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Research Paper

Updating reliability of single piles and pile groups by load tests

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ABSTRACT

Pile load tests are used to refine designs and for quality assurance. They can also be used to verify the reliability of piles and pile groups. Stochastic methods have previously been developed to verify the reliability of single piles. A general stochastic method to verify the reliability of pile groups is developed in this paper. The method can be used to assess the reliability of groups where pile tests have been conducted to the ultimate capacity, to below the ultimate capacity but exceeding specified capacity, and where pile tests fail to achieve the specified capacity. In the latter case, the method allows decisions to be made as to whether the reliability of the entire pile group is satisfactory or whether additional piles need to be installed.

1. Introduction

There are many uncertainties in the design, construction and testing of piles and pile groups (e.g., [11]). Geotechnical material parameters are subject to measurement errors and spatial variability across a site, and are usually assumed based on a small sample of the total ground volume. Analytical or numerical models used for design will thus be a simplification of a complex physical reality. Moreover, construction processes will vary from pile to pile and affect the variability of the ultimate pile capacity. These uncertainties are often managed by performing load tests on a small sample of piles from the total population of constructed piles, or by adopting conservative factors of safety in design when pile tests are not performed. Results from load tests can provide a better estimate of the ultimate pile capacity and also greatly reduce the uncertainty of the ultimate pile capacity, since the error associated with load test measurements is, in principle, much smaller than that associated with predictions depending on the skill of the tester/interpreter.

Although direct load tests can provide a wealth of information for the design and construction of pile foundations and are the most accurate method of determining pile capacity, the pile load test itself involves some degree of uncertainty too. For example, although static load tests are believed to be more accurate than dynamic load tests, there are still uncertainties associated with the interpretation of load–displacement relationships (e.g., [16]).

Nevertheless, confirmation of pile-soil capacity through static load testing is considerably more reliable than capacity estimates from static capacity analyses and dynamic formulas [19]. By using direct load tests as part of the design process, an improved knowledge of pile-soil behaviour is obtained that may allow a reduction in pile lengths or an increase in the pile design load, either of which may result in potential savings in foundation costs. With the improved knowledge of pile-soil behaviour, a lower factor of safety (FS) may be used on the pile design load. For example, the FS can be reduced from 3.50 for static analyses based on the standard penetration test (SPT) or the cone penetration test (CPT) to 2.00 for the same analyses that are verified with a sufficient number of static loading tests (ASSHTO, 1998). If reliability-based design is adopted, the resistance factors can be increased (e.g., [18,25,16]). The Australian Standard for Piling-Design and Installation (1995) provides ranges of resistance factors. When static load tests are conducted, resistance factors (0.7–0.9) can be used and applied to the maximum load (proof test) or measured capacity. When only static pile analyses are conducted, small resistance factors (0.40–0.65) should be used relating to the source of soil parameters and soil type (SPT in cohesionless soils). Detailed recommendations are provided for resistance factors to be used with the dynamic methods ranging from 0.45 to 0.65 for methods without dynamic measurements, to between 0.50 and 0.85 when utilizing dynamic measurements with signal matching analysis. In the case of the Australian Standard, these resistance factors were generated

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Nomenclature

C	N by N covariance matrix
C_i	covariance matrix of proposal distribution at step i
C_0	initial covariance matrix of proposal distribution
$\mathrm{cov}(\theta_0, \ldots, \theta_{i-1})$	covariance of previous samples
D	data collected
FS	factor of safety
$f_y(y_1, \ldots, y_N)$	joint distribution of pile capacity
$f'(\mu)$	prior distribution of mean pile capacity
$f''(\mu\|\widehat{\mathbf{y}})$	posterior distribution of mean pile capacity
g	limit state function
i_0	the maximum steps of initial covariance matrix
$\mathbf{I}_d$	d-dimensional identity matrix
m	number of failed piles
n	number of tested piles
N	number of piles in a group
$N()$	standard normal distribution
$P(\theta)$	prior distribution of the parameters
$P(D\|\theta)$	likelihood
$P(D)$	evidence
p_f	probability of failure
q_1	proposal distribution
q_2	proposal distribution
s_d	a scaling parameter
T	maximum applied load in load tests
y	pile capacity
$\widehat{\mathbf{y}}$	pile capacities obtained by load tests
$\bar{y}$	average of $\mathbf{y}$
ε	a small value
η	coefficient of group efficiency
θ	parameters
θ_{i-1}	current sample
$\theta_i^{(1)}$	first proposal sample
$\theta_i^{(2)}$	second proposal sample
μ	mean pile capacity
μ_0	prior mean of mean pile capacity
μ_1	posterior mean of mean pile capacity
μ_{err}	mean test error
$\mu_{\ln y}$	mean of underlying normal distribution
σ	standard deviation of pile capacity
σ_0	prior standard deviation of mean pile capacity
σ_1	posterior standard deviation of mean pile capacity
σ_{err}	standard deviation of test error
$\sigma_{\ln y}$	standard deviation of underlying normal distribution
π	target distribution
ρ	correlation coefficient of pile capacity
Φ	cumulative distribution function of the standard normal distribution

based on the judgement of an expert panel rather than through statistical calibration.

Calculations of pile and pile group reliability based on load test results have been reported by Kay [10], Baecher and Rackwitz [1], Zhang et al. [25], Zhang [23], and Zhang et al. [26,24,27,22]. There are two approaches, namely frequentist and Bayesian statistics. Liang and Yang [12] evaluated the confidence interval of the population mean of pile capacities. It was shown that the required measured capacity decreases with an increase in the number of load tests to achieve the same level of reliability. Most of the work published to date adopts Bayesian methods to update the reliability of single piles. Zhang [23] developed methods to incorporate the results of proof load tests not conducted to failure into the design of pile foundation. Similar approaches have been applied to steel grid reinforced soil walls by Bathurst et al. [2]. Najjar and Gilbert [15] assumed that the capacities of individual piles follow a mixed lognormal distribution. Instead of treating the mean capacity as a random variable, it was assumed that the lower bound of the mixed lognormal distribution is a random variable. It was shown that the lower-bound capacity can cause a significant increase in the calculated reliability for a geotechnical design. The uncertainties in the measured proof load have also been studied. The reliability of large pile groups has been shown to be greater than the reliability of individual piles due to redundancy in the system (e.g., [9,25]). Zhang et al. [25] used single pile analyses to assess group reliability by adopting a redundancy factor. Paikowsky [16] suggested that the target reliability for pile group can be reduced to 2.0–2.5 compared to 3.0 for single piles. Pile groups may be able to support the design load when one or more piles are defective (e.g., [17]). If the reliability of the pile group with defective piles can be quantified, it may be possible to use the defective pile rather than install a replacement pile and increase the size of the pile cap.

Probabilistic methods have not been developed to assess the reliability of pile groups as a function of individual pile test results. Although several studies on the system reliability of pile groups are available (e.g., [25]), a systematic framework for updating the reliability of pile groups has not been developed. In this study we propose a rigorous framework for updating the reliability of single piles and pile groups. It is assumed that load tests are subject to uncertainty. The proposed framework can be used to assess the reliability of single piles and pile groups subject to general loadings and stratigraphic conditions. The method can be used to assess the reliability of groups where pile tests have been conducted to the ultimate capacity, to below the ultimate capacity but exceeding specified capacity, and where pile tests fail to achieve the specified capacity (or are unknown). In the latter case, the method allows decisions to be made as to whether the reliability of the entire pile group is satisfactory or whether additional piles need to be installed. However, as the purpose of this paper is to outline a general stochastic methodology, a number of simplifying assumptions have been made. These are:

(1) The piles in the group are geometrically identical, loaded equally in the vertical direction only and are perfectly plastic.
(2) Uncertainties relating to design methodology, site characterization, soil properties and construction quality have been quantified or assessed and form prior knowledge.
(3) The reliability for the piles has been specified and a proper design method has been chosen. A probabilistic assessment of pile capacity has been performed.
(4) Load tests have been conducted. This could be for design and the load tests are used to refine the design, or at the stage of construction where the load tests are used to make sure the design have a sufficient level of reliability.
(5) The accuracies of the load test methods, including result interpretations, have been assessed or are known.
(6) The uncertainties in external loads are not considered, but the proposed methods can be extended to include the uncertainty of loads in a straight forward manner.

The first part of this paper summarizes Bayesian updating and the adopted method for performing the numerical computations.