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Modeling coupled fluid-grain deformation, with implications for landslides, fault-zones, and liquefaction

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Coupled shear deformation of granular media and pore-fluids often gives rise to catastrophic failures above and below ground: landslides, soil liquifaction and earthquakes. However pysical understanding of this coupled system is surprisngly limited. We study coupled granular-deformation and fluid pore pressure changes within a shearing layer, using a new two-scale two-phase model: the grains are modeled at the grain scale using a granular dynamics algorithm, while the fluid is simulated on a slightly coarser Darcy porous-flow scale. The formulation for the fluid is based on first principles and is general enough to account for the fluid response to both elastic and inelastic finite deformation of the granular matrix. We find that the presence of fluid influences all aspects of deformation, and introduces important physical constraints on upscaling lab results to the field scale. In simplified models that assume an infinitely stiff matrix, pore pressure responds to granular deformation, but granular deformation is assumed to not be affected by pore pressure gradients, When the timescale for fluid flow (system size over flow velocity) is large compared to the timescale for deformation of the solid matrix, pore pressure responds to strain in the granular layer (porosity variations), and the magnitude of pressurization is controlled by fluid compressibility; when the fluid flow timescale is short, pore pressure responds to strain rate (rate of porosity variation). When the timescales are comparible, there is a mixed visco-elastic response. Pore pressure may rise even if the system is drained, and if the overall trend of the system is dilative, provided there are periods of abrupt or spatially localized compaction. Fully coupled simulations reveal that the relations between granular deformation, drainage conditions, and pore pressure variations that were derived under the infinite stiffness assumption remain generally valid even when this assumption is relaxed. Coupled simulations also highlight the transition in layer support (from stress-chains through the grains to fluid pressure) that occurs during pressurization. This transition is accompanied by a significant reduction of the shear stress, that potentially allows the development of runaway dynamic slip. Additional insights are offered regarding the time scales controlling dilatancy hardening and the relation between pore fluid pressurization/depressurization and stick-slip motion.