On risk-based geotechnical site investigation of flood defenses

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ABSTRACT: Site investigation planning in practice is largely based on intuition, engineering judgment, habits or the client’s willingness to pay. Despite decision theory having been studied for geotechnical site investigation, for example by Baecher (1972), already in the early 1970’s, applications seem to be restricted to academia. Elaboration of more specific examples close to practical questions and the provision of guidance and tools may aid the concept finding its way into practice, providing a framework for consistent decision-making. This paper applies decision theory to site investigation of flood defenses such as river dikes in order to demonstrate the usefulness and applicability to a common problem. After pointing out the specific requirements for assessing existing structures with explicit reliability requirements as opposed to design problems and pointing out the role of geotechnical site investigation herein, the framework is presented. A simplified example of the detection of an adverse geological detail by means of CPT illustrates how an optimal inter-CPT distance is determined by the soil investigation strategy with the least expected cost. Even if it cannot eliminate subjectivity from site investigation planning, the approach provides means of consistently deriving and justifying site investigation strategies based on prior information and accounting for the relevant costs and uncertainties involved.

1 INTRODUCTION

The current guidance material for determining the scope of Geotechnical Site Investigations (GSI) is mainly qualitative and relies mainly on engineering judgment. There is a lack of methods, guidance and examples of quantitative risk-motivated decision making, both, in practical guidance as well as in the literature. This paper proposes both, a conceptual and a computational framework for determining the most cost-effective site inspection strategy in a safety assessment situation. The scope of a geotechnical investigation concerns choosing the techniques, the quality or the density or frequency of the measurements.

2 SAFETY ASSESSMENT OF FLOOD DEFENSES

The purpose of Safety Assessments (SA) of existing structures is to either extend their lifetime or to (re)define inspection and maintenance intervals. Flood defenses failing to meet the safety requirements have to be reinforced. A starting point for the methodology presented in this paper is the existence of an acceptable probability of flooding representing the safety requirement. Thus potential consequences of flooding are only treated implicitly.

3 GEOTECHNICAL INVESTIGATION

The vast majority of flood defenses are dikes, embankments and flood walls. Besides overtopping, the main threats are geotechnical failures like slope instability or internal erosion (e.g., piping). These failure mechanisms are predominantly influenced by the composition of the subsoil, which is the result of natural deposition processes. The resulting heterogeneity is the main challenge in geotechnical investigations. Heterogeneity manifests itself in several ways: (a) in the stratification of the subsoil, (b) in the spatial variability of properties within the strata and (c) in the occurrence of adverse geological (or man-made) details. Detection of the latter is a key issue for flood defenses. From a reliability point of view, flood
defense systems can be characterized as serial systems where failure of any element leads to system failure. Hence, the weakest element of a flood defense determines its strength. Therefore, the role of geotechnical investigations in SA is principally the identification and characterization of weak spots.

4 CONCEPTUAL FRAMEWORK

The core concept and theory used in the presented approach is Bayesian Decision Analysis (Raiffa and Schlaifer (1961), Benjamin and Cornell (1970)). In this specific case, the often encountered difficulty of specifying an appropriate utility function has a simple solution, because the appropriate scope of geotechnical investigation for SA purposes is a cost-minimization question. As opposed to most risk-based decision problems, the cost of failure is out of the scope of the analysis, though still implicitly covered through the target reliability.

4.1 Decisions in safety assessments

The purpose of SA is to assess whether or not a structure is safe enough. We define safe enough in terms of an admissible probability of failure \( P_{\text{f,adm}} \) (failure = unsatisfactory performance) or the equivalent target reliability:

\[
\beta_{\text{req}} = \Phi^{-1}(1 - P_{\text{f,adm}})
\]

A negative SA outcome (i.e., unsafe or disapproval) implies that either reinforcement or more investigation (to reduce uncertainty) is required to achieve an acceptable state \( (\beta > \beta_{\text{req}}) \). The decision tree in Figure 1 illustrates the decision options \( a \), possible outcomes (or states of nature) \( \theta \) and marginal cost \( C \) that are involved in the decision problem of getting to approval of an initially unsafe structure.

The main alternative actions are initiating a geotechnical investigation and directly reinforcing or replacing the structure. Within option (b) more choices to be made, such as the type and parameters (e.g., grid) of the geotechnical investigation. After the investigation, the result will be either approval or disapproval of the structure. The marginal cost for option (a) is mainly the cost of uncertainty reduction by means of analysis of readily available data. While the marginal cost for option (c) is simply the reinforcement cost, for option (b) it is either the inspection cost in case of approval or the cost of inspection plus the cost of reinforcement in case of disapproval. Notice that the required reinforcement after investigation might be less (in rare cases also more) extensive than option (c) due to additional information. For example, having identified weak spots in some reaches and excluded anomalies in other reaches, local reinforcements may be sufficient. Optimal inspection and maintenance strategies are regarded as the ones achieving the objective (a safe structure) with minimum cost:

\[
s^* = \min_{s} E[C_f(s) + C_R(s, \varepsilon(\Theta))]
\]

where \( s \) is the decision strategy (incl. the decision parameters) for the investigation (experiment) to be carried out. The cost of investigation \( C_f(s) \) is assumed to be deterministic, while the cost of reinforcement \( C_R(s, \varepsilon(\Theta)) \) depends on the outcome \( \varepsilon(\Theta) \) of the investigation (evidence), which itself depends on the state of nature \( \Theta \). In other words, the decision problem treats the question whether reinforcement (cost) can be either avoided or reduced by geotechnical site investigation and

![Figure 1. Decision tree for geotechnical investigation in safety assessments of flood defenses.](image)
which type and setup can achieve this most cost-effectively.

5 MAIN RESULTS AND CONCLUSIONS

The paper demonstrates the usefulness of probability and decision theory for a specific application, the safety assessment of river dikes. It presents a decision framework and a simple but illustrative simple example of detecting adverse geological details by CPT. has demonstrated the applicability of the framework. Using such a framework does not eliminate subjectivity from site investigation planning, since assessing prior probabilities still requires (subjective) expert judgment. Nevertheless, it provides a tool for consistent rational decision making. For practical application, the development of tools and guidance and the elaboration of examples are necessary.