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Long embankment failure accounting for longitudinal spatial variation – A probabilistic study

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ABSTRACT

For long earth embankments or levees, it is of interest to investigate the slope failure mode in the longitudinal direction. However, this is less commonly discussed in comparison to the plane-strain failure mode. In this paper, the longitudinal failure mode of a long embankment consisting of homogeneous soils is examined. A probabilistic approach using the first-order reliability method (FORM) is adopted to consider the uncertainty of soil properties. In particular, the spatial variability of the undrained shear strength of the soil is modelled in the probabilistic analysis. Parametric studies are subsequently conducted to examine the influence of this soil characteristic on the failure mode of the long embankment.

1. Introduction

In earth slope stability analysis, the uncertainty of soil properties significantly influences the failure mode. A literature search shows that many recent publications have introduced various probabilistic methods for earth slope stability analysis to account for the uncertainty of soil properties. Most of the studies were based on plane strain analysis. A more rational study should be carried out using three-dimensional (3-D) analysis, as all slope failures are 3-D in reality. Three-dimensional earth slopes can be analysed deterministically using either the limit equilibrium method (LEM) of columns [1–5], which involves various assumptions about the inter-column forces and the locations/shapes of the sliding surface, or the strength-reduction finite element method (SRFEM) [6–10]. The 3-D strength-reduction FEM is simpler in concept and does not involve assumptions about the failure zone.

Extension of the deterministic 3-D stability analysis to a probabilistic treatment has been recently performed. The pioneering work by Vanmarcke [11–13] showed that the spatial variability of soils would significantly influence the 3-D failure mode. The random finite element method (RFEM) has recently been developed for the probabilistic study of 3-D earth slopes [14–16]. It was shown that the length of the slope in the out-of-plane direction affects the performance of 3-D stability. These probabilistic finite element stability analyses were carried out by Monte Carlo simulations. As a result, they all yielded system failure probability but did not reveal the local failure mode or the critical failure width, as rightly noted by Vanmarcke [11].

This study aims at investigating the 3-D failure mechanism by probabilistic analysis. Using an improved algorithm for the first-order reliability method (FORM), the design point subjected to implicit limit state surface (involved in the 3-D failure mechanism by the strength-reduction factor of safety analysis) can be directly obtained in the space of the original random variables, and the probabilistic critical failure mode of a long earth embankment is vividly illustrated. The probabilistic analysis accounts for the out-of-plane spatial variability of the undrained shear strength of soils.

2. Deterministic stability analysis of a long embankment and its shortcomings

Consider a section of long embankment consisting of homogeneous soils, as shown in Fig. 1. The height of the slope, H, is 5 m, with a foundation depth, D, of 2 m. The undrained shear strength, c_u, is 25 kPa for the homogeneous soil. In this study, the longitudinal failure mode will be first investigated using a deterministic approach. The strength reduction method (SRM) will be adopted for the stability analysis. The elastic-perfectly plastic constitutive model with the Mohr–Coulomb failure criterion is used. As such,

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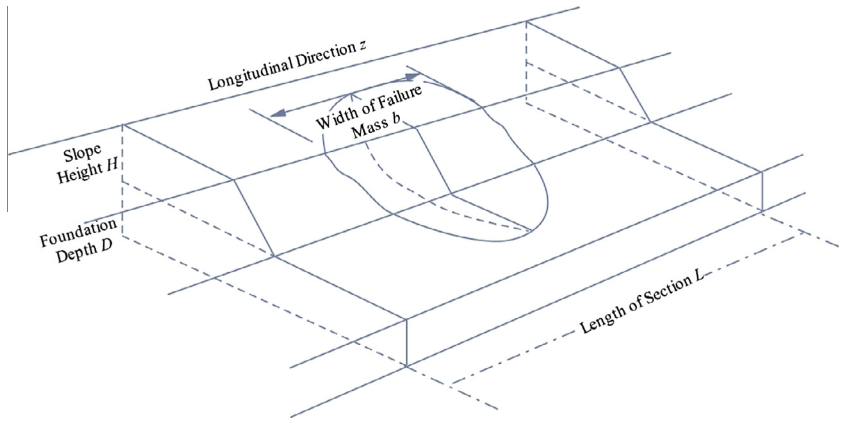

Fig. 1. Simplified geometry of the slope failure of a long embankment.

the elastic modulus, E, and Poisson's ratio, v, are required, and they are assumed to be 8 MPa and 0.495 (undrained analysis), respectively, which are typical for clay soils. It is noted that the factor of safety, *FoS*, by SRM is seldom affected by E or v [17,18].

The commercial software FLAC3D version 3.1 (finite difference method) is employed to compute the *FoS*. To determine the critical *FoS*, FLAC3D uses the non-convergence failure criterion (unique to factor of safety analysis, not to be confused with the Mohr–Coulomb failure criterion). For each step of strength reduction, the FLAC3D computes the total out-of-balance force; at a calculation step where the computed total out-of-balance force cannot converge to a prescribed small limit, e.g., 1×10^{-5} by default, the reduction factor is taken to be the critical *FoS*.

For FEM or finite difference method (FDM) stability analysis of the embankment section, the end-section boundary conditions should be applied properly because 3-D failure could be very sensitive to these conditions [19]. Most conventional deterministic FEM/FDM stability analyses adopt fixed end-section boundary conditions (displacements are fully fixed in all three dimensions at the two end sections) to model the 3-D failure mode. As the deterministic modelling involves homogeneous material and symmetric geometry, symmetric analysis is used where appropriate to reduce the computational effort. Fig. 2 shows the typical failure modes (in terms of nominal incremental displacements at the failure) of long embankments subjected to such boundary conditions. It is found that the failure mass tends to reach the predefined end-section. The *FoS* consistently decreases as the length of the embankment section increases in the longitudinal direction. This finding is similar to the 3-D analysis by many others using either the limit equilibrium method [3] or the finite element strength reduction method [20].

One question arising from the use of fixed end-section boundary conditions is whether the 3-D failure is a consequence of real slope behaviour or is due to the fixed end-section boundary conditions applied. In contrast, considering the fact that the section is taken from a long embankment, smooth end-section boundary conditions (i.e., zero displacement in the longitudinal/out-of-plane direction and unrestrained otherwise) will be more appropriate when studying the 3-D failure mode. The smooth end-section boundary conditions will be used in the subsequent study unless stated otherwise. Fig. 3 shows a typical embankment failure mode under this assumption. Obviously, it is equivalent to plane-strain analysis, and no 3-D failure mode is observed. Additionally, the computed F_{3D} is 1.58, which is the same as the plane strain *FoS*.

From the above comparison, it is concluded that the 3-D failure mode of the long embankment is merely an artificial phenomenon produced by the end-section boundary conditions applied in the deterministic analysis. In fact, most deterministic 3-D stability analyses implicitly impose fixed end-section boundary conditions. Otherwise, it is impossible to model the 3-D failure mechanism unless weak zones exist that can produce a 3-D failure. Moreover, because the deterministic 3-D failure mode is extremely dependent on the pre-defined length of the embankment section, it is difficult to investigate the most critical longitudinal failure mechanism of a long embankment. To overcome these shortcomings of the deterministic analysis, a more reasonable study using probabilistic methods that take into account soil uncertainty and spatial variability is introduced in the following sections.

3. Probabilistic study of long earth slopes by the strength reduction method

3.1. Modelling longitudinal spatial variation using the spatial-autocorrelation approach

Consider again the long embankment. The undrained shear strength, c_u, is treated as a Gaussian random field (with a coefficient of variation of 0.25); the uncertainty of other geotechnical parameters and the model uncertainty are excluded from this study. Note that the discretisation for the Gaussian random field is unbiased, whereas, for a Non-Gaussian random field, there are still some limitations [21–23]). Alternately, a Gaussian random field inevitably encounters negative sampling data (in Monte Carlo simulations), which is not suitable for geotechnical parameters. This limitation can be overcome by limiting the sampling data by the Three-Sigma rule [24], for most geotechnical problems. The spatial-autocorrelation approach is a simple but robust method to discretise the random field of geotechnical variables in probabilistic analysis [25–27]. In terms of the longitudinal random field of c_u for the long earth embankment, the c_{ui} values at discrete (control) points are treated as spatially correlated random variables subjected to a correlation function, given by Eq. (1):

$$\rho\{c_{ui}, c_{uj}\} = e^{-|z_i - z_j|/\delta_z} \tag{1}$$

where z_i and z_j are the z-coordinates of the control points or discrete points i and j, respectively; δ_z is the autocorrelation distance in the longitudinal direction. For the random field of c_u, δ_z usually varies between 5 and 40 m [28–31]. The c_u values at other non-control points within the random field are linearly interpolated from these spatially correlated control-point random variables.

In the previous deterministic modelling of the embankment, numerical simulations were only performed on the right side of the 3-D model due to the symmetries of both the slope geometry and soil properties over the longitudinal direction. However, such symmetries are not applicable for probabilistic analysis when