. Finally, normal drilling procedures are used when boring up toward the exit location. The drill head is the removed, the multiple-port sampler placed on the end of the drill string, and the assembly pulled back through the borehole, stopping at pre-determined locations to take soil samples from the bore's wall.

The sampler's length is 40", diameter 7.5", weight 220 lb., max. punch force 1000 lb. The sample tube has a length of 12" and a diameter of 0.75". The MPSS is best suited for geo-environmental investigations but cannot operate in gravel, cobble or solid rock. The current status on the device is that the patent is pending and it is currently undergoing final evaluation in the form of pilot projects.

Natural Gamma

Gamma-ray measurements detect variations in the natural radioactivity originating from changes in concentrations of the trace-elements uranium, thorium and the major rock forming element potassium. The concentrations of these elements vary between different rock types. Natural gamma ray logging can therefore be used as an important tool for lithologic mapping, stratigraphic correlation and provision of information on rock types. While the probe used for the logging operation moves down the bore hole, the gamma rays are sorted into an energy spectrum and the number of gamma rays in three pre-selected energy windows centred over peaks in the spectrum are computed each second, as the total gamma-ray count. The data is recorded along with the depth and are displayed on the chart recorder to produce gamma-ray spectral logs. The raw gamma-ray spectral logs provide more information than a non-spectral log. Gamma rays can be detected through steel and therefore logging can be done inside drill rod casing with a slight decrease in sensitivity.

A number of factors determine the logging speeds and sample times during the acquisition of gamma-ray data. The critical factors are the anticipated levels of radioactivity and the size of detector in the probe. Gamma-ray spectral logging is usually done at 3m/minute but can be done as fast as 6 m/minute or as slow as 0.5 m/minute for more detailed information. The volume sampled is about 0.5 cubic metres of rock surrounding the detector, at each measurement but it is important to note that this depends on the rock density.

Neutron

Neutron logging is similar to gamma-gamma logging in the sense that the ground is subjected to radiation from a source and the degradation of energy of the radiation is determined by detectors which pick up the radiation after it has travelled through the ground. The artificial neutron source radiates the fast neutrons in the borehole where they collide with atoms of the drilled rock and thereby lose their energy. Neutrons are subatomic particles with a mass that is essentially equivalent to that of a hydrogen nucleus. When neutrons travel through matter they lose energy in collisions with particles of the same mass, but lose little energy with particles of heavier or lighter mass. The neutron log is therefore sensitive to water and provides a measure of the ground's moisture content. After borehole effects of diameter, mud, etc., are corrected, the calculations of the material properties can begin. The porosity of the particular soil can be determined from the moisture content using various calibration curves. The moisture contents from the neutron log can be combined with the bulk densities of the gamma-gamma log in order to calculate the dry densities of the various strata in the ground.

Punch Master 2000

Perhaps the first to develop a sampler to be used in conjunction with horizontal boring machine for the purpose of characterising contaminated sites was Eastman Christens Environmental systems in the early 1990's. The sampler, designated as the PunchMaster 2000, is capable of cutting a two inch diameter by five feet long undisturbed sample in soft to medium soils. It can be used for vertical and horizontal sampling through a minimum 100' radius curve in a 5-$^1/_2$" borehole. The sampler works based on a principal similar to a split-spoon or a Shelby Tube core sampler. The PunchMaster 2000 is advanced into a borehole to the target area while the load on the outer tube is kept constant with an applied hydraulic pressure. At a pre-determined location an inner tube is accelerated into the formation by a hydraulic pressure to a calculated punch release force. The sample is drawn back into the outer tube while pressure is maintained to prevent drilling media from contaminating the sample. The PunchMaster 2000 is then brought to the surface with an undisturbed sample. This process is repeated for each sample. Core 2000 is suitable primarily for large drilling rigs. The sampler dimensions are:

Operating length: 22'	Max. Push Down Force: 75,000 lbs.
Tool outer diameter: 4-3/4"	Max. pulling force: 100,000 lbs.
Sample inner diameter: 2"	Max. Core Punch Force: 25,000 lbs.
Sample length: 5'	Transportation Weight: 600 lbs.

Resistivity

Resistivity is the reciprocal of conductivity. It is a measure to the resistance to current flow by a medium. Under some circumstances, resistivity rather than conductivity is preferred to describe the electrical property. A current is injected into the ground through a pair of electrodes and the pattern of subsurface current flow reflects the resistivity of the subsurface. These current patterns can be mapped on the surface by another pair of electrodes that measure the associated voltage variations. This voltage is a measure of the energy that must be expended to pass current through the earth material. This technique is used in ground water studies to detect the depth of the ground water table.

SEAMIST

A new technology that was specially designed for hydrologic investigations designed by Eastman Cherrington Environmental. The intention behind the technology was to replace the usual casing and backfill operation of a typical monitoring well, therefore effectively allowing access to the entire geologic medium for measurement. The system's principal feature is a hole liner that consists of a coated fabric, called an impermeable membrane, which is fed from a reel into the borehole. The membrane is pressured by air or water and "everts" or turns inside out as it descends into the borehole, and is pressed against the borehole walls. The process effectively lines the surface like a continuous packer and prevents the flow into the bore. The SEAMIST membrane can propagate in vertical and horizontal holes, traverse curves and washouts to a depth of over 60m. Instruments such as logging tools, video cameras, absorbent collectors or gas-sampling ports can be transported in and out horizontal well-bores quickly (20-50ft/min.) and the instruments can be isolated from other points of measurement in the same hole. SEAMIST can be installed into horizontal, vertical or partially obstructed holes quickly and inexpensively.

Seismic

There are two basic seismic exploration methods: reflection and refraction. Seismic methods rely on the contrast in acoustical properties between geologic materials to delineate boundaries. In the reflection method, the incident rays are reflected directly back to the surface while in the reflection method, the incident rays are critically refracted along the boundary and then re-radiated back to the surface. This method records the time required for energy to travel to an array of geophones. From a plot of arrival time versus geophone distance, the velocities of the layers and the depth to their interfaces can be determined. Traditionally the refraction method has been used to determine the site's subsurface topography. Penetration ranges between 10 and 30 meters depending on the equipment used and site conditions.

Technology - Horizontal Directional Drilling

Horizontal drilling technology provides the ability to recover undisturbed, high quality, samples from areas that cannot be reached using vertical drilling technology, such as beneath structures. Multiple target points, at different depths, distances and directions can be collected without a need to reset the rig. Also, this highly automated, remote access drilling technique offers an elevated safety level to field personnel since exposure to contaminants is dramatically reduced (Langseth, 1990). Finally, the risk of penetrating impermeable layers, potentially increasing the extent of contamination is significantly reduced.

APPENDIX 'D'

Codification of the Domain of Compliance Utility Method

Using

MATLAB Version 5.3

D.1 User Manual

D.2 User Interface

D.3 Sample Input Data file

D.4 Soft Copy of Program on a 3.5" Floppy Disk

APPENDIX 'D'

Codification of the Domain of Compliance Utility Method

D.1 - USER MANUAL - DOMAIN OF COMPLIANCE UTILITY MODEL

D.1.1 Running The Program

1. Start MATLAB

2. Change the working directory to a:/ by using the 'path browser icon or by using the *cd* command in the line prompt.

3. Run the 'script' by typing *doc* in the line prompt.

4. The graphic window shown in Section D.2 will appear on the screen.

5. Click the 'Enter DataFile name' bottom.

6. Browse for your data file (e.g., DataFile.m) and select it by double clicking the file.

7. The 'Start Simulation' button will turn active.

8. Press the 'Start Simulation' button.

9. The simulation results will appear in the four windows

- 'Doc-Likelihood' - The likelihood that the utilization of a construction method will result in an outcome that lies within the desired solution space (domain-of-compliance).

- 'Tol.-Likelihood' - The likelihood that the utilization of a construction method will result in an outcome that lies within the tolerable solution space.

- 'Outside Tol. Likelihood' - The likelihood that the utilization of a construction method will result in an outcome that lies outside the tolerable solution space.

- The overall utility score (OUS) for a particular candidate method, that is equal to the Euclidean distance of the 'center-of-gravity' of the method solution subspace for the origin of the Domain-of-Compliance.

10. Repeat 1 through 9 for each candidate method.

D.1.2 Preparing a Data File

Complete updating the data file by defining the following parameters (see for example: DataFile.m):

- NumberOfSamples - number of *solution points* to be generated.
- NumberOfVariables – number of preference attributes to be considered (1-8).
- NumberOfConstraints – number of constraints to be considered in the analysis.

For each preference attribute input the:

MaxTolVal – Maximum Allowable Value (MAAV),

MinTolVal – Minimum Allowable Value (MIAV),

MaxTargVal – Maximum Desirable Value (MADV),

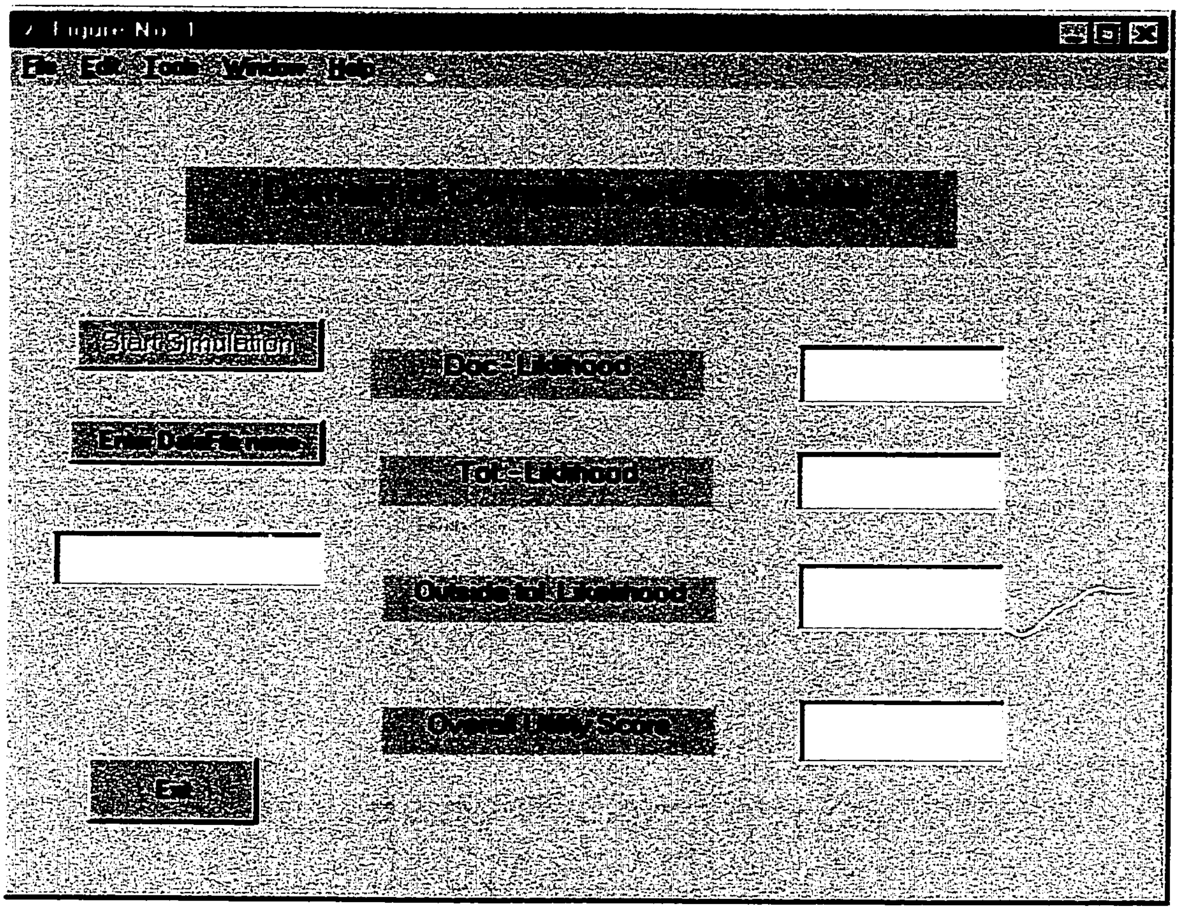
MinTargVal – Minimum Desirable Value (MIDV).

Input constraint functions.

Input Importance Factor for each preference attribute (A to H).

Specify type of distribution its parameters for each preference attribute (A to H).

D.2 USER INTERFACE



D.3 SAMPLE INPUT DATA FILE

```
% Specify Global Parameters

%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NumberOfSamples    = 15000;

NumberOfVariables  = 8;

NumberOfConstraints = 2;


% Specify Boundaries of Domain-of-Compliance (Min/max Allowable; Min/Max

% Desirable values for each preference attribute)

MaxTolValA  = 1000;  MaxTolValB  = 1  ; MaxTolValC  = 45;

MinTolValA  = 10  ;  MinTolValB  = 0  ; MinTolValC  = 4 ;

MaxTargValA = 800 ;  MaxTargValB = 0.9; MaxTargValC = 35;

MinTargValA = 50  ;  MinTargValB = 0.1; MinTargValC = 6 ;


MaxTolValD  = 100;  MaxTolValE  = 19; MaxTolValF  = 999;

MinTolValD  = 10 ;  MinTolValE  = 1 ; MinTolValF  = 100;

MaxTargValD = 80 ;  MaxTargValE = 15; MaxTargValF = 800;

MinTargValD = 30 ;  MinTargValE = 5 ;    MinTargValF = 200;


MaxTolValG  = 60;  MaxTolValH  = 500;

MinTolValG  = 4 ;  MinTolValH  = 20 ;

MaxTargValG = 50;  MaxTargValH = 450;

MinTargValG = 1 ;  MinTargValH = 25 ;
```

```
% Specify Constraints

%*************************************************************

% Constraints are to be specified in the 'CheckConstraints' function

%*************************************************************

% Obtain sample set

%**************************************************

A =  100*rand(1,NumberOfSamples );

B =      rand(1,NumberOfSamples );

C =   50*rand(1,NumberOfSamples );

D =  100*rand(1,NumberOfSamples );

E =   20*rand(1,NumberOfSamples );

F =  100*rand(1,NumberOfSamples );

G =   60*rand(1,NumberOfSamples );

H =  500*rand(1,NumberOfSamples );


% Obtain Respective Probability Values for Sample Set

% **************************************************

ProbA = pdf('Uniform',A,0,500);

ProbB = pdf('Uniform',B,0,1)   ;

ProbC = pdf('Uniform',C,0,50)  ;

ProbD = pdf('Uniform',D,0,100) ;

ProbE = pdf('Uniform',E,0,20)  ;
```

```
ProbF = pdf('Uniform',F,0,500);

ProbG = pdf('Uniform',G,0,60)  ;

ProbH = pdf('Uniform',H,0,500) ;


% Specify Importance Factors for preference Attributes A – H

%*******************************************************

IF =[2 1.2  1  2.5  3.3 2.1  1  1.2 ];

% Generate Solution Value

%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

++

SampMat  = [A ;B ;C ;D ;E; F;G; H];

Prob =[ProbA; ProbB; ProbC; ProbD; ProbE; ProbF; ProbG; ProbH];
```

D.4 SOFT COPY OF PROGRAM ON A CDROM

D.5 WORKING EXAMPLES

Case 1. Basic Evaluation

Case	% Range Within Desirable Allowable		Prob. DoC	Prob. Allowable	Prob. Not Allowable
1	0%	0%	0	0	1
2	0%	100%	0	1	0
3	100%	100%	1	1	0
4	11%	77%	0.09	0.79	0.21
5	11%	55%	0.09	0.59	0.41
6	11%	22%	0.12	0.22	0.78

- Parameter 1 as a Uniform distribution, a = 210, b = 300.
- The values of parameters 2 through 8 are fixed within DoC.
- Manipulate limits for parameter 1 to verify the model's basic performance.

Case 2. Forest Lane Ravine – St. Albert, AB

Description: Install a gravity sewer by-pass in an wooded area used frequently for recreation purposes to eliminate current overflow problems.

L = 340m; min.drive length = 180m; depth = up to 7 m; Dia. = 400mm; Soil: silty-clay; Accuracy = High.

Table D.1. Qualifying Attributes Assessment

Attribute	Value	M/T	HDD	O/C	H. Boring	A. Boring
Soil	Silty-clay	✓	✓	✓	✓	✓
GWT	Low	✓	✓	✓	✓	✓
Depth	7m	✓	✓	✓	✓	✓
Dia.	400mm	✓	✓	✓	X	✓
Length	180m	✓	✓	✓	X	X
Accuracy	Medium-High	✓	✓	✓	X	X

Table D.2. Preference Attributes

	Cost	Impact	Duration	Improvements
Desirable	220	2	80	5
Allowable	280	4	120	20
O/C	220-300	1-2.5	50-60	3-5
HDD	120-200	1.5-2.5	40-70	3-5
M/T	68-130	2-5	60-100	10-17
IF	1	1	1	1

- Constraint = Cost + Improvements+0.5*{Dur-55}<=280
- A uniform distribution used for all attributes.

Table D.3. Model Output

	Desirable	Allowable	Not-Allowable	OUS
M/T	0	0.77	0.23	0.47
HDD	0.28	1.0	0.0	0.56
O/C	0	0.66	0.34	0.97

APPENDIX 'E'

Raw Data and Analysis

A Survey of HDD Contractors in North America

(soft copies provided on enclosed CD-ROM)