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Failure of fluid-saturated granular materials: a unified approach to capture diffuse and localized instability mechanisms

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Granular materials are susceptible to a wide variety of failure and deformation mechanisms, especially because of their interaction with the pore fluids and the surrounding environment. An adequate modeling of their mechanical response is therefore essential for understanding a number of geological processes, such as the onset of rapid landslides, hillslope denudation and sediment transport, or even the mechanics of fault gauges. Depending on the type of material, the groundwater conditions and the surrounding kinematic constraints, both diffuse and localized mechanisms are possible, and these may occur under either drained or undrained conditions. In the geomechanics literature, failure modes are usually explained and modeled with the tools of continuum mechanics, such as the mathematical theory of plasticity. Due to the complexity of granular material behavior, however, most classical models for frictional strength are unable to capture the variety of instability mechanisms observed for such class of geomaterials (e.g., liquefaction, shear banding, etc.). Sophisticated strain-hardening plasticity models are therefore required for numerical modeling purposes, thus making the evaluation of critical failure conditions less straightforward than in perfect plasticity theories.

Here we propose a mathematical strategy that can be adapted to any elastoplastic model and allows the onset of failure in elastoplastic geomaterials to be expressed in a more general manner. More specifically, our theory expresses the failure conditions as a function of local kinematics and solid-fluid interactions. The stability criterion used in this study is based on the so-called stability modulus, a scalar index of failure that was formulated by linking the physical concept controllability to the mathematical notion of plastic admissibility upon an incremental loading path [Buscarnera et al, 2011]. In this contribution, different loading constraints are considered, accounting for the possible occurrence of diffuse and localized failure mechanisms. While the mathematical strategy to calculate the failure indices is discussed in a general manner, a particular application is presented, focused on the simulation of the mechanical response of loose, saturated sands. Failure mechanisms are simulated under axisymmetric, plane-strain and simple shear conditions. For each of these cases, the indices are used to infer whether a failure mode is more likely to occur in a localized or homogeneous manner. At this reference, the role of drainage conditions is specifically explored. The results of numerical analyses are compared to data from classical experiments available in the literature. Finally, the theory is used to explain the mechanisms of failure that may have provoked a series of underwater flow failures in the shallow sand veneers located along the banks of the Jamuna River, in Bangladesh [Hight et al, 1998]

The analyses conducted in this work elucidate the remarkable dependence of geomaterial stability on both kinematic conditions and pore-fluid constraints. In particular, the links between generalized failure mechanisms and the onset of landslides has been elucidated through numerical simulations. The results obtained by our analyses therefore provide a simple and consistent strategy to unify the mathematical description of the material instabilities that are involved in a variety of failure mechanisms of geological settings.

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