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Probabilistic analysis of piled earth platform under concrete floor slab

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Abstract

This paper proposes a two-dimensional axisymmetric numerical modelling of an earth platform over a clayey sand improved by stiff vertical piles using a finite-difference continuum approach. The study focuses on the surface settlements and the stress efficacy of the improvement system. Only the soil parameters are considered as random variables and two assumptions (normal distribution or non-normal distribution) are used. The first-order reliability method (FORM) is applied to calculate the reliability index. Response surface methodology (RSM) allows for access to the Hasofer-Lind reliability index and is optimized by the use of a genetic algorithm. The Hasofer-Lind reliability index is calculated for two distinct cases. Firstly, only the geomechanical parameters of the clayey sand are considered as random variables; secondly, the parameters of both the clayey sand and the earth platform are considered. The results show that the reliability of a single soil layer is safer than the reliability of the whole system.

Keywords: Earth platform; Pile; FORM; Response surface reliability; Limit state; Genetic algorithm

1. Introduction

Civil engineers are aware of the important role uncertainty plays in designs. Unlike in structural designs, the traditional way that geotechnical engineers introduce uncertainties into their designs is by using a global safety factor. Thus, reliability methods have become rational alternatives for considering the effects of uncertainties in engineering designs. Designs based on reliability have been applied to geotechnical engineering by Kulhawy and Phoon (2002), Griffiths et al. (2002) and Mollon et al. (2009a,b, 2011, 2013).

Nowadays, the improvement method involving construction on soft soils improved with rigid piles and involving granular platforms is widely implemented throughout the world due to its low cost, speediness and the resulting small total and differential settlements compared to other traditional improvement methods such as grouting injection, vertical drains or preloading.

The reliability of pile foundations designed on the basis of soil tests depends mainly on the reliability of the calculation method used to evaluate the pile resistance and on the approach adopted for the spatial variability. A closed form of a lognormal reliability formula can be employed to calculate the reliability index of a pile foundation in cases where different sources of uncertainty related to the stiffness and the monitoring effects of the pile installation are met (Bauduin, 2003; Paikowsky, 2002). Studies on the numerical modelling of piled raft foundations, conducted to determine the influence of the soil variability on the soil-structure interaction model, were used by Niandou and Breysse (2006) and Amšiejus and Dirgelien (2007).

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The response surface method was adopted to determine an acceptable value for the bearing pressure.

Probabilistic approaches to multi-layered problems in geotechnical engineering were not often considered in literature. Recently, however, an important advance in slope reliability analyses using the RSM, the multiple response surface method, was proposed to evaluate the reliability of a slope stability system using a limit equilibrium method (LEM) to determine the FOS (Zhang et al., 2011; Ji and Low, 2012).

For the case of piled earth platforms, only deterministic numerical and experimental models can be found in literature. They often focus on a numerical modelling for evaluating the effects of the shearing mechanisms on the earth platforms (Jenck et al., 2009a,b; Hassen et al., 2009; Nunez et al., 2013; Girout et al., 2014; Briancon and Dias, 2015; Dias and Simon, 2015). Kempton et al. (1998), Nunez et al. (2007) and Jenck and Dias (2007) showed that a 2D plane strain numerical model cannot correctly simulate the behaviour of this 3D complex system. Other authors showed that an axisymmetric 2D numerical model can accurately represent the shearing mechanisms (Naughton and Kempton, 2005; Okyay and Dias, 2010). 3D numerical calculations of piled embankments, explicitly representing earth platforms and the improved soft soil, are recent and remain uncommon, as the models are time-consuming. This is most likely the reason why probabilistic studies have not yet been developed (Laurent et al., 2003).

In this article, a study on the reliability of a piled earth platform under a concrete floor slab at the serviceability limit state is presented. As for the deterministic model, a 2D axisymmetric model using FLAC 2D is employed. The serviceability limit state (SLS) is considered. In this study, the uncertain soil parameters are modelled by random variables. The reliability index of Hasofer-Lind's β_{HL} was adopted to calculate the reliability of the system. The calculation is performed with the response surface methodology (RSM) optimized by a genetic algorithm. The reliability index was calculated for two cases. In the first case, only the geomechanical parameters of the clayey sand (soft soil) are considered as random variables. Then, in the second case, the parameters of both the clayey sand and the earth platform are considered as random variables. The influence of the normal and the non-normal parameter distributions on the failure probability is studied.

2. Reliability analysis using FORM

2.1. Reliability index and FORM method

To show the influence of the uncertainty of the soil parameters, different methods have been proposed to assess the probability of failure. Among the most famous is the FORM method; it necessitates the mean value, the variance and a distribution type for each variable. The probability of failure is then estimated from the reliability index.

The β_{HL} reliability index was proposed by Hasofer and Lind (1974) for uncorrelated normal variables. For correlated normal variables, the index can be deduced by a geometric interpretation. The formulation of the matrix for the Hasofer-Lind index is expressed as follows (Hasofer and Lind, 1974; Ditlevsen, 1981):

$$\boldsymbol{\beta_{HL}} = \min_{\boldsymbol{x}\in \boldsymbol{F}} \sqrt{(\boldsymbol{x}-\boldsymbol{u})^{\boldsymbol{T}}(\boldsymbol{C})^{-1}(\boldsymbol{x}-\boldsymbol{u})} \quad (1)$$

where x is a vector representing the set of random variables, x_i, μ is the vector of mean values, C is the covariance matrix and F is the failure domain.

According to Eq. (1), the Hasofer–Lind index can be regarded as the minimum distance between the point of the mean values of the random variables and the performance function.

In this paper, the method of Low and Tang (2004) was used. These authors set up a tilted ellipsoid and used an optimization algorithm to minimize the dispersion ellipsoid. The concept of the iso-probability ellipsoid leads to a simpler calculation method for the reliability index in the original physical variable space (Fig. 1). They demonstrated that the Hasofer-Lind reliability index was equal to the ratio between the axes of the critical dispersion ellipsoid (that is to say, the smallest ellipsoid dispersion tangent to the boundary surface condition) and the ellipsoid in the unit dispersion (the one obtained for $\beta_{HL} = 1$ in Eq. (1), without minimization). They also demonstrated that finding the critical dispersion ellipsoid is equal to finding the most probable point of failure, namely, at the point of tangency between the ellipsoid and the limit state surface which is called the design point (Fig. 1). β_{HL} can then be expressed as follows (Low and Tang, 2004):

$$\boldsymbol{\beta_{HL}} = \min_{\boldsymbol{x}\in \boldsymbol{F}} \sqrt{\left[\frac{\boldsymbol{x}-\boldsymbol{\mu}_{\boldsymbol{x}}^{\boldsymbol{N}}}{\boldsymbol{\sigma}_{\boldsymbol{x}}^{\boldsymbol{N}}}\right]^{\boldsymbol{T}} [\boldsymbol{R}]^{-1} \left[\frac{\boldsymbol{x}-\boldsymbol{\mu}_{\boldsymbol{x}}^{\boldsymbol{N}}}{\boldsymbol{\sigma}_{\boldsymbol{x}}^{\boldsymbol{N}}}\right]} \quad (2)$$

in which $[R]^{-1}$ is the inverse of the correlation matrix. This equation will be used to set up the ellipsoid since the correlation matrix $[R]$ displays the correlation structure more explicitly than the covariance matrix $[C]$.

To extend the Hasofer-Lind method to the case of non-normal random variables, Rackwitz and Fiessler (1978) proposed transforming each non-normal random variable

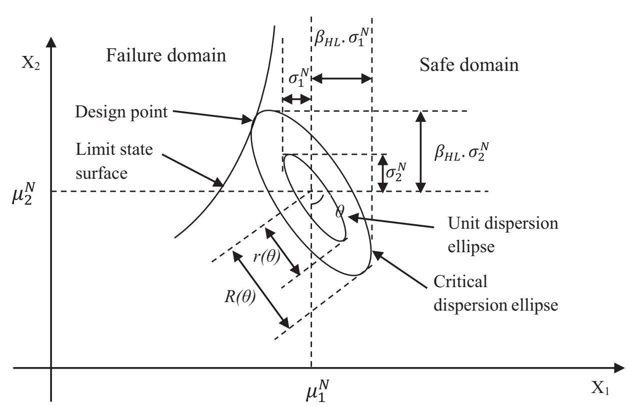

Fig. 1. Design point and equivalent normal dispersion ellipses in space of two random variables (example of 2D case).