AN UNCERTAINTY-BASED FRAMEWORK TO SUPPORT DECISION-MAKING IN GEOTECHNICAL ENGINEERING PROJECTS

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Abstract: Construction projects are inherently risky undertakings. They are exposed to uncertainties that can either result in failures or the impediment of the project to achieve some of its objectives. This is particularly true in the case of geotechnical engineering. Uncertainties of ground conditions can adversely affect project time, costs as well as safety on any construction project. Conventional techniques used by project management are in many cases insufficient to deal with these uncertainties.

This paper describes a PhD project in its very early stages, with the objectives of dealing with the issues of geotechnical engineering and in particular ground related uncertainties. The paper defines the research problem and provides a comprehensive review of literature available on the subject.

A main objective of this research project is to identify principal drivers and sources of uncertainties in ground related construction and to develop a framework to support decision-making in managing these uncertainties.

The development of the framework will be based on the information collected from the literature review and which will be complemented by data elicited from cases and during interviews with experts.

The paper discusses elements that will be required to be included in the framework and how it will be used in supporting decision making.

Keywords: Decision-making under uncertainty, Geotechnical engineering, Risk management, Uncertainty management.

1. INTRODUCTION

Incomplete information and lack of knowledge about ground conditions are relevant sources of uncertainty in geotechnical engineering. These conditions are considered the major drivers of risk in many construction projects. Managing geotechnical risks, however, entails significant challenges. A special area of interest to this research is the control of unforeseen risks. Research evidence has shown that the occurrence of failures associated with unforeseen risks is strongly related to the misuse of available information, faulty decisions and high levels of uncertainty in projects (Sowers, 1993; Bea, 2006; De Meyer, Loch and Pich, 2006; Van Tol, 2007; Wearne, 2008). In addition, Baecher (2005) stated that uncertainty related to the decision-making process is ignored in most part of current applications of geotechnical risk engineering. Recent research identified potential uncertainty and information conditions such as uncertainty underestimation, assumptions incorporation, incomplete information, lack of knowledge, misuse of information, and bias in judgement as factors influencing decision-making in geotechnical projects (Baecher and Christian, 2003; Christian, 2004; Baecher, 2005). These factors can affect the ability to make optimal decisions and suggest the need for improving geotechnical decision-making processes.

The objective of this research is to design an operational framework to support decision-making in geotechnical projects to address the shortcomings described above. The framework is conceived as a structured portfolio of criteria and procedures to analyse uncertainties of geotechnical risks and suggest optimum courses of action. To develop this framework a central research question is formulated as follows:

What are the suitable and relevant definitions, criteria, approaches and strategies to structure an operational framework to support decisions under conditions of uncertainty in geotechnical projects?

The following sections of this paper describe a PhD project in its very early stages. Relevant definitions derived from a comprehensive review of literature available on geotechnical uncertainty are contained in section 2. The proposed theoretical framework is described in section 3 whilst some aspects of the proposed research framework are discussed in section 4. Section 5 includes the conclusions.

2. RELEVANT DEFINITIONS

2.1 Geotechnical Uncertainty and Risk

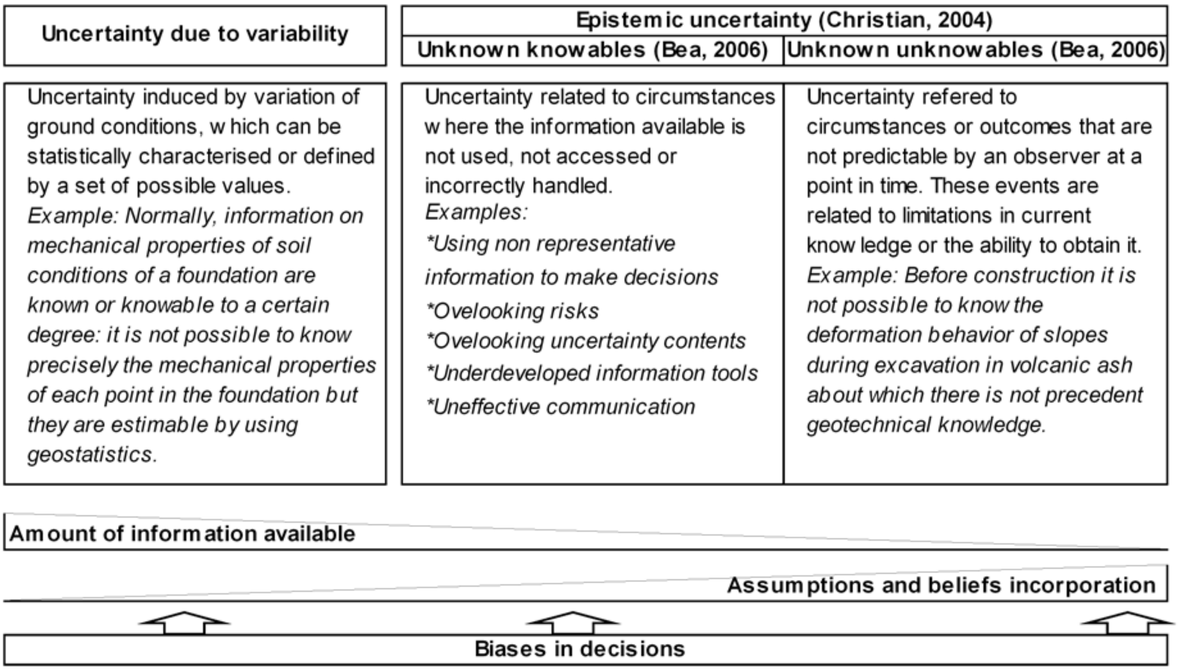
In the literature many definitions of uncertainty and risk are found. Lipshitz and Strauss (1997), and Samson, Reneke and Wiecek (2009) offer reviews on this matter. Lipshitz and Strauss (1997), Zimmermann (2000), and Samson, Reneke and Wiecek, (2009) led to the conclusion that each definition of uncertainty and risk depends on the specific problem addressed and its context. The same is also true when dealing with geotechnical uncertainty and risks. For the proposed research project described in this paper, Zimmermann’s definition of uncertainty will be adopted. The definition assumes that uncertainty implies situations in which a person does not have the required information to describe, prescribe or predict precisely an event or its characteristics (2000). Therefore, uncertainty entails situations that can range from incomplete to total lack of information. Likewise, uncertainty is a different concept to risk which is defined as event or outcome that, if it occurs, has unfavourable effects (PMI, 2004). Following on from the above definitions, it is asserted that uncertainty is a property of risk.

In line with given definitions of uncertainty and risk, geotechnical uncertainty is that uncertainty related to ground conditions. According to Christian (2004) and Baecher (2005), geotechnical uncertainty is classified into two main categories, uncertainty due to variability and epistemic uncertainty which can be defined as follows:

- **Uncertainty due to variability**: uncertainty induced by variation of ground conditions which can be statistically represented, or at least, defined by a set of possible values.

- **Epistemic uncertainty**: that part of uncertainty due to the difficulty of obtaining precise and enough information or knowledge about the ground conditions.

Likewise, Bea (2006) used two additional categories for classifying uncertain events: *unknown knowables* and *unknown unknowables* events. The term *unknown unknowable* refers to events that are not predictable by an observer at a point in time. *Unknown unknowable* events are related to limitations in current knowledge or in the ability to obtain it (Bea, 2006). Conversely, *uncertainty due to variability* refers to circumstances or outcomes that are known to be possible, but they cannot be characterised precisely. Likewise, *unknown knowables* events are related to circumstances where information available is not used, not accessed or incorrectly handled (Bea, 2006) which lead to uncertainty. The categories of geotechnical uncertainty described above can be depicted as shown in the scheme in figure 1.



Uncertainty due to variability	**Epistemic uncertainty (Christian, 2004)**	
	Unknown knowables (Bea, 2006)	**Unknown unknowables (Bea, 2006)**
Uncertainty induced by variation of ground conditions, which can be statistically characterised or defined by a set of possible values. *Example: Normally, information on mechanical properties of soil conditions of a foundation are known or knowable to a certain degree: it is not possible to know precisely the mechanical properties of each point in the foundation but they are estimable by using geostatistics.*	Uncertainty related to circumstances where the information available is not used, not accessed or incorrectly handled. *Examples:* **Using non representative information to make decisions* **Ovelooking risks* **Ovelooking uncertainty contents* **Underdeveloped information tools* **Uneffective communication*	Uncertainty refered to circumstances or outcomes that are not predictable by an observer at a point in time. These events are related to limitations in current knowledge or the ability to obtain it. *Example: Before construction it is not possible to know the deformation behavior of slopes during excavation in volcanic ash about which there is not precedent geotechnical knowledge.*

Figure 1: Geotechnical uncertainties

2.2 Nature of Geotechnical Uncertainty and Decision-Making

Christian (2004) stressed that geotechnical uncertainty is particularly epistemic rather than due to variability. This is further discussed by Baecher (2005) who explained how trade-offs occur between epistemic uncertainty and variability when assumptions or beliefs are incorporated into geotechnical decision-making in circumstances in which there is not precise or enough information available, as shown in figure 1. Experienced decision makers can address an uncertain problem within their domain of expertise with very little information by using assumptions or beliefs (Lipshitz and Strauss, 1997). Information scarcity and the difficulty to acquire it are typical situations in geotechnical engineering (Christian, 2004) and therefore assumptions and beliefs are frequently used. Thus, the identified trade-offs between epistemic uncertainty and variability and the assumptions incorporation imply the need to follow various approaches in modelling, decision-making and management of geotechnical uncertainties.

Biases in decision-making are also relevant uncertainty factors in geotechnical engineering. Decisions are subjected to numerous biases, many of which are at the subconscious level (Kahneman, Slovic and Tversky, 1982). People do not have a clear rational and normative choice behaviour and this drives more uncertainty when making any decision (Tversky and Kahneman, 1988; Elliot, 1998). According to literature on behavioral and organisational decision theories (Tversky and Kahneman, 1981; Kahneman, Slovic and Tversky, 1982; Tversky and Kahneman, 1984; March, 1988; Tversky and Kahneman, 1988; Shapira, 1990; Brockner, 1992; Keil, 1995; Lipshitz and Strauss, 1997), biases occur in all stages of the decision process. They come in information perception, information processing and in making selections from options. Decision making is governed by certain heuristics (reasoning patterns) and decision frames from which arise deviations from rational and optimal decisions. Overestimations and underestimations of uncertainty, overconfidence about data, overconfidence about assumptions and overlooking rare events are, among others, potential biases when decisions are made in conditions of uncertainty (Tversky and Kahneman, 1981; Tversky and Kahneman, 1984; Brockner, 1992; Keil, 1995; Christian, 2004).

The classification scheme of uncertainties shown in figure 1 is a preliminary approach to understanding the underlying nature of uncertainty in geotechnical projects and how it affects decision-making. The scheme also shows how failures associated with unforeseen risks occurs: De Meyer, Loch and Pich (2006) and, to some degree, Bea (2006) stated that projects containing high uncertainty are prone to failures related to unforeseen risks. According to them, such failures can be due to any of the uncertainty categories shown in figure 1. Nevertheless, evidence assessed by Sowers (1997), Bea (2006), Van Tol (2007) and Wearne (2008) showed that a significant proportion of geotechnical failures are due to *unknown knowables* risks, in other words, to failures to use available information in a project as well as to shortcomings in decision-making.

2.3 Decision-making under Uncertainty

The intricate relationship between uncertainty and decision-making in geotechnics will be further investigated in this research. A preliminary definition of this relationship is presented in this sub-section.

Uncertainty is a major obstacle to effective decision-making (Lipshitz and Strauss, 1997) since any decision problem involves selecting feasible actions from alternatives, given *some* information about the current state of the world and the consequences of potential courses of action (Amgoud and Prade, 2009). Based on the definition given by Bellman and Zadeh (1970), decision-making under uncertainty are made under uncertainty when at least, some of the targets (objectives or goals) or some of the constraints (criteria) or some of the estimated outcomes, course of actions or their consequences or alternatives in analysis involve uncertainty.

The above definition indicates that decision-making is a process used to determine a course or courses of actions by analysing alternatives. Such analyses consist of comparisons of possible outcomes or alternatives with targets, constraints or criteria. Each of these elements -targets, constraints and alternatives- can involve uncertainty.

3. PROPOSED FRAMEWORK TO SUPPORT DECISION-MAKING IN GEOTECHNICAL PROJECTS.

The proposed framework is intended to support the explicit and structured understanding, processing and treatment of relevant geotechnical sources of uncertainty such as incomplete information, lack of knowledge, bias in decision-making, assumption incorporation. The framework is focused on understanding, identifying, analysing, processing and treating relevant uncertainties in order to provide additional information about uncertainties of geotechnical risks for decision-making.

The proposed framework is also an operational tool which is intended to be applied in real projects in order to obtain a more effective control of failures associated with unforeseen risks. Decisions are made in every process in solving an engineering problem and typically they have to be done in uncertain conditions. The risk of making non-optimum decisions is introduced or left without control when decision making processes are not clearly defined. The chance that relevant key uncertainties are overlooked when decisions are made is a risk that can affect decision-making. Factors affecting decision-making such as underestimation of uncertainty, overlooking people's decision biases and misuse of information are potential threats that can lead to failures. A framework to support decisions under uncertainty tends to reduce the risk of making non-optimum decisions and therefore should contribute to reducing failures related to unforeseen risks.

In addition, high project uncertainty is not easily manageable only by applying *ad-hoc* or implicit decision-making. Thus, the proposed framework is intended to facilitate decision-making with certain levels of consistency and confidence in order to achieve desirable outcomes in high uncertain projects.

The proposed framework to support decision-making in geotechnical projects is specifically aimed to provide information about risks and recommendations of options to deal with risks under consideration at various stages of the project. These characteristics determine the operational features of the framework. Figure 2 shows a preliminary configuration of the proposed framework.

In the framework, information such as generic data about the conditions of the project, its status and individual task that are being performed or particular abnormal events observed in the project are processed as input data. Once input information is processed, the framework renders as output a comprehensive characterisation of potential risks and feasible measures of control.

During the processing stage, information from *risks* and *options catalogues* is used. The concepts of *risk* and *options (actions) catalogues* were introduced by Carr and Tah (2001). The risk catalogue is a collection of generic risks which have been identified and researched previously. The options catalogue is also a collection of investigated measures for controlling the identified generic risks. Risks and options catalogues can be developed from data of similar projects in the past as well as from the particular risks and options characterisation of the specific project. Therefore, in the design of the framework, the development of generic risks and options catalogues is one of the main tasks of this research.

In the risk catalogue each geotechnical risk is characterised by identifying its consequences, sources, attributes and potential interactions among other risks. Properties such as likelihood, magnitude, severity, duration, spatial distribution, reversibility, among others, can be the attributes of each risk (Aven, Vinnem and Wiencke, 2007). According to Carr and Tah (2001) information about interactions among risks is also used in the characterisation of risks. The risks can also be characterised into three categories of events or stages: *initiating, contributing and propagating* events (Bea, 2006). This is useful information in order to understand how a determined risk can be initiated and propagated that can lead to a major failure.

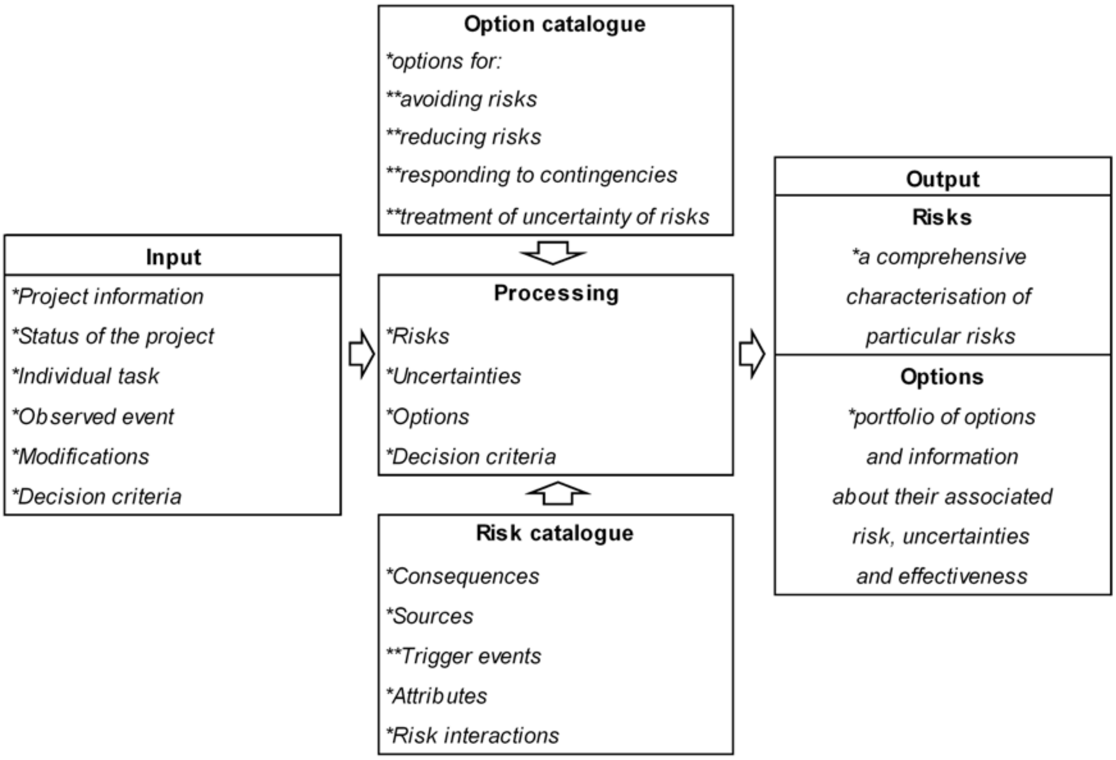


Figure 2: Proposed elements of the operational framework.

Similarly, an options catalogue is composed of options for avoiding, reducing, responding to contingences related to the identified risks. Options catalogue also includes specific measures to deal with uncertainty of risks.

The step of processing information is further detailed in figure 3. The processing phase consists of analysing uncertainties and prioritising risk and options by using the information available in the risks and options catalogues. Uncertainty existing in risks, their consequences, sources, attributes and risk measures (options) is analysed in the processing module of the framework. Uncertainty of each risk is assessed in order to establish the level of information available and required which provides information for risks classification and determining specific measures according to the level and type of uncertainty. Uncertainty analysis comprises uncertainty quantification or uncertainty estimation, if possible; and the evaluation of the sufficiency of the evidence that supports the available information of the risk under consideration as well as particular gaps or lacks of knowledge in its characterisation.

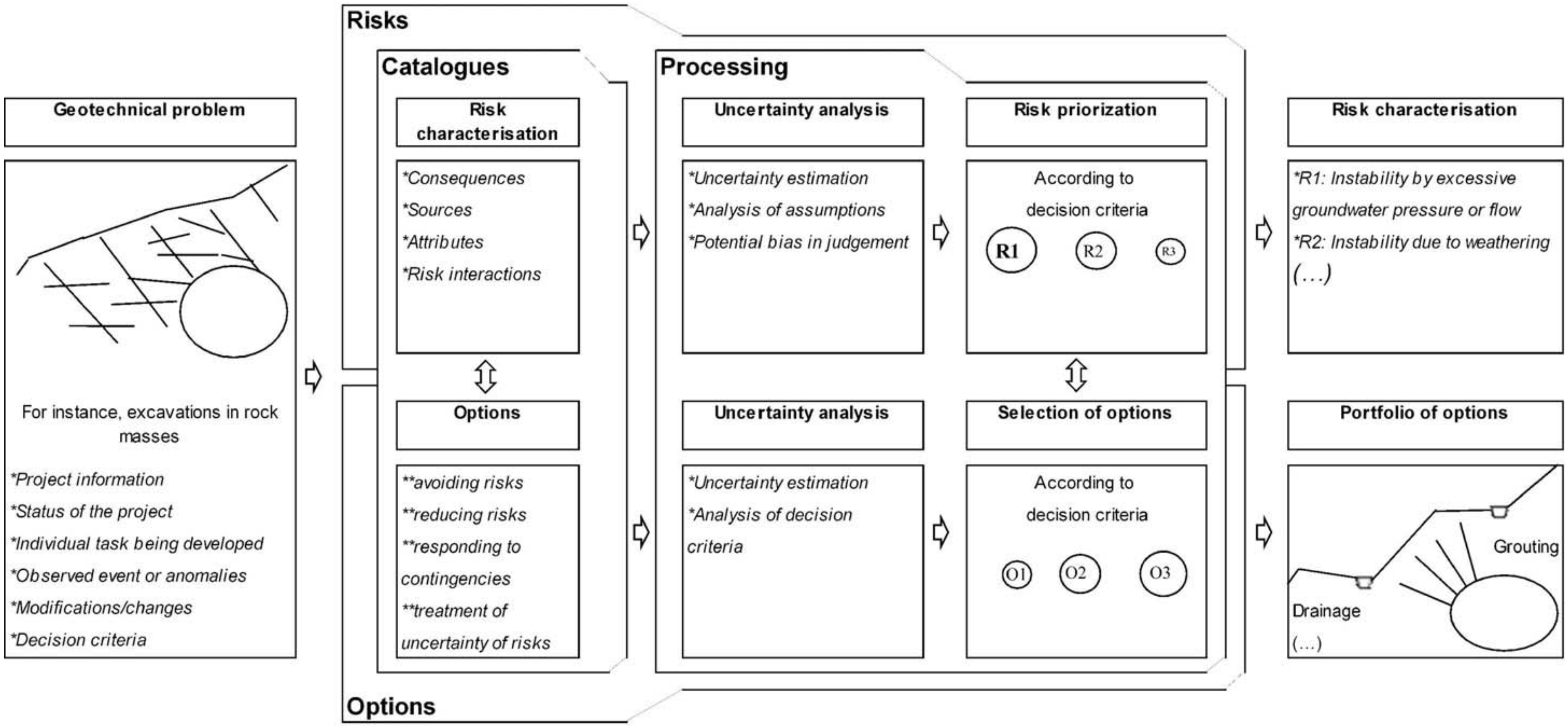


Figure 3: Process of analysis of uncertainties containing in risks and options

Reduction of risk of underestimation of uncertainty, analysis of assumptions and identification of potential biases in judgement are steps that complete the uncertainty analysis. A similar assessment of uncertainties of options is proposed in the framework. The uncertainty analysis also includes the assessment of criteria of decision and analysis of its uncertainties.

In order to evaluate options, investigation of suitable criteria and tools to support decision-making under various levels of uncertainty is one of the main tasks of this research. Also, the processing module of the framework will need to be automated, and to this end, this research will investigate suitable tools and automation techniques that facilitate the processing step in the framework.

The above operational specifications of the proposed framework offer a direct response to the need for controlling failures related to unforeseen risks which are related to the misuse of information, overlooking uncertainty and failures in decision-making. The framework is designed to provide comprehensive information about risks and their uncertainties as well as a portfolio of options to deal with these risks. This information could be provided quickly at any stage in a project without unnecessary delays, using few resources and with consistency and confidence in order to achieve desirable outcomes in high uncertain projects.

4. RESEARCH PHASES AND METHODS

The specified phases for the research are detailed in the following paragraphs:

4.1 Phase 1: Relevant Elements to Deal with Geotechnical Uncertainties

Phase 1 is oriented towards obtaining existing knowledge about coping with uncertainty which includes a research on suitable methods and tools for identifying, measuring, representing, modelling and managing geotechnical uncertainty.

To determine the relevant elements of the framework to deal with geotechnical uncertainty, a *literature survey* on decision-making under uncertainty theories and uncertainty treatment is proposed by using available knowledge reported by Bellman and Zadeh (1970), Shafer (1976), Tversky and Kahneman (1984), Saaty (1990), Lipshitz and Strauss, (1997), Zimmermann (2000), Car and Tah (2001), Dester and Blockley (2003), McManus and Hastings (2005), De Meyer, Loch and Pich (2006), Ozdemir and Saaty (2006), Aven, Vinnem and Wiencke (2007), Loch, Solt and Bailey (2008). In addition relevant literature concerning geotechnical uncertainty will be consulted. Literature related to geotechnical uncertainty is provided by Morgenstern (1995), Einstein (1996), Whitman (2000), Baecher and Christian (2003), Einstein (2003), Christian (2004), Baecher (2005) and Bea (2006), among others.

At the end of this phase it is expected to have defined completely the proposed classification scheme of uncertainties in geotechnical projects and identified suitable strategies and tools to deal with geotechnical uncertainty. In phase 1, *interviews* with experts will be performed in order to determine understanding, coherency, applicability and communicability of the classification scheme and the investigated strategies and tools to deal with uncertainty. The experts will be composed by a number of practitioners who have experience in geotechnical risks and their management. The interviews will be conducted using specific questions to be asked to the experts.

4.2 Phase 2: Design of the Operational Framework to Support Decision-making.

As mentioned earlier, the framework will be composed of risk and options catalogues as existing sources of information. According to literature, research on generic risk and options in geotechnical projects is an enormous task. To make achievable the research objective, the research on generic risk and options will be conducted on a specific geotechnical problem. The selection of the geotechnical problem will require its own specific research. The level of current knowledge, experts' suggestions, information about most frequent types of large construction projects, historical frequency of failure, level of current management and amount of information and data reported in the literature are feasible criteria for selecting the specific geotechnical problem.

Once the particular geotechnical problem is selected, the development of the risk and options catalogues and the identification, analysis and processing of their particular uncertainties will be performed. A comprehensive characterisation of risks according to the attributes of risk suggested by Aven, Vinnem and Wienck (2007) and their uncertainties is proposed. In the design of the framework, efficient identification and modelling of risks interactions and uncertainty processing are further research challenges. Nevertheless, previous work of Car and Tah (2001) and Lee, Park and Shin (2009) offer promising proven tools, in this respect.

Characterisation of risks and their uncertainties will be based on information from risk assessments reports, project failure reports, guidelines for failures investigation, secondary information from previous research, guidelines for geotechnical risk management and, naturally, from experts' knowledge. Risks identification, risk interactions modelling, uncertainty representation and measuring, and decision criteria definition are the main tasks on which knowledge from experts will be elicited by using interviews. *Delphi method* is proposed as an appropriate technique for collecting data from experts. Specific procedures for applying interviews will be designed, calibrated and applied.

The characterisation of risks and representation and analysis of uncertainties will be performed by using the elements and criteria found in phase 1.

In addition, further knowledge will be obtained by investigating and selecting specifications of the framework in order to ensure its operationability and effectiveness which will be researched by using experts' knowledge elicitation methods in conjunction with review of monitoring reports of risk management plans, secondary information from previous research and existing literature.

4.3 Phase 3:Testing and Application of the Framework to Support Decision-making.

To determine framework effectiveness, a set of *experiments* will be conducted. Experimentation is a strategy to assess the effects of methods or changes. It consists of determining differences in performance in the research units (system, organisation, groups, etc.). Certain research units are subjected to changes or training in applying a given method or procedure (experimental unit) and the other does not (control unit). In this project, the specific experiments are described as follows: a sampled set of cases of documented failures will be prepared by the researcher to determine specific preconditions of failure. Preconditions of a given case will be examined and analysed by various groups of experts. A trained group using the framework will then determine the course of action to be performed. The other group will conduct decisions about the problem without using the framework. A comparative analysis of decisions performed should allow to draw conclusions on the effectiveness and validity of the framework and to provide information for its optimisation and application.

5. CONCLUSIONS

This paper describes a research project that addresses the problem of uncertainty and risk in geotechnical projects. To this end, an operational framework to support decisions is proposed and preliminarily described. Relevant geotechnical uncertainties are investigated. For the developing of the framework it is proposed to search for *suitable* criteria and tools to cope with geotechnical risks and their uncertainties.

In addition, it is proposed to investigate suitable specifications of the framework that ensure its efficient operationalization and effectiveness.

Specific research methods are described. They are intended to generate valid and suitable knowledge and information based on evidences and experts’ knowledge. The effectiveness of the framework to support decisions will be investigated through the use of experiments. A number of particular sources of information are identified.

Since the proposed framework is a tool for procuring better *decisions* based on providing comprehensive *information* about risks, uncertainties, options and decision criteria, the framework is important for achieving efficient response to the need of controlling failures related to unforeseen risks, which as mentioned, are caused by failures in using available *information* and by shortcomings in *decision-making*. These characteristics of the framework represent a contribution to advancing the knowledge to understanding and management of uncertainty and decision-making in geotechnical engineering as well as to the engineering practice.

6. ACKNOWLEDGMENTS

This research is supported by DELTARES. The financial support is gratefully acknowledge.

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