Micro-mechanically enhanced multi-yield surface modeling of drained sand behavior in dynamic boundary value problems

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Abstract

Soil behavior plays a crucial role in the seismic analysis of geotechnical infrastructures. The wave propagation velocity and the amplitude depend on the soil stiffness, resulting in amplified accelerations. At the same time, structural movements may be modified due to the additional soil flexibility and the energy dissipation provided by the hysteretic response. The nonlinear cyclic sand behavior is often represented by a phenomenological equation and a set of material internal variables. Relatively more straightforward models [1], [2] miss some of the most crucial soil behaviors, such as dilative-contractive transformation, strain softening, and anisotropy due to initial fabric, but enjoy numerical stability and low computational cost. In comparison, mathematically complex models [3] capture the desired behavior but may suffer from convergence issues in extreme cases, a high number of iterations for convergence, and a strenuous calibration procedure.

Alternatively, the desired mechanics may be modeled using micro or multiscale simulations. Some multiscale approaches abandon the constitutive model [4], using direct FEMxDEM bridging, whereas others keep the constitutive model and couple FEMxDEM to update the material internal variables [5]. The double-scale approaches are robust and accurate in modeling the sand response. However, they have yet to solve an engineering scale transient problem due to their computationally intensive nature. The data-driven multiscale approach can be used as a remedy, which relies on a database of low-level simulations to do the return mapping without the need for constitutive equations [6].

This study proposes a micro-mechanically enhanced constitutive model to capture the desired soil behavior at the macro scale. First, a response database is obtained by analyzing a granular unit cell under various stress paths. The homogenized stress, strain, and fabric tensors are recorded at each step. Then, the database is used to update the material internal variables of a multi-yield surface model. At each Gauss point, the strain tensor is downscaled. A "micro-scale-like" problem is solved by searching the database for the closest data point by comparing the tensor invariants or the tensor-to-tensor distance. Then, information such as the shear strength, kinematic modulus, and dilatancy is transferred to the macro scale through yield surface parameters. The return mapping is done with an implicit solution, and the stiffness and residual tensors are upscaled. The database to constitutive model communication is repeated when there is a need to define the next yield surface during the analysis. Finally, the stress reversals are handled via a back-stress-like tensor that stores the material

state at the reversal. The memory variables are reverted once the material returns to the threshold state.

The proposed approach captures the dilative-contractive transformation, strain hardening/softening, induced anisotropy, and anisotropy due to the initial fabric. Furthermore, since the model formulation results in a piece-wise linear modulus between yield surfaces, increased numerical stability and a mathematically simpler consistent tangent definition is available.

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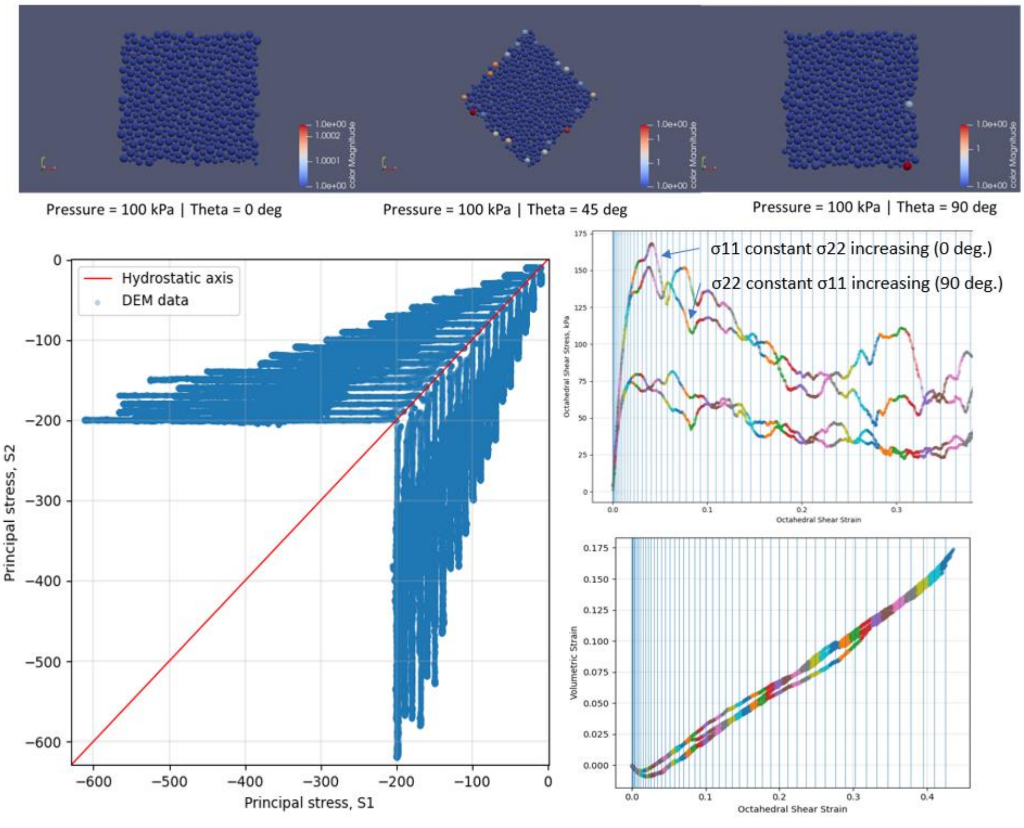
Figures



a) **b)**

Figure 1: *The database generated based on various stress paths (a). Monotonic shearing cases for initial isotropic stresses of 100 kPa and 200 kPa with yield surfaces shown as vertical lines (b).*