Compaction front controls soil liquefaction dynamics of drained saturated grain layers, as evident by theory, numerical simulations and lab experiments

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Soil liquefaction is one of the most impactful secondary hazards of earthquakes. For example, it played a crucial role in driving the devastating landslides following the 2018 Palu earthquake, Indonesia. While traditionally, the initiation of liquefaction is treated as an undrained phenomenon, evidence shows that a well-drained end-member exists.

We develop a theory for the coupled grains - pore fluid system, and conduct numerical discrete element – fluid dynamics simulations and lab experiments under well-drained conditions. Here, a well-drained layer means that the interstitial fluid can flow out of the layer faster than a single earthquake shaking period. Theory, simulations, and experiments, all suggest that a saturated granular layer, although well-drained, can liquefy when subjected to horizontal cyclic shear. The liquefaction event, evident by high pore pressure, loss of shear strength, and dissipation of shear waves is spatially and temporally controlled by a compaction front that swipes upward through the layer. The compaction front separates the grain-fluid system into two sub-layers: The bottom sub-layer, below the front, is fully-compacted, and the pore pressure gradient across it is hydrostatic. The top sub-layer, above the front, is actively subsiding, and its pore pressure gradient reaches the total solid stress gradient. I.e., the fluid fully supports the granular skeleton. The velocity of the compaction front depends on the permeability of the soil layer and the viscosity of the interstitial fluid. Analytic considerations of the propagation rate of the compaction front allows us to evaluate the duration of a liquefaction event, the magnitude of soil subsidence, and the timing of water seepage at the surface level, which are all independent of the time scales related to the earthquake shaking. Our approach, when combined with field stratigraphy and groundwater level data, could explain and predict the occurrence and duration of soil liquefaction when the soil layer is effectively drained.