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Deformation and localization analysis of partially saturated soil

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Abstract

Deformation and localization analysis is a crucial issue and has thus been intensively investigated in the last decades. However, in contrast to solid mechanical problems, geotechnical applications do not only concern a single solid material, the soil, but they also affect the pore-fluids, water and air, and, consequently, the coupling of the solid deformation with the pore-fluid flow. As a result, both the deformation and the localization analysis must be applied to a triphasic material consisting of the soil skeleton, the pore-water and the pore-gas, which, in geotechnical engineering, is known as unsaturated or partially saturated soil. Based on a continuum mechanical approach, unsaturated soil can be described within the well-founded framework of the Theory of Porous Media (TPM), thus including saturated soil (solid matrix and pore-water) as well as empty soil (solid matrix and pore-gas) as special cases.

It is the goal of the present contribution to investigate the deformation and the localization behavior of unsaturated soil and to exhibit the influence of the solid–fluid coupling on the localization analysis. In the framework of a triphasic formulation, unsaturated soil is considered as a materially incompressible elasto-plastic or elasto-viscoplastic skeleton saturated by two viscous pore-fluids, a materially incompressible pore-liquid and a materially compressible pore-gas. Assuming quasi-static situations, the numerical computations proceed from weak formulations of the momentum balance of the overall triphasic material together with the mass balance equations of the pore-fluids and Darcy-like relations for the seepage velocities. As a result, a system of strongly coupled differential-algebraic equations (DAE) occurs, which is solved by use of the FE tool PANDAS. In particular, various initial boundary-value problems are treated on the basis of time- and space-adaptive methods, thus demonstrating the efficiency of the overall formulation. Furthermore, the influence of the pore-gas constituent on the material behavior of partially saturated soil is studied with respect to fluid-flow simulations or embankment and slope failure problems.

Keywords: Theory of Porous Media (TPM); Triphasic material; Solid elasto-plasticity; Viscous pore-fluids; Deformation and localization analysis; Adaptive computations

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1. Introduction

In geotechnical engineering, there is a rapidly growing interest in the coupled analysis of the soil deformation and the pore-fluid flow. To set an example, it is evident that dykes or embankments, which are built to protect the environment from the elements of water, are generally loaded by gravitation and by a water table on one side. As a consequence, one observes both the deformation of the porous embankment structure and a flow process of the pore-content, water and air, cf. Fig. 1. Furthermore, if the water table rises or decreases rapidly driven, e.g., by natural hazards, stability problems occur, which are initiated by the localization of plastic solid deformations in narrow bands (shear bands). In order to correctly predict the overall behavior of such constructions, it is necessary to carefully investigate the coupled solid–fluid behavior of a biphasic material (solid matrix and pore-liquid) or of a triphasic material (solid matrix, pore-liquid and pore-gas). In the triphasic case, which is of course more general and contains the "saturated" material (solid matrix and pore-liquid) or the "empty" material (solid matrix and pore-gas) as special cases, a partially saturated porous solid material is considered and described within the well-founded Theory of Porous Media (TPM). Concerning the general TPM approach, the reader is referred, e.g., to the work by Truesdell and Toupin [1], Bowen [2], de Boer [3] or Ehlers [4,5]. In the present contribution, the triphasic material under consideration is assumed to consist of a materially incompressible, elasto-plastic or elasto-viscoplastic, cohesive-frictional solid skeleton saturated by two viscous fluids, a materially incompressible pore-liquid (water) and a materially compressible pore-gas (air).

Concerning the localization analysis of solids as well as of multiphasic materials, it is well known that the computation of shear band localizations generally leads to a mathematically ill-posed problem that has to be regularized by means of additional assumptions as, e.g., the consideration of additional kinematical degrees of freedom in the sense of a micropolar continuum [6–9], by the assumption of viscoplastic skeleton behavior [10–12] or by proceeding from further techniques like the consideration of gradient plasticity models [13] or of non-local approaches [14].

With regard to the organization of the following contribution, there is firstly the triphasic material for the description of partially saturated soil presented in Section 2. Therein, proceeding from a geometrically linear framework of the solid deformation, the soil matrix is considered as a cohesive-frictional material governed by a general elasto-viscoplastic description of the solid stresses based on a Hookean type elasticity law and a single-surface yield criterion [15] together with an additional plastic potential function in order to catch the non-associativity of the plastic behavior of geomaterials. Viscoplasticity is not only a convenient tool for the regularization of the shear band problem, but it also represents the basic matrix behavior of typical embankment materials like clayey silt. Furthermore, it additionally allows for a simple transfer to geomaterials plasticity. Concerning the pore-fluids, the effective pressure of the materially incompressible liquid acts as a Lagrangean, whereas the effective gas pressure is assumed to be governed by the ideal gas law. The interaction between the constituents, solid matrix, liquid and gas, is taken into consideration by additional constitutive relations for the momentum production terms, thus leading to Darcy-like relations for the seepage velocities. Finally, the fluids interact by a capillary-pressure-saturation relation based on relative permeabilities to consider the mutually interacting pore-fluid mobilities. In Section 3, the numerical

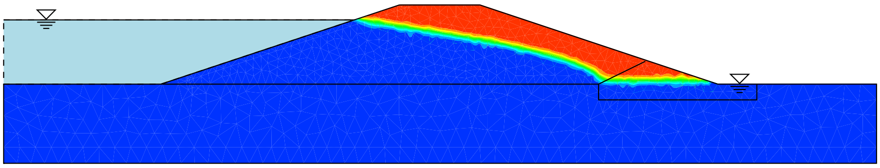

Fig. 1. Pore-liquid distribution in an embankment.