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Robust Geotechnical Design – A New Design Perspective
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Motivation and Research Objective
In routine geotechnical engineering practice, the engineer has to work with a small sample of data due to budget constraint. Because of complexity of soil deposits, it is often difficult to determine correctly the statistics of soil parameters that are required for reliability-based design of foundations. Furthermore, the traditional reliability-based design is sensitive to the variation of noise factors such as uncertain soil parameters. To address this dilemma, the authors present a new design methodology, termed Robust Geotechnical Design (RGD). The RGD aims to make the response of a geotechnical system immune to, or robust against, the variation of noise factors by carefully adjusting the design parameters. A multi-objective optimization is performed to identify designs that satisfy all the design requirements, safety, robustness, and cost efficiency.

Framework for Robust Geotechnical Design
The robust geotechnical design (RGD) methodology is outlined with three steps shown in Figure 1. Step 1 is to quantify the uncertainty in sample statistics and specify the design domain. Step 2 is to evaluate the variation of system response caused by uncertain sample statistics. Step 3 involves a multi-objective optimization to identify the Pareto Front. As shown in Figure 2, when conflicting objectives are enforced, it is likely that no single best design exists. However, a set of designs may exist that are superior to all other designs in all objectives; but within the set, none of them is superior to others in all objectives. This set of optimal designs constitutes a Pareto Front. In this paper, the Non-dominated Sorting Genetic Algorithm (NSGA-II) as shown in Figure 3 is used to establish the Pareto Front.

Design Example of Shallow Foundations
An example of shallow foundation design is used to illustrate the proposed RGD approach. A square foundation, as shown in Figure 4, is to be designed to support vertical compressive loads with a permanent component of G with a COV of 10% and a transient component of Q with a COV of 15%. The soil profile at the site is a homogeneous dry sand. Ten effective friction angles are obtained from triaxial tests conducted on samples of this homogeneous sand. The design parameters are the foundation width B and the embedment depth D. They are discretely distributed in the design domain. The ULS capacity adopts the Vesic model and SLS capacity adopts the method of normalized load-settlement curve.

Characterization of Uncertainty in Sample Statistics
With a small sample of only 10 data of effective friction angles, there is uncertainty concerning the mean and standard deviation derived from this sample. In this paper, bootstrapping technique shown in Figure 5 is applied to evaluate the uncertainty of the sample mean and standard deviation. The histograms of the sample mean and standard deviation of effective friction angles are obtained. As shown in Figure 6, COV of sample mean is estimated as 1.7% and COV of sample standard deviation is estimated as 13.9%. Similarly, the variation of the statistics of model parameters can also be obtained based on limited data from field load tests.

Traditional-Reliability-Based Geotechnical Design
For the shallow foundation example, if statistics of uncertain parameters are assumed with a fixed value (that is, taking only mean values of these statistics). The probability of SLS and ULS failure for each design is determined as shown in Figure 7. If the minimum cost is the only criteria for selecting the best design after screening with reliability requirements defined in Eurocode, then the design with $B = 1.9$ m and $D = 2.0$ m will be selected.

For the shallow foundation example, non-dominated designs are selected into the Pareto Front, as shown in Figure 10. It can be observed that there is an obvious trade-off relationship between cost and robustness. The obtained Pareto Front can be used as a design aid for the decision maker to select the best design based on the desired target cost or robustness level.

Conclusion

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