Structural Safety 63 (2016) 81–89

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Characteristic soil strength for axial pile capacity and its estimation with confidence for offshore applications

Knut O. Ronold

DNV GL, Veritasveien 1, N-1322 Høvik, Norway

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 28 August 2016
Accepted 28 August 2016

Keywords:
Soil strength
Pile capacity
Model uncertainty
Probabilistic analysis
Code calibration
Confidence estimation

ABSTRACT

Many offshore design codes require the characteristic soil strength for axial pile capacity to be estimated with caution or conservatism, i.e. – in statistical terms – it has to be estimated with confidence. This study is concerned with a reliability-based calibration of the necessary minimum confidence for such estimation. The study demonstrates how to estimate characteristic soil strength for axial pile capacity with confidence and provides an approach to such estimation that will render an incentive to obtain more soil strength data and thereby give credit to the geotechnical designer who opts to test more. The study capitalizes on existing load and resistance models for an offshore example pile from the literature and refers to a number of relevant offshore foundation design codes. In order to accomplish the purpose, a number of prerequisites for a successful study are dealt with before the confidence calibration itself is presented.

A suitable approach to represent model uncertainty associated with axial pile capacity predictions is presented and implemented in the reliability analyses that are used for the calibrations. The approach implies that the standard deviation of the ratio between true and predicted capacity is represented as a function of the pile length rather than as a constant. This approach is supported both by theory and by data.

Based on stochastic models for load and resistance in conjunction with a method for prediction of axial pile capacity, a second-order reliability analysis of the example pile is carried out. With an assumption of perfect knowledge of the soil strength, with characteristic soil strength defined as the mean value and with prescribed load factors for permanent and environmental loads, the necessary requirement for the material factor on the characteristic soil strength is calibrated by tuning the reliability analysis to meet a prescribed target failure probability.

With the calibrated material factor kept unchanged, the reliability analysis is repeated, now with the stochastic model for soil strength altered to include statistical uncertainty owing to limited soil data. The value of the characteristic soil strength is adjusted downward until the result of the reliability analysis again meets the prescribed target failure probability. The resulting value of the characteristic soil strength is interpreted as "the conservatively assessed value" to be used in design when soil data are limited and this value is subsequently used to find the corresponding minimum confidence for characteristic value estimation by capitalizing on the properties of the Student's *t* distribution. Results are presented for target annual failure probabilities in the range 10^{-5}–10^{-4}.

1. Introduction

For geotechnical design of axially loaded offshore piles, the characteristic value of the soil strength as a function of depth is used in conjunction with a capacity prediction model and a material factor to determine the design capacity. A number of different capacity prediction models exist; see for example Lehane et al. [17] and Lacasse et al. [14].

The characteristic value of the soil strength is usually defined in the design standard which is used for the geotechnical design of the pile, and the definition is usually some objective measure in the probability distribution of the strength, for example the mean value or some lower-tail quantile. Sometimes the design standard also provides requirements for the estimation of the characteristic soil strength with caution and conservatism, i.e. – in statistical terms – estimation with confidence, such as when the estimation is to be based on statistical methods and limited data. Requirements for the material factor to be used in the geotechnical pile design are also given in the design standard and these require-

E-mail address: knut.ronold@dnvgl.com

http://dx.doi.org/10.1016/j.strusafe.2016.08.004
0167-4730/

ments are specific for the specific definition of characteristic soil strength employed by the standard.

The offshore standard NORSOK G-001 [20] specifies that the characteristic value of soil strength to be selected for use in design shall be a "conservatively assessed mean value". This implies that the definition of the characteristic value is the mean value and that the assessment of this characteristic value shall be conservative, i.e. in statistical terms that it has to be estimated with confidence. The offshore standard NORSOK N-001 [21] has similar wording for characteristic soil strength, but neither NORSOK G-001 nor NORSOK N-001 specifies any particular requirement regarding which confidence level shall be used for the conservative estimation.

DNVGL-OS-C101 [5] is a standard for design of offshore steel structures and their foundations. For cases where a large soil volume is involved, such as for geotechnical design of a long offshore pile, DNVGL-OS-C101 specifies that the characteristic soil strength is defined as the mean value, thereby reflecting that fluctuations of the soil strength from point to point within the soil volume tend to average out over the length of the pile. DNVGL-OS-C101 requires this characteristic soil strength estimated with caution in design and – when statistical methods are used for the estimation – recommends that the estimation be carried out with at least 95% confidence.

When the mean value has to be estimated from limited data, the resulting central (unbiased) estimate – the sample mean – will be encumbered with uncertainty. There will be about equal probability for the true but unknown mean value of being greater than respectively smaller than this central estimate. It is not attractive to use this estimate in design when there is such a large probability – about 50% – that the true but unknown mean value is smaller. As exemplified above, the design standards therefore often require that a smaller estimate than the central estimate be used in design, i.e. an estimate with confidence. The confidence is the probability that the true but unknown mean value is greater than the smaller estimate used in design. The smaller the estimate used, the larger is the confidence. Statistical methods exist that specify how much smaller than the central estimate a smaller estimate needs to be in order to meet a specified confidence level. Rather than referring to confidence, some design standards refer to "the probability of a worse value", which is the complement of the confidence; for example 5% probability of a worse value corresponds to 95% confidence.

Because of the uncertainty in the central estimate of the mean value when data are limited, use of this estimate in design will imply that the safety level which is achieved under an assumption of perfect knowledge, including known mean value, cannot be met. This can be remedied by using a smaller estimate in design, i.e. an estimate with confidence. The smaller the estimate used, i.e. the larger the confidence applied, the larger the safety level achieved in design will be. Because perfect knowledge is usually assumed when design codes are calibrated and because it is a goal to maintain the safety level achieved under perfect knowledge when carrying out designs based on limited data, the requirement for minimum confidence can be established as the confidence level which is such that the safety level achieved in design is equal to the safety level achieved under perfect knowledge.

This paper presents the probability calculations necessary to determine which confidence level should be required as a minimum for the estimation of characteristic soil strength for axial pile capacity prediction when data are limited and when the characteristic soil strength is defined as the mean value. A site-specific example case referring to an offshore jacket pile is used for this purpose. The resulting requirement for minimum confidence represents what should be a lower bound for the confidence level from a safety perspective. The determination of the requirement for minimum confidence serves as support for deciding which confidence level should be used in design.

The calculations are based on structural reliability methods applied to a case study which capitalizes on axial pile capacity predictions by means of a recognized method. The case study considered is a study of a jacket pile foundation in clay reported by Lacasse et al. [14] and the capacity prediction method considered is the so-called NGI-05 method described by Karlsrud et al. [13].

To accomplish the calculations, an initial reliability analysis of the pile in question is carried out, leading to calibration of a case-specific set of partial safety factors that will provide a design meeting a prescribed target safety level. This requires an adequate stochastic model for the model uncertainty associated with the chosen method for axial pile capacity prediction. A new such model, which accounts properly for the prediction uncertainty's dependency on the pile length, is developed for this purpose and is presented first. This is followed by a presentation of the particular example case together with probabilistic and deterministic modelling for the initial reliability analysis. This probabilistic analysis is executed under the assumption of perfect knowledge of the stochastic soil strength, i.e. no statistical uncertainty in the soil strength properties is included. This is a standard approach in code theory as outlined in Madsen et al. [18]. The characteristic soil strength is defined as the mean value which leads to a characteristic axial pile capacity equal to the mean value of the capacity. The results of the probabilistic analysis are presented in terms of the required material factor on capacity as a function of the target annual failure probability.

A modification of the probabilistic model is subsequently introduced by which the assumption of perfect knowledge is omitted and replaced by a stochastic model for soil strength which reflects the effect of limited data. This is done by including statistical uncertainty in the reliability analysis by means of probability distributions of the statistically uncertain soil strength parameters. The reliability analysis is repeated based on this revised model and the numerical value of the characteristic soil strength is adjusted downward until the reliability analysis with this model provides the same annual failure probability as the one achieved under the assumption of perfect knowledge. The thus adjusted value of the characteristic soil strength corresponds to a characteristic strength estimated with confidence. This confidence can now be calibrated by means of statistical formulas for estimation of mean values with confidence. The paper shows how this is done and presents the resulting calibrated necessary minimum confidence.

The paper may serve as a contribution to ongoing discussions in the geotechnical community regarding the characterization of soil properties. The paper may thereby supplement other recently published material relevant to this issue of characterization and dealing with the same topics that are addressed in the paper. DNV-RP-C207 [2] addresses on a general basis the issue of definition of characteristic values and how to estimate them with confidence. Schneider and Schneider [31] deal with an interpretation of the current definition of characteristic soil strength in Eurocode 7 (EN 1997-1) [6] for onshore foundations and present a simplified way to account for the variance reduction that comes with spatial averaging of soil properties. Orr [22] reviews how important aspects of risk and reliability in geotechnical engineering are addressed in Eurocode 7. ISO 2394:2015 [10] has a wider scope than Eurocode 7 and provides state-of-the-art guidelines for how to carry out reliability-based safety factor calibrations. Fenton et al. [8] provides a review of current practice in various standards regarding definition and estimation of characteristic soil strength. Phoon and Kulhawy [23,24] deal with statistical characterization