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Dynamically induced spatial variations of pore pressure and the meaning of Terzhagi's effective stress

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Terzaghi's principle of effective stress [1] states that deformation and shear resistance of fluid-saturated porous and granular material are the result of changes in the effective stress, which is a linear combination of the externally applied confining stress and the internal pressure of the pore fluid. The validity of Terzaghi's principle has been demonstrated in simple macro-scale systems [2]. However, when attempting to apply the effective stress concept to natural complex systems, two fundamental questions arise: What is the range of scales over which Terzaghi's principle is valid?, and how should the effective stress be defined when the fluid pressure is not homogeneous throughout the domain of interest? In order to address these questions, we develop a micro-mechanical model of fluid-saturated granular layer that can undergo both elastic and plastic deformation in response to external and internal (fluidinduced) forcing. The model is based on two scales for the two phases: grains and fluid. Each grain is represented by a discrete element and the interstitial fluid is described on a coarser, Darcy, scale [3]. The coupling between the grains and the fluid is bidirectional. The effect of grains deformation on the pore fluid arises from changes of granular packing [4] and grain motion that induce fluid pressurization and flow. For the other direction, the effect of the pore fluid on the grains, we find that explicitly applying Terzaghi's principle along grain contacts is erroneous. Instead, the micro-scale force exerted by the fluid on the grains arises from fluid pressure gradients over individual grains. This micro-scale formulation gives rise to the desired macroscopic effective stress behavior. We perform simulations of shearing a densely packed saturated granular layer at a constant velocity and a constant confining stress. When the layer is undrained and the internal permeability is high, the deformation-induced pore pressure is homogenous within the layer. Simulation results show a good correlation between the effective stress and the shear resistance, following Terzaghi's principle. For drained systems with relatively low internal permeability, granular deformation during shear generates heterogeneous distribution of pore pressure. Under such conditions it is not clear how the macroscopic effective stress of the layer should be evaluated. Therefore, we measure instead the global shear resistance of the layer, and investigate the value and distribution of pore pressure when the shear resistance zeroes out and the macro view would have predicted that the effective stress is also zero. We define this situation as liquefaction. Simulation results show that a value of pore pressure that is larger than the confining stress in a small zone is not a sufficient condition for liquefaction, on the one hand, and that an average pore pressure that is larger than or equal to the applied confining stress is not a necessary condition for liquefaction, on the other hand. Instead, simulation demonstrates and theory shows that a necessary and sufficient condition for a complete loss of shear resistance and for liquefaction is the existence of a geometrically connected zone that cuts the system in two parts, along which the pore pressure is equal to or greater than the confining stress. We conclude that point measurements of pore pressure during dynamic and drained conditions are not sufficient for evaluating liquefaction potential.

References

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