Numerical modeling of liquefaction-induced failure of geostructures subjected to earthquakes

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The increasing importance of performance-based earthquake engineering analysis points out the necessity to assess quantitatively the risk of liquefaction. In this extreme scenario of soil liquefaction, devastating consequences are observed, e.g. excessive settlements, lateral spreading and slope instability.

The present PhD thesis discusses the global dynamic response and interaction of an earth structure-foundation system, so as to determine quantitatively the collapse mechanism due to foundation's soil liquefaction. As shear band generation is a potential earthquake-induced failure mode in such structures, the FE mesh dependency of results of dynamic analyses is thoroughly investigated and an existing regularization method is evaluated. The open-source FE software developed by EDF R&D, called Code Aster, is used for the numerical simulations, while soil behaviour is represented by the ECP constitutive model, developed at CentraleSupélec.
Starting from a simplified model of 1D SH wave propagation in a soil column with coupled hydromechanical nonlinear behavior, the effect of seismic hazard and soil's permeability on liquefaction is assessed. Input ground motion is a key component for soil liquefaction apparition, as long duration of mainshock can lead to important nonlinearity and extended soil liquefaction. Moreover, when a variation of permeability as function of liquefaction state is considered, changes in the dissipation phase of excess pore water pressure and material behavior are observed, which do not follow a single trend. The effect of a regularization method with enhanced kinematics approach, called first gradient of dilation model, on 1D SH wave propagation is studied through an analytical solution. Deficiencies of the use of this regularization method are observed and discussed, e.g. spurious waves apparition in the soil's seismic response.
Next, a 2D embankment-type model is simulated and its dynamic response is evaluated in dry, fully drained and coupled hydromechanical conditions. Two criteria are used to define the onset of the structure's collapse. The second order work is used to describe the local instability at specific instants of the ground motion, while the estimation of a local safety factor is proposed by calculating soil's residual strength. Concerning the failure mode, the effect of excess pore water pressure is of great importance, as an otherwise stable structure-foundation system in dry and fully drained conditions becomes unstable during coupled analysis.
Finally, a levee-foundation system is simulated and the influence of soil's permeability, depth of the liquefiable layer, as well as, characteristics of input ground motion on the liquefaction-induced failure is evaluated. For the current levee model, its induced damage level (i.e. settlements and deformations) is strongly related to both liquefaction apparition and dissipation of excess pore water pressure on the foundation. A circular collapse surface is generated inside the liquefied region and extends towards the crest in both sides of the levee. Even so, when the liquefied layer is situated in depth, no effect on the levee response is found.

This research work can be considered as a reference case study for seismic assessment of embankment-type structures subjected to earthquake and provides a high-performance computational framework accessible to engineers.