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Efficient and consistent reliability analysis of soil slope stability using both limit equilibrium analysis and finite element analysis

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ABSTRACT

Limit equilibrium methods (LEMs) and finite element methods (FEMs) of slope stability analysis can be used in computer-based probabilistic simulation approaches (e.g., direct Monte Carlo Simulation (MCS) and Subset Simulation (SS)) to evaluate the slope failure probability (P_f). For a given slope problem, the computational effort for the LEM is generally much less than that required for the FEM, but the FEM tends to give a more realistic prediction of slope failure mechanism and its associated factor of safety. To make use of the advantages of both the LEM (e.g., computationally more efficient) and FEM (e.g., theoretically more realistic and rigorous in terms of slope failure mechanisms), a new probabilistic simulation method is developed in the paper. The proposed approach combines both a simple LEM (i.e., Ordinary Method of Slices considering a limited number of potential slip surfaces) and FEM with the response conditioning method to efficiently calculate P_f of slope stability and to give an estimate of P_f consistent with that obtained from directly performing MCS and SS based on the FEM. It is illustrated through two soil slope examples. Results show that the proposed approach calculates the P_f properly at small probability levels (e.g., $P_f < 0.001$). More importantly, it significantly reduces the number of finite element analyses needed in the calculation, and therefore improves the computational efficiency at small probability levels that are of great interest in slope design practice. In addition, the proposed approach opens up the possibility that makes use of the information obtained using a simple model (e.g., LEM) to guide the reliability analysis based on a relatively sophisticated model (e.g., FEM).

1. Introduction

During the past few decades, several probabilistic simulation methods have been developed to evaluate the reliability (or failure probability, P_f) of slope stability, such as direct Monte Carlo Simulation (direct MCS) (e.g., [1–4]), importance sampling (e.g., [5]), and Subset Simulation (SS) (e.g., [6–8]). These methods involve repeatedly evaluating the safety margin of slope stability using a prescribed deterministic analysis method during the simulation, such as limit equilibrium methods (LEMs) (e.g., [1,5,6,9,10]) and finite element methods (FEMs) (e.g., [2,3,11,12]).

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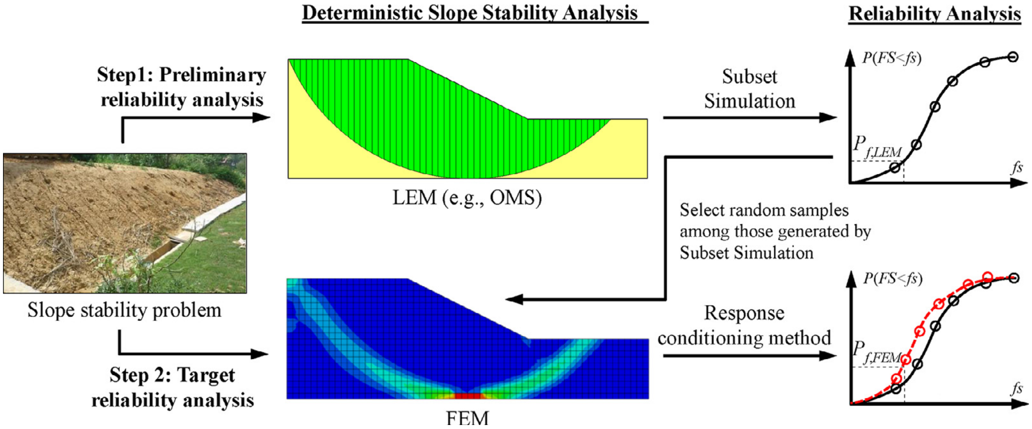

Fig. 1. Slope reliability analysis based on different deterministic analysis models.

LEMs (e.g., Ordinary Method of Slices (OMS), simplified Bishop's method, and Spencer's method) are widely used in slope engineering practice [13]. Compared with FEMs, LEMs are conceptually simple and require much less computational effort for slope stability analysis, particularly when OMS that has an explicit performance function is applied. However, as pointed out by Griffiths and Lane [14] and Griffiths et al. [2], LEMs need to assume the shape (e.g., circular) and location of slope failure surfaces in the analysis, which are rarely known prior to the analysis, particularly when spatial variability of soil properties is explicitly considered. Inappropriate assumptions on slope failure surfaces in LEMs might lead to negligence of the actual critical slope failure mechanism and, subsequently, result in the estimate of P_f inconsistent with that obtained using more rigorous slope stability analysis methods (e.g., FEMs) in simulation-based reliability analysis. FEMs provide a rigorous and versatile tool for slope stability analysis and alleviate assumptions on slope failure surfaces required in LEMs (e.g., [14,15]). However, FEM-based probabilistic simulation methods (e.g., random finite element method (RFEM)) are sometimes criticized for a lack of computational efficiency and requiring intensive computational power (e.g., [16–18]), particularly at small probability levels (e.g., $P_f < 0.001$). Then, an interesting question arises that how to make use of advantages of both LEMs (e.g., computationally more efficient) and FEMs (e.g., theoretically more realistic and rigorous in terms of the failure mechanism) in reliability analysis of slope stability so as to efficiently obtain consistent reliability estimates. Such a possibility has not been explored in geotechnical literature.

Note that it is not uncommon that there exist different deterministic analysis models/methods (e.g., LEMs and FEMs) for the same geotechnical problem (e.g., slope stability analysis). These methods can be applied in different design stages. For example, at the preliminary design stage, site information (e.g., soil properties) might be too limited to use a relatively sophisticated model (e.g., FEMs) in slope reliability analysis and risk assessment. In such a case, a relatively simple method (e.g., OMS) is an appropriate choice for evaluating slope failure probability and risk. As more site information is collected from site investigation and/or project construction, the understanding of site ground conditions improves, which may allow using a more sophisticated model (e.g., FEM) in slope reliability analysis to make risk-informed decisions. Such different analyses are separately performed at different design stages without interaction. This is somewhat wasted in the sense that the information obtained from the reliability analysis based on the simple model at the preliminary design stage does not inform the later design based on the sophisticated model.

This paper develops a new probabilistic simulation method for slope reliability analysis, which utilizes assets of both LEMs and FEMs in reliability analysis of slope stability to efficiently calculate P_f. The proposed approach provides an estimate of P_f consistent with that obtained by directly performing the finite element analysis of slope stability in probabilistic simulation, but significantly reduces the number of finite element analyses needed in the calculation. As shown in Fig. 1, the proposed approach consists of two major steps: (1) preliminary reliability analysis of slope stability based on SS and a simple LEM (e.g., OMS), which can be finished with practically negligible computational effort; and (2) target reliability analysis of slope stability based on the FEM. The information generated using the LEM in the first step is incorporated into the second step to facilitate the FEM-based slope reliability analysis through "response conditioning method (RCM)" [19]. The paper starts with the introduction of the preliminary reliability analysis of slope stability using SS and OMS, followed by the target reliability analysis based on RCM and FEM. Then, the implementation procedure of the proposed approach is presented and illustrated through two soil slope examples.

2. Preliminary reliability analysis of slope stability using a simple LEM and SS

OMS is one of the simplest LEMs and has an explicit performance function. This section aims to use OMS in SS to generate information on a slope problem concerned and to obtain a preliminary estimate $P_{f,LEM}$ of P_f. Herein, the subscript "*LEM*" indicates that the safety factor of slope stability is evaluated by the LEM during SS. The algorithm of SS and its implementation in reliability analysis of slope stability are provided in the following two subsections, respectively.