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Reliability analysis of piles in spatially varying soils considering multiple failure modes

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ABSTRACT

In most limit state design codes, the serviceability limit checks for drilled shafts still use deterministic approaches. Moreover, different limit states are usually considered separately. This paper develops a probabilistic framework to assess the serviceability performance with the consideration of soil spatial variability in reliability analysis. Specifically, the performance of a drilled shaft is defined in terms of the vertical settlement, lateral deflection, and angular distortion at the top of the shaft, corresponding to three limit states in the reliability analysis. Failure is defined as the event that the displacements exceed the corresponding tolerable displacements. The spatial variability of soil properties is considered using random field modeling. To illustrate the proposed framework, this study assesses the reliability of each limit state and the system reliability of a numerical example of a drilled shaft. The results show the system reliability should be considered for the serviceability performance. The importance measures of the random variables indicate that the external loads, the performance criteria, the model errors of load transfer curves and soil strength parameter are the most important factors in reliability analysis. Moreover, it is shown that the correlation length and coefficient of variation of soil strength can exert significant impacts on the calculated failure probability.

1. Introduction

The presence of uncertainties in the resistance and loading is widely recognized in the analysis and design of geotechnical engineering systems. In allowable stress design (ASD), the uncertainties are simply lumped into a factor of safety (FS). A common criticism of the ASD approach is that ASD cannot provide a consistent measure of safety. In order to appropriately account for uncertainties and ensure the desired safety, the U.S. Federal Highway Administration has implemented load and resistance factor design (LRFD) [1]. In LRFD, the uncertainties are considered by using the load and resistance factors which are calibrated according to reliability theories. Practicing engineers select appropriate load and resistance factors based on the desired reliability level and the variability levels of limit state functions. Unfortunately, the LRFD approach handles the serviceability limit state deterministically, which leads to an inconsistency in the design for the strength and service performance. As noted in [2], currently serviceability limits are still considered using a conventional deterministic approach in most limit state design codes.

In an attempt to tackle the uncertainties in the serviceability limit state and to address those issues described above, a performance based design approach has been developed for pile foundations [3,4]. The performance of a pile is defined in terms of the displacements induced by external loads. Failure is defined as the event in which the displacements exceed the corresponding tolerable displacements. In the previous studies, the failure probability can be evaluated only for the individual limit states using the performance based design approach [3,4]. However, deep foundation systems are often subjected to combined axial and lateral loads. Therefore, it is desirable to develop a probabilistic approach for considering the system reliability with multiple failure modes.

In this paper, the serviceability performance of drilled shafts under combined lateral and axial loading is investigated using a reliability analysis. Drilled shafts are widely-used to resist axial and lateral loads. Note that the terms "pile" and "drilled shaft" will be used interchangeably in this paper. Under the loading, a drilled shaft typically has three distinctive displacements, that is, lateral deflection (δ), angular distortion (ψ), and axial movement (w) at the top of the shaft. To conduct a reliability analysis for each limit state (δ, ψ or w) and assess the system reliability, Monte Carlo

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simulation (MCS) is applied. Since there are various sources of uncertainties involved in the reliability analysis, an importance analysis is conducted to identify the sources of uncertainties that significantly affect the serviceability performance.

2. Reliability assessment

The failure (or unsatisfactory performance) event in this study is said to occur if the induced displacements at the top of the pile are greater than the corresponding allowable displacements. System failure in this study is defined as the event in which any of the individual failure modes occurs. Following the conventional notation in structural reliability theory [5], the probability of system failure, P_f, can be expressed by:

$$P_f = P\left(\underset{k}{\cup} g_k[C_k, D_k(\mathbf{x})] \leqslant 0\right) \tag{1}$$

where the subscript k represents a serviceability failure mode (i.e., $k = \delta$, ψ and w), $g_k(\cdot)$ refers to the kth limit state function, C_k represents the allowable displacement, D_k is the induced displacement due to the external loads, and $\mathbf{x} = (\mathbf{x}_r, \mathbf{x}_d)$ refer to the input variables (e.g., geometry and material properties) in which $\mathbf{x}_r$ are random variables and $\mathbf{x}_d$ are deterministic variables. In this study, the limit state function for the kth failure mode is defined as:

$$g_k = C_k - D_k(\mathbf{x}) \tag{2}$$

Using the probability of failure for the kth limit state ($P_{f,k}$), the corresponding reliability index, β_k, can be determined by

$$\beta_k = \Phi^{-1}(1 - P_{f,k}) = -\Phi^{-1}(P_{f,k}) \tag{3}$$

where $\Phi^{-1}(\cdot)$ is the inverse of the cumulative distribution function of the standard normal variable.

In this study, the induced displacement D_k is obtained through the analysis of drilled shafts subjected to axial and lateral loading where the load transfer methods (e.g., t–z model [6] and p–y method [7]) are applied to model the non-linear soil–pile interactions. The t–z model can be used to calculate the vertical movement where the axial soil–pile interaction is modeled as t–z curves and q–w curves, in which t and q represent side shear on the shaft and the tip resistance at the toe, respectively, and z and w represent the vertical displacements of the shaft segment and the toe of the drilled shaft, respectively. The p–y method can be used to calculate the lateral deflection and the angular distortion where the lateral soil–pile interaction is modeled as p–y curves, in which p represents the soil reaction and y represents the lateral deflection. The schematic diagrams of the t–z model for axial loads and the p–y method for lateral loads are shown in Figs. 1 and 2, respectively.

The reliability can be assessed using the MCS method such as to simulate various sources of prevailing uncertainties. In the MCS method, the probability of failure for the kth failure mode, $P_{f,k}$, is written as

$$P_{f,k} = \int I[g_k \leqslant 0] f(\mathbf{x}_r) d\mathbf{x}_r \approx \frac{1}{n}\sum_{i=1}^{n} I_i[g_k \leqslant 0] \tag{4}$$

where $I[\cdot]$ is an indicator function, $f(\cdot)$ is the joint probability density function of $\mathbf{x}_r$, and n is the number of simulations. As $n \to inf$, the estimator in Eq. (4) approaches its exact value. The advantage of using MCS is that it is mathematically simple and provides unbiased estimates of the failure probabilities. Furthermore, the accuracy of the probability estimate by MCS is not affected by the shape of the failure surface.

3. Importance measure

There are a number of random variables entering the limit state functions. The variations of some random variables would cause significant variations in the reliability index β of the designed drilled shaft, while the variations of other random variables only produce minimal variations in β. The former are classified as important while the latter are classified as less important or unimportant. It is instructive to identify the random variables that have maximum influences on the performance reliability. Thus, practicing engineers can pay more attention to the important random variables.

Importance measure can be used to identify the importance of random variables. According to [8], an importance measure $\boldsymbol{\kappa}$ is defined as follows

$$\boldsymbol{\kappa}^T = \frac{\boldsymbol{\alpha}^T \mathbf{J}_{u^*,x^*}\mathbf{B}}{\left\|\boldsymbol{\alpha}^T \mathbf{J}_{u^*,x^*}\mathbf{B}\right\|} \tag{5a}$$

$$\boldsymbol{\alpha} = -\frac{\nabla G(\mathbf{u})}{\|\nabla G(\mathbf{u})\|} \tag{5b}$$

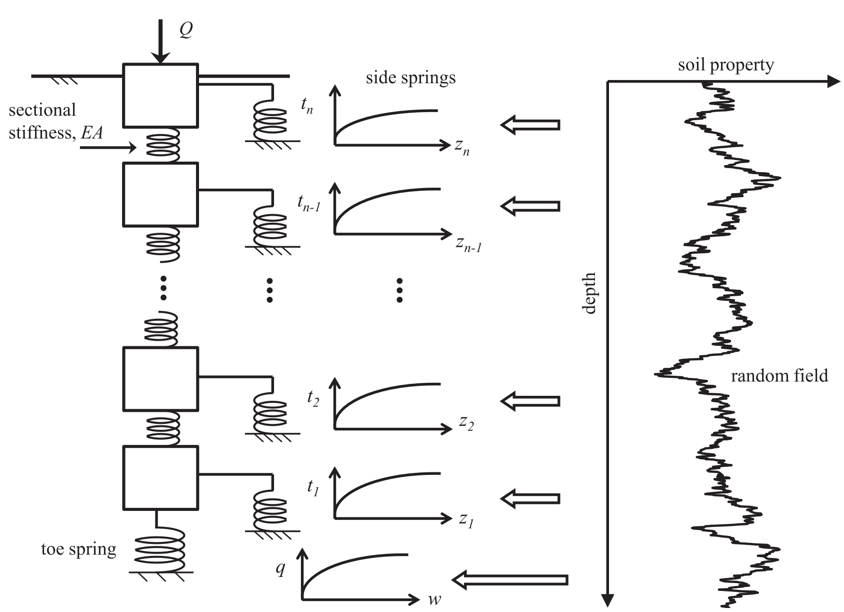

Fig. 1. t–z model for axial load.