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The dynamic response of fluid-saturated porous materials with application to seismically induced soil liquefaction

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ABSTRACT

The numerical simulation of liquefaction phenomena in fluid-saturated porous materials within a continuum-mechanical framework is the aim of this contribution. This is achieved by exploiting the Theory of Porous Media (TPM) together with thermodynamically consistent elasto-viscoplastic constitutive laws. Additionally, the Finite Element Method (FEM) besides monolithic time-stepping schemes is used for the numerical treatment of the arising coupled multi-field problem. Within an isothermal and geometrically linear framework, the focus is on fully saturated biphasic materials with incompressible and immiscible phases. Thus, one is concerned with the class of volumetrically coupled problems involving a potentially strong coupling of the solid and fluid momentum balance equations and the algebraic incompressibility constraint. Applying the suggested material model, two important liquefaction-related incidents in porous media dynamics, namely the flow liquefaction and the cyclic mobility, are addressed, and a seismic soil–structure interaction problem to reveal the aforementioned two behaviors in saturated soils is introduced.

1. Introduction

The tendency of saturated porous materials to liquefy under the impact of dynamic loading is of a great importance especially in the fields of geomechanics, coastal engineering and seismology. As examples, consider the hazardous impacts of the seismically-induced liquefaction in offshore areas and near bodies of water or the wave-induced soil liquefaction under and around marine structures.

For the theoretical description of different physical phenomena in porous materials, the use of multiphasic continuum mechanics is a standard practice. In this regard, when biphasic porous media like water-saturated soils are concerned, the Theory of Porous Media (TPM) is proven to provide a comprehensive and elaborated macroscopic modeling framework. Thereby, fluid-saturated materials are treated as multiphasic aggregates consisting of solid and fluid constituents, which, independent of their usually unknown microtopology, are assumed to be in a state of ideal disarrangement over a representative elementary volume (REV). Applying a homogenization process to the REV yields a smeared-out averaged continuum model with overlapped, statistically distributed and interacting solid–fluid aggregates. This way of treating multiphasic porous materials can be traced back to the Theory of Mixtures (TM), cf. Bowen [8] or Truesdell and Toupin [76], where the TM was extended later by the concept of volume fractions to additionally incorporate information about the local composition of the homogenized continuum (cf. Goodman and Cowin [39]), which is fundamental to the TPM. This approach has been employed by Drumheller [24] to describe an empty porous solid. Bowen [9,10] extended this study to fluid-saturated porous media considering compressible as well as incompressible constituents. Subsequent developments of the TPM are mainly related to geomechanical investigations and have substantially been contributed by the works of de Boer and Ehlers, see [16,31,30] for detailed references.

Another popular macroscopic approach to model porous materials, which is based on a generalization of the theory of elasticity, is Biot's Theory (BT) introduced in the early works of Biot [5,6]. In fact, the BT and the TPM share a number of important features and yield the same results in particular cases. However, two intrinsic differences between them are important to be mentioned: first, unlike the TPM, the BT does not require that the constitutive laws fulfill the thermodynamic constraints. Second, BT treats sealed pores as a part of the solid phase, whereas the TPM assumes that all pores are interconnected. This leads to differences in the definition of constituent volume fractions and the partial densities, see, e.g., Schanz and Diebels [71] or Steeb [74] for quantitative and

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detailed comparisons between the two mentioned approaches. In the literature, BT, the TM, and the TPM are considered as the bases of many works in the modeling of porous media dynamics, see Zienkiewicz et al. [78,79], Diebels and Ehlers [22], Lewis and Schrefler [54], Breuer [11] and Coussy [14] among others.

In the current treatment of fluid-saturated biphasic aggregates, the compressibility of the solid constituent is neglected in favor of the solid matrix compressibility. The pore fluid is also considered materially incompressible and the degree of saturation is 100%. This choice helps to concentrate on the aim of this paper in showing the ability of the considered constitutive model to capture different liquefaction-conjugate soil behaviors, such as the shear strength reduction, the development of the plastic volumetric strain and the accumulation of the pore pressure, and not to simulating a particular soil taken from a construction site. For real problems, choosing an incompressible pore fluid could overestimate the accumulated pore pressure as given in, e.g., Magda [56] or Okamura and Soga [66]. Moreover, this choice has impacts on the structure of the governing balance relations of biphasic porous materials. Considering a compressible pore fluid, a constitutive evolution equation for the pressure variable exists yielding a coupled system of ordinary differential equations (ODE). For a materially incompressible pore fluid, the time derivative of the pore pressure vanishes and the governing equations turn to be differential-algebraic equations (DAE) with singular generalized mass matrix, which can only be solved using special time integration schemes, see Markert et al. [61] or Zienkiewicz et al. [79] for a detailed discussion.

In talking about the response of structures founded on saturated soils, foundation soil affects the structural behavior during dynamic excitation (e.g., due to earthquakes) in two significant ways: by transmitting the ground motion in a form of applied dynamic loadings (a wave propagation problem), and by imposing permanent deformations caused by collapse of the underlying soils (a soil liquefaction problem). The response of the soil skeleton for the modeling of dynamic wave propagation is usually considered linear elastic and is governed by the Hookean elasticity law. In this regard, three apparent types of bulk waves are generally expected to propagate in a saturated porous medium: (1) The fast and weakly damped compressional waves (p1) with an in-phase motion of the solid and fluid constituents. The appearance of this type of waves is mainly governed by the compressibility of the constituents, which in the case of the materially incompressible two-phase model yields a theoretically infinite propagation speed. (2) The slow (p2 or Biot) longitudinal waves with out-of-phase motion of solid and fluid. In the case of a materially incompressible pore fluid, the appearance of the p2-wave is mainly governed by the deformability of the solid skeleton. (3) The transverse shear waves (s) are transmitted only in the solid skeleton and are mainly governed by its shear stiffness. For more details, we refer to the works of Biot [6,7], Heider et al. [47], Markert et al. [61] and Steeb et al. [75] among others.

For simulation of liquefaction events in saturated porous materials, the solid constituent response is treated in this work within an elasto-viscoplastic framework. This comprises the implementation of a hyperelastic model for the nonlinear elastic solid behavior (cf. Ehlers and Avci [32], Müllerschon [63] and Scholz [73]), and also the application of the single-surface yield function of Ehlers [28,29] for capturing the plastic response. The viscosity in this model is mainly added to the elasto-plasticity treatment in order to improve the numerical stability of strain-localization problems and to reduce the mesh-dependency of the solution. In this, the viscosity parameters of sandy soils, which could be obtained from evaluation of experimental tests, are usually not sufficient to attain the aim of regularized solutions, and thus, higher viscosity parameters are used in the numerical simulations, see, e.g. di Prisco and Imposimato [21] and Scholz [73] for more details.

The definitions and terminology of liquefaction-related phenomena are based on important publications in the fields of computational geomechanics and earthquake engineering such as the works by Castro [13], Ishihara et al. [49], Verdugo and Ishihara [77], Zienkiewicz et al. [79], Kramer and Elgamal [52] and de Groot et al. [20]. In this connection, liquefaction in saturated biphasic media is characterized by accumulation of the pore-fluid pressure and softening of the solid granular structure. Such behavior comprises a number of physical events such as the 'flow liquefaction' that appears in loose cohesionless soils and the 'cyclic mobility' that usually occurs in medium-dense to dense cohesionless soils, see Section 5 for details.

In the literature, a number of constitutive models have been devoted to simulate the response of granular materials under shear stress, which leads to volumetric strains under drained conditions and a build-up of the pore-fluid pressure under undrained conditions. In the realm of the plasticity theory and within the critical state framework, the Cam-Clay model [70] and the modified version of it are eligible to capture different liquefaction-conjugate soil behaviors. The complex and eventually anisotropic response of porous materials under dynamic loading required the development of more advanced material models. As examples, consider the bounding surface model (see, [55]) and the two-surface plasticity model as discussed in Manzari and Dafalias [58].

Another approach to soil liquefaction modeling, which is mainly based on phenomenological observations, is the densification model, cf., e.g. Zienkiewicz et al. [80,79] and Pastor et al. [67]. With this model and its modifications the densification of soil under cyclic loading, which leads to build-up of the pore-water pressure under undrained conditions, can be simulated. In this case, it is necessary to distinguish between the loading and the unloading stages, as well as to define a damage parameter to capture the dilatancy of soil. Besides the densification model, the relatively recent theory of hypoplasticity shows an increase in popularity in the field of soil dynamics modeling among other fields of geomechanics. The hypoplasticity is an incrementally nonlinear material model, which does not require the existence of a yield surface or the distinction between elastic and plastic strain increments. For details about this theory and its empirical extensions, see, e.g., Kolymbas [51] and Niemunis [64].

To give a brief overview of the topics in this paper, Section 2 describes the basics of the Theory of Porous Media, the concept of volume fractions, the kinematics of multiphasic continua as well as the governing balance relations. In Section 3, thermodynamically consistent constitutive laws, which are able to describe various behaviors of the biphasic porous material, are presented. This includes the introduction of the nonlinear hyperelastic and the viscoplastic material models. Section 4 is concerned with the numerical treatment of the coupled problem, including the derivation of the weak formulation as well as the spatial and temporal discretization. Section 5 focuses on the investigation of liquefaction phenomena in saturated granular materials. In this, the basic features of liquefaction events like the pore-pressure build-up and the softening of the granular structure are figured out using a well-formulated elasto-viscoplastic constitutive model with isotropic hardening. A number of important factors that affect the response of saturated porous media, such as the loading rate and the boundary drainage, are discussed on the basis of a canonical initial-boundary-value problem (IBVP) in Section 6. The discussed constitutive formulations and schemes are applied in Section 7 to solve a realistic soil–structure interaction problem, which helps to illustrate the occurrence of seismically induced liquefaction events. Finally, Section 8 gives a brief summary and conclusions of the presented research work.