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Reliability-based robust geotechnical design of spread foundations using multi-objective genetic algorithm

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ABSTRACT

This paper presents a new geotechnical design concept, called robust geotechnical design (RGD). The new design methodology seeks to achieve a certain level of design robustness, in addition to meeting safety and cost requirements. Here, a design is considered *robust* if the variation in the system response is insensitive to the variation of noise factors such as uncertain soil parameters and construction quality. When multiple objectives are considered, a single best design may not exist, and a trade-off may be necessary. In such a case, a genetic algorithm is adopted for multi-objective optimization and a Pareto Front, which describes a trade-off relationship between cost and robustness at a given safety level, is established. The new design methodology is illustrated with an example of spread foundation design. The significance of the RGD methodology is demonstrated.

1. Introduction

It is well recognized that uncertainty of soil parameters is usually unavoidable in the geotechnical design [1]. The uncertainty in the soil parameters, as well as the uncertainty in the adopted solution model, can lead to the uncertainty in the solution (e.g., predicted response or performance of a system). In a deterministic approach, the engineer uses factors of safety that have been "calibrated" by experience to cope with the uncertainty in the solution (i.e., predicted response). Of course, the factor of safety adopted in a particular design depends not only on the degree of uncertainties but also on the consequence of failure; in other words, it depends on the "calculated risk" [2,3]. To better deal with the uncertainties, the probabilistic or reliability-based approach that considers explicitly the uncertainties in the soil parameters and solution model has been proposed (e.g., [3–12]).

In a traditional geotechnical design, regardless of whether the deterministic approach or the probabilistic approach is adopted, the design is often based on a trail-and-error process considering safety and cost. Safety is usually checked first to ensure the candidate design satisfying the prescribed "safety" requirements (in terms of factor of safety or probability of failure). Then the design with the least cost is selected from the pool of all acceptable designs that have been screened based on safety requirements [13–15]. Thus, the reliability-based design is quite straightforward if the results of the reliability analysis are accurate and precise so that there will be no question whether a given design satisfies the safety requirement. The accuracy and precision of a reliability analysis, however, depends on how well the random soil parameters are characterized. If the knowledge of the statistical distribution of soil parameters is "perfect", the results of reliability analysis will be accurate and precise and the reliability-based design can be easily implemented with least cost objective constrained with a minimum reliability index requirement.

In a real-world geotechnical project, the distribution of a soil parameter is quite uncertain due to lack of data, measurement error, and/or error caused by use of empirical correlations. The variation range of geotechnical parameters is usually quite large [16] and thus the variation can be either overestimated or underestimated. Such overestimation or underestimation of the variation of soil parameters can lead to over-design or under-design.

While reduction of the uncertainty in soil parameters is important, which should be pursued whenever it is deemed cost-effective, in this paper, we focus on a different approach by achieving robustness in the design without eliminating the sources of uncertainty. Here, a design is considered *robust* if the variation in the system response is insensitive to (or robust against) the variation of uncertain soil parameters (called noise factors in this paper). The essence of a robust design is to select a design (through

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the adoption of a set of design parameters) that yields a minimal variation in the system response without eliminating the sources of uncertainty or reducing the level of uncertainty.

In this paper, a robust geotechnical design (RGD) methodology is proposed to fulfill the goal of minimizing the effects of the uncertainty of soil parameters. Robust design was originated from the field of Quality Engineering [17], which has been applied to many structural or mechanical problems in the last two decades [18–22]. One widely accepted definition of robust design [18] is manipulating design parameters (i.e., the so-called "easy to control" factors) so that the system response of the design is insensitive to, or robust against, the variation of noise factors (i.e., the so-called "hard to control" factors). In a geotechnical design, the noise factors are the uncertain soil parameters and other factors such as those related to construction. Thus, in a robust design, regions in the design space that yield low variation in the system response should be sought. The robust design will have an acceptable performance even with unexpected variation in soil parameters.

In this paper, the design of spread foundation is employed as an example to illustrate the robust design philosophy. In the sections that follow, a brief review of a reliability-based model for design of spread foundation [14] is first provided. Then, the RGD framework is presented with an illustrated example. It should be noted that the RGD methodology presented in this paper does not depend on the reliability-based procedure described by Wang [14]; rather, the latter is used for convenience in presenting a reliability-based RGD methodology.

It should be noted that robust geotechnical design (RGD) is not a design methodology to compete with the traditional approach such as the reliability-based design; rather, it is a design strategy to complement the traditional methods. With the RGD approach, the focus is to satisfy three design requirements, namely safety, cost, and robustness (against the variation in system response caused by noise factors). The safety requirement is usually implemented through constraints of reliability, and hence the design becomes a bi-objective optimization problem. For the bi-objective problem examined in this paper, it is possible that no single best solution exists that is most optimal with respect to both objectives (cost and robustness). In such a situation, a detailed study of the trade-offs between these objectives can lead to a more informed design decision.

2. Reliability-based design of spread foundation

A review of reliability based design of a spread foundation [14] based on the design example presented in an international workshop of Eurocode 7 [23,24] is provided herein. As illustrated in Fig. 1, a spread foundation is to be installed in a stiff till with a deterministic total unit weight of γ = 22 kN/m^3 and mean effective friction angle ϕ' of 36.4° (c' = 0). The spread foundation is designed to support a deterministic permanent load G = 900 kN and a random variable load component of Q. The weight of foundation is considered herein by assuming a unit weight of foundation (concrete) as γ_c = 24 kN/m^3. The foundation is founded at just above the ground water table with a foundation depth of D = 0.8 m. Other parameters regarding soil and loading properties are listed in Table 1. It should be noted that the assumed coefficient of variation (COV) of the coefficient of volume compressibility m_v is slightly different from the one assumed by Wang [14]. The typical range of COV of m_v is estimated by Orr and Breysse [24] to be 0.2–0.4, and thus a mean value of 0.3 for COV of m_v is selected in this example.

In Wang [14], the spread foundation is assumed to be square foundation and only footing width B is modeled as a design parameter. Furthermore, in Wang [14], the footing width B is assumed to vary from a minimum value of 1.0 m to a maximum value of 3.0 m with an increment of 0.1 m and thus, only 21 possible designs exist in the design pool. In this paper, both the footing width B and footing length L are considered as design parameters; and B and L are further assumed to vary from a minimum value of 1.0 m to a maximum value of 4.0 m with an increment of 0.1 m. Thus, the number of possible designs in the design pool is 961. For a typical rectangular footing, the range of the length-to-width ratio (L/B) is between 1 and 10 [25]. When screened with this geometry constraint ($1 \leqslant L/B \leqslant 10$), the design pool is reduced to 496 designs.

The procedure for calculating the ultimate limit state (ULS) and serviceability limit state (SLS) capacity of spread foundation proposed by Orr [23] and Orr and Breysse [24] is adopted herein for reliability-based design. The drained ULS capacity (R_{uls}) of spread foundation with a width B, length L, and Depth D can be calculated based on Annex D of Eurocode 7 [14,26] as follows:

$$R_{uls} = [(1/2)B(\gamma - \gamma_w)N_\gamma s_\gamma + \gamma D N_q s_q](BL) \tag{1}$$

where γ = unit weight of soil; γ_w = unit weight of water; N_γ and N_γ are bearing capacity factors and s_γ and s_q are shape factors, defined as follows:

$$N_\gamma = 2(N_q - 1)\tan\phi' \tag{2}$$

$$N_q = e^{\pi \tan\phi'} \tan^2(45 + \phi'/2) \tag{3}$$

$$s_\gamma = 1 - 0.3(B/L) \tag{4}$$

$$s_q = 1 + (B/L)\sin\phi' \tag{5}$$

The ULS failure is checked by comparing the bearing capacity (R_{uls}, as "resistance") with the applied loading $G + Q$. The condition,$R_{uls} < G + Q$, denotes ULS failure of the spread foundation. The SLS failure is checked by comparing the estimated total foundation settlement s_t with the maximum allowable settlement of 25 mm [24]. The total foundation settlement is constituted by two parts, the immediate settlement s_i and the consolidation settlement s_c. Determination of s_i is based on the equations given in Annex F.2 of Eurocode 7 [14,26]:

$$s_i = \frac{p(1 - \upsilon_u^2)Bf}{E_u} \tag{6}$$

where p is the net bearing pressure at the base level of the foundation; υ_u is the undrained Poisson's ratio (υ_u = 0.5); f is the settlement coefficient (f = 1.12 in this example as per Orr and Farrell [26]), E_u is the undrained Young's modulus for till, which is calculated as follows:

$$E_u = 750c_u \tag{7}$$

The consolidation settlement is determined by dividing the ground below the foundation into k layers of equal thickness and summing the settlement of each layer using the following equation [24]:

$$s_c = \mu \sum_{i=1}^{k} m_{vi} h_i \Delta\sigma'_i = \mu m_v h \sum_{i=1}^{k} \alpha_i p \tag{8}$$

where μ is the settlement reduction coefficient accounting for the fact that consolidation is not one-dimensional, which is determined as 0.55 for this example [27]; m_v is the coefficient of volume compressibility (m_v = 0.0015 m^2/MN); h is the thickness of each layer; $\Delta\sigma'_i$ is the increase of vertical effective in ith layer determined by $\alpha_i p$; α_i is the coefficient for increase of vertical effective stress in ith layer determined using following equation [28]:

$$\alpha_i = \frac{2}{\pi}\left[\tan^{-1}\frac{BL}{4z_i R_3} + \frac{BLz_i}{4R_3}\left(\frac{1}{R_1^2} + \frac{1}{R_2^2}\right)\right] \tag{9}$$