Finite deformation analysis of liquefaction-induced flow failure in soil embankments

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Summary

A finite element formulation is proposed for finite deformation dynamic analysis of saturated soil systems. The formulation is based on an updated Lagrangian approach and specifically considers the finite deformation effects on the flow of water through a soil element which undergoes a large deformation or rotation. A two-surface plasticity model is used to model the stress-strain behaviour of the soil skeleton. The proposed formulation has been implemented and is applied to simulate the response of a centrifuge model embankment. The calculated response is in good agreement with the observed behaviour of the soil embankment in the centrifuge test.

Keywords: Deformation, finite element, liquefaction, large strain, embankments

Introduction

Liquefaction-induced flow failure is one of the most dramatic consequences of liquefaction that has been observed in many parts of the world. Such a failure may cause significant lateral spreading in the case of mildly sloping ground, and it may cause flow slides and slope instability in the soil embankments containing liquefiable soils (Seed, 1987). The significance of flow failure and lateral spreading phenomena has long been recognized and many investigators have attempted to characterize liquefiable soils and to evaluate the potential of these soils to undergo permanent deformations due to earthquake shaking. Compiling the results of many laboratory and field observations, Ishihara (1993) has suggested empirical relationships in order to distinguish 'flow' and 'no-flow' conditions in sandy soils that are susceptible to soil liquefaction. Based on a large number of case studies, Bartlett and Youd (1992) established empirical correlations between in situ properties of the soil (such as those obtained from CPT and SPT measurements) and permanent deformations after a flow failure occurs. This type of correlation is very useful for a quick and rough estimate of the permanent deformations that are likely to occur during severe ground shaking in ground containing liquefiable soils.

In addition to the study of field results, some investigators have attempted to simulate...
the flow failure phenomenon in the laboratory and to investigate the mechanisms involved in this phenomenon under controlled boundary conditions. One of the first successful pieces of work was reported by Arulanandan et al. (1988) who modelled a two-layered soil embankment (a sandy core overlain by a layer of clay) in the centrifuge. They showed that due to significant excess pore water pressure developed in the sandy core, the clay layer that rested on top of it slid and flowed off towards the toes of the embankment. A similar experiment, but using a different soil for the top layer (silt instead of clay), has recently been repeated in the course of a comprehensive centrifuge study (Arulanandan et al., 1993) and has confirmed this mechanism of flow.

In the realm of computational soil mechanics, many investigators have analysed the geotechnical problems involving soil liquefaction as a special class of boundary value problems in soil dynamics where the use of a nonlinear soil model is critical in obtaining meaningful results (Ghaboussi and Dikmen, 1978; Zienkiewicz et al., 1978). In these investigations, Biot’s formulation (Biot, 1962; Zienkiewicz and Shiomi, 1984) has often been used in combination with a suitable plasticity model (e.g. Zienkiewicz et al., 1990; Arulanandan and Scott, 1993, 1994). A state-of-the-art review of the current analytical methods available for soil liquefaction analysis is given by Smith (1994). The problem of large deformations occurring due to liquefaction, however, has not been investigated thoroughly. Some investigators have studied the finite deformation of consolidating soils due to static loading (e.g. Carter et al., 1977; Prevost, 1982), but theoretical developments and applications related to finite deformation analysis of soil structures containing liquefiable soils are scarce (Zienkiewicz et al., 1990).

This paper presents a finite element formulation and numerical technique to analyse finite deformations due to liquefaction-induced flow failure in soil structures. Comparing the results of numerical simulations to the observed behaviour of a centrifuge experiment, it will be shown that the formulation is capable of capturing subtle features of large deformations occurring in a flow-slide phenomenon.

The governing equations and boundary conditions

For a saturated earthen structure which occupies an initial volume \( V \) with the boundary surface \( S \) at time 0, it is assumed that specified displacements, surface traction, pore water pressure, or water-flow boundary conditions are defined on different portions of the boundary surface \( S \) at a generic time \( t + \Delta t \). These portions of the boundary surface are named \( S_u, S_T, S_p, \) and \( S_q \), respectively. In order to deal with nonlinearities involved in the problem, an incremental analysis is adopted and the equilibrium position at time \( t + \Delta t \) is searched assuming that the solutions for all time steps from time 0 to time \( t \) are known. We adopt a Lagrangian (material) formulation and follow the material points in their motion. Therefore, in a generic time step from time \( t \) to time \( t + \Delta t \), it is assumed that the initial configuration of the soil body \( \mathbf{0} \) and the configuration at time \( t \) \( \mathbf{t} \) are known and we are searching for the configuration of structure at time \( t + \Delta t \). In the process of deformation from the initial configuration at time 0 to the configuration at time \( t \), coordinates of a generic material point with respect to a fixed Cartesian coordinate system change from \( (0x_1, 0x_2, 0x_3) \) to \( (t_1x_1, t_2x_2, t_3x_3) \), where the left superscripts refer to the configuration of body and the subscripts refer to different axes of the Cartesian coordinate system.