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Sensitivity analysis of vertically loaded pile reliability

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Abstract

The purpose of this paper is to examine the influence of geotechnical uncertainties on the reliability of vertically loaded pile foundations and the use of this information in decision-making support, especially when gathering the information necessary for reliability analyses. Two case studies of single pile foundations were selected, and each uncertainty source was investigated to identify which are the most important and influential in the evaluation of vertical pile resistance under axial loading. Reliability sensitivity analyses were conducted using FORM (the first-order reliability method) and MCS (Monte Carlo simulations). The characterisation of uncertainties is not an easy task in geotechnical engineering. The aim of the analyses described in this paper is to optimise resources and investments in the investigation of the variables in pile reliability. The physical uncertainties of actions, the inherent variability of soil and model error were assessed by experimental in situ standard penetration tests (SPT) or from information available in the literature. For the cases studied, the sensitivity analysis results show that, in spite of the high variability of the soils involved, model error also plays a very important role in geotechnical pile reliability and was considerably more important than soil variability in both case studies. From a comparison of the two reliability methods (FORM and MCS), it was concluded that FORM is applicable in simple cases and as a first approach because it is an approximate method and sometimes does not have the capability to incorporate every detail of the problem, namely a specific probability density function or more specific limit conditions.

Keywords: Deep foundation; Pile design; Probability of failure; Reliability theory; Spatial variability; Standard penetration test; Uncertainties; Vertical bearing capacity

1. Introduction

Pile foundations are often used for important structures, and thus, reliability evaluation is an important aspect of the design of such structures. Unlike the approach to reliability evaluation used in structural engineering, the traditional procedure used in geotechnical design addresses uncertainties through high global or partial safety factors, mostly based on past experience. This approach to addressing uncertainties does not provide a rational basis for understanding their influence on design. For this reason, and because of regulation codes (JCSS, 2001; CEN, 2002a;

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Watabe et al., 2009; Honjo et al., 2010b), and social concerns (such as sustainability), geotechnical engineers need to improve their ability to deal with uncertainties and probabilities to help with decision-making.

Reliability methods have become increasingly important as decision support tools in civil engineering and in geotechnical applications, especially over the past two decades (Einstein, 2001; Honjo et al., 2002; Paikowsky, 2004; Honjo et al., 2005; Yang, 2006; Cherubini and Vessia, 2007; Fenton and Griffiths, 2007; Phoon, 2008; Juang et al., 2009; Honjo et al. 2010a; Huang et al., 2010; Wang, 2011). Reliability analyses are conducted for the purpose of determining the probability of reaching a behavioural limit and involve introducing estimates of geometric, material and actions variability into the design process. The main benefit of reliability analysis is that it provides quantitative information about the parameters that most significantly influence the behaviour under study. This makes risk control, the determination of the potential causes of adverse effects on the structure, possible.

The design of pile foundations still involves many limitations and uncertainties, particularly when there is not enough investment in soil characterisation and pile load tests. In addition to the uncertainties associated with soil characterisation (pile design based on insufficient data and using theoretical approaches that do not characterise the model error well), physical, statistical, spatial and human uncertainties exist. However, because it is technically and economically impossible to produce designs of pile foundations in the most unfavourable of cases, it is the engineer's goal to minimise the risk and limit it to an acceptable level in the most economical manner possible.

First developed for other areas of engineering design, reliability theory needs to be adapted to the needs and objectives of geotechnical engineering. This requires consideration of spatial correlations and attention to the influence that the number of samples analysed has on the quantification of the standard deviations and means of geotechnical parameters. Although the extent to which this can be accomplished depends on the engineer's knowledge and the project's budget for investigation, geotechnical engineering definitely benefits from the consideration of reliability in design (Christian, 2004; Najjar and Gilbert, 2009).

The primary purpose of this paper is to demonstrate the application of reliability methods to two distinct case studies of vertical single pile foundations under axial loading. This paper also presents a simple and practical approach to performing reliability-based design (RBD) in geotechnical problems and obtaining valuable information from it. For that purpose, sensitivity analyses were conducted to study the influence of each uncertainty type. In addition, two well-known RBD methods, the first-order reliability method (FORM) and Monte Carlo simulations (MCS) were applied to the case studies for comparison.

Another purpose of this paper is to demonstrate the advantages of employing RBD in the decision-making process for pile foundation design. The decision-making related to the economic and research investments required for gathering the information necessary to characterise the uncertainties associated with important random variables, in both pile design and its reliability, is facilitated by this type of balanced reliability analysis. Therefore, this work makes a significant contribution to the application of RBD to pile design. This type of approach is important not only for decision-making but also for identifying the direction in which geotechnical design research should proceed (Honjo, 2011).

2. Reliability approach

2.1. Reliability levels

A construction project can be evaluated by different methods, the level of accuracy of each one depends on the way that uncertainties are considered in the design (Madsen et al., 1986; Nowak and Collins, 2000; Zhang and Chu, 2009a, b). Very briefly, these levels are classified as follows:

- Level zero: deterministic methods, in which the random variables (RVs) are taken as deterministic and uncertainties are taken into account by a global safety factor (SF) based on past experience.
- Level I: semi-probabilistic methods, in which deterministic formulas are applied to representative values of RVs multiplied by partial SFs. The characteristic values are calculated based on statistical information, while the partial SFs are based on level II or level III reliability methods, defined subsequently.
- Level II: approximate (simplified hypothesis) probabilistic methods, in which RVs are characterised by their distribution and statistical parameters (mean and standard deviation (SD) or coefficient of variation (COV = SD/mean)). The probabilistic evaluation of safety is then achieved using approximate numerical techniques.
- Level III: full probabilistic (simulation) methods, based on techniques that take into account all of the probabilistic characteristics of the RVs.
- Level IV: risk analysis, in which all of the probabilistic characteristics and the consequences of failure are taken into account. The risk (consequences multiplied by the probability of failure) is then used as a measure of the reliability. This allows for the comparison of solutions on an economic basis, taking into account uncertainty, costs and benefits.

Levels zero and I (one) are traditional approaches to design, while levels II (two) and III (three) are approaches commonly used for the evaluation of the probability of failure. Within reliability analysis, the most popular methods are the first-order reliability method and Monte Carlo simulations, which correspond to level II and level III, respectively. MCS is widely used because of its higher level of accuracy and because it is the most straightforward method for reliability analysis, while FORM is