Simulating undrained loading of sand with the discrete element method

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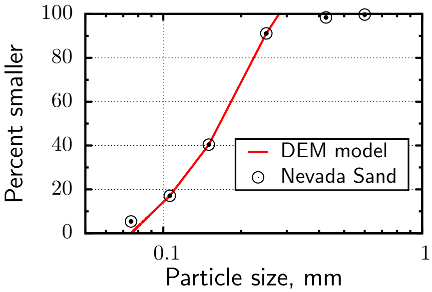
Creating the DEM model

Target material: Nevada Sand

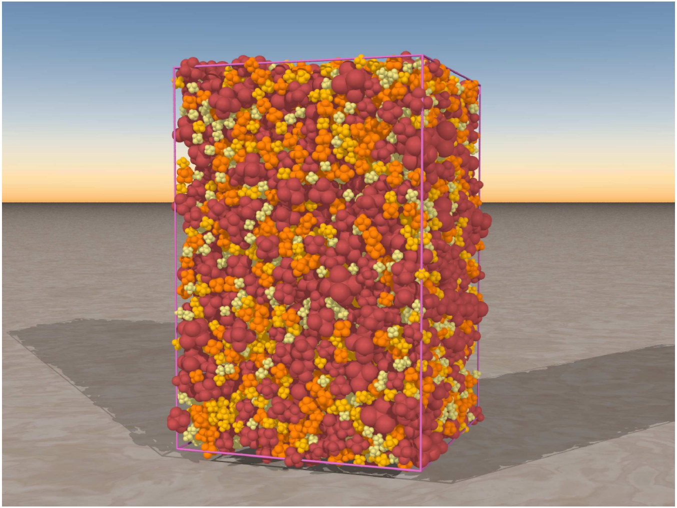
	Nevada Sand *	DEM assembly
D_{50}	0.165 mm	0.165 mm
C_u	2.2	2.0
e_{min}–e_{max}	0.511–0.887	0.514–0.897

* Arulmoli, K. et al. (1992)
Kutter, B. L. et al. (1994)
Kammerer, A. M. et al. (2000)

Grain size distributions

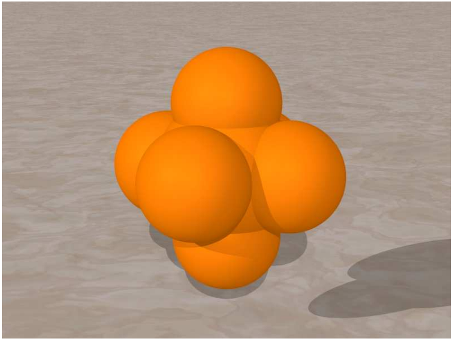


DEM assembly of 6400 "bumpy" particles



Particle shape

An octahedral cluster of 7 overlapping spheres:



DEM model

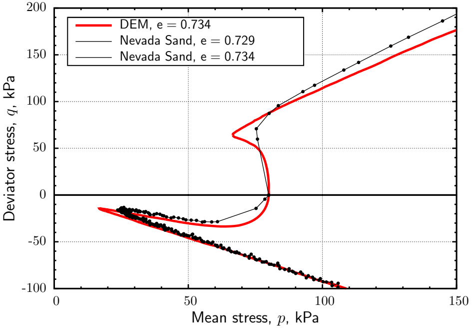
Contact properties:

- Hertz-Mindlin (elastic-frictional) contact model
- $E = 29$ GPa, $\nu = 0.15$
- $\mu = 0.60$ friction coefficient
- Sphere-sphere contact

The DEM model should approximate the loading response of Nevada Sand — in both a qualitative and quantitative manner.

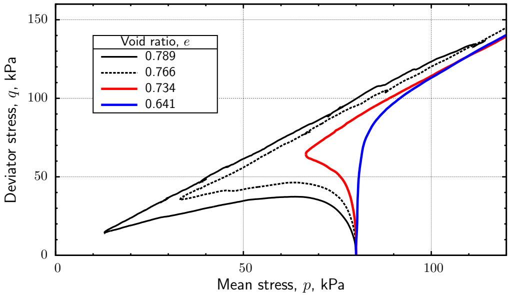
Verifying the DEM model

Undrained triaxial compression and extension tests



Verifying the DEM model

Undrained triaxial compression tests — range of densities



DEM modeling — advantages

Modeling soil behavior with DEM “element” simulations:

- Experiments can be initiated (or restarted) from the same assembly.
- Full stress and strain tensors can be measured.
- Arbitrary control of 6 stress or strain increments.
- Behavior simulated in the absence of shear bands.

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DEM modeling — disadvantages

Shortcomings of DEM simulations:

- Realistic particle shapes and arrangements are difficult to create and to calibrate.
- Relative density is difficult to surmise.
- Roughness, texture, and sharp edges of particles are not modeled.
- Idealized contact models (Hertz-Mindlin, etc.)
- Particle breakage or chipping is (usually) disallowed.

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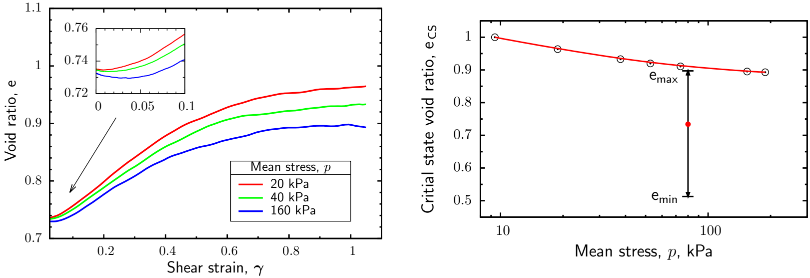
Critical state behavior

Drained simple-shear (constant-p) tests



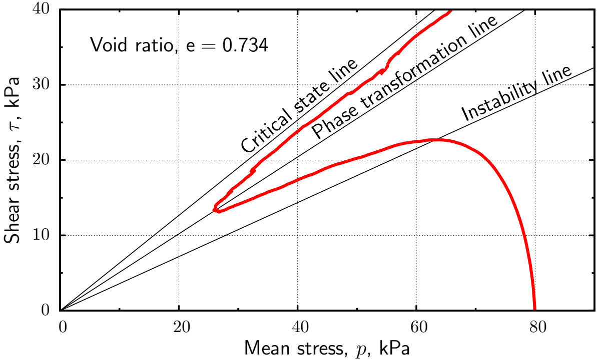
Undrained simple-shear

Undrained simple-shear simulations:

- Isotropic consolidation, 80 kPa
- Uni-directional shearing: $\gamma_{12} > 0$, $\gamma_{13} = 0$, $\gamma_{23} = 0$
- Undrained conditions: $\varepsilon_{11} = 0$, $\varepsilon_{22} = 0$, $\varepsilon_{33} = 0$
- Effective stresses inferred from the contact forces (total stresses not measured)

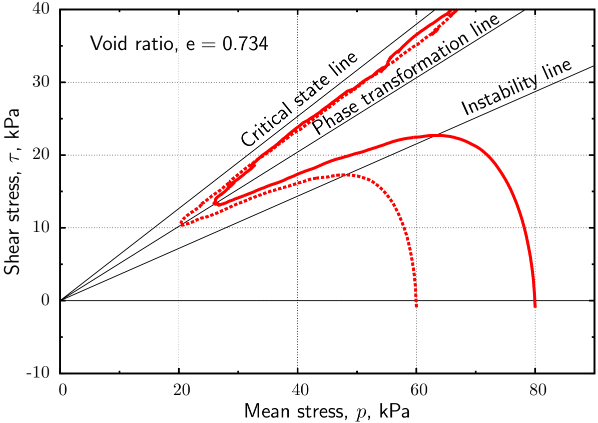
Undrained simple-shear results

Undrained simple-shear:



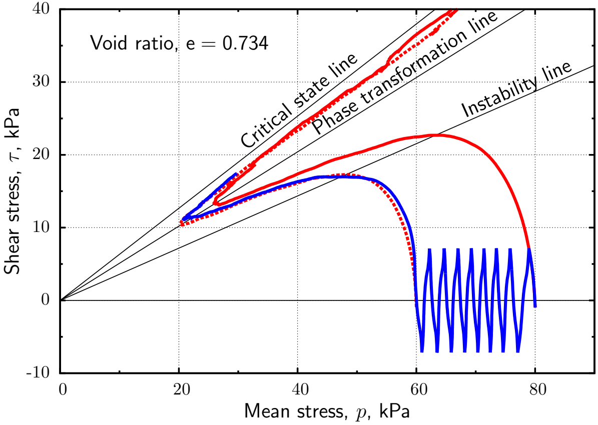
Undrained simple-shear results

Undrained simple-shear at two consolidation levels:



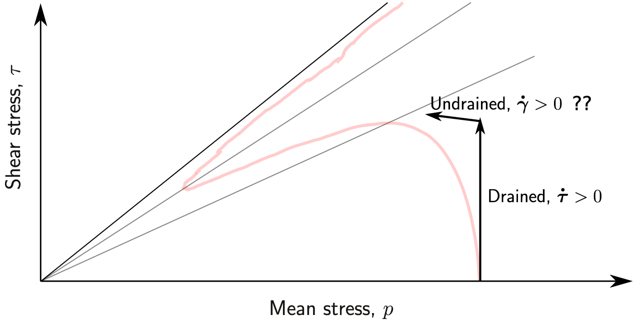
Undrained simple-shear results

Undrained simple-shear following cyclic loading:



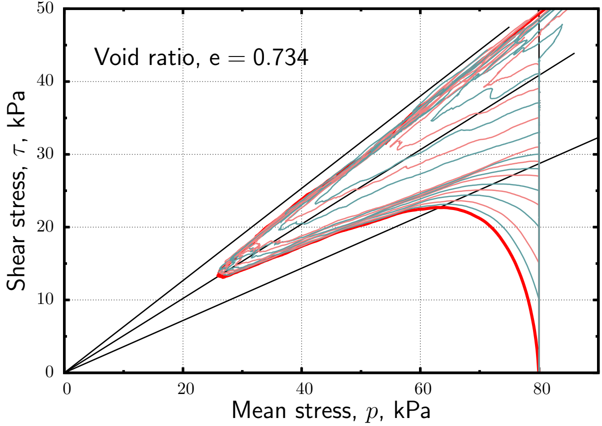
Static liquefaction

Stress path for inducing static liquefaction



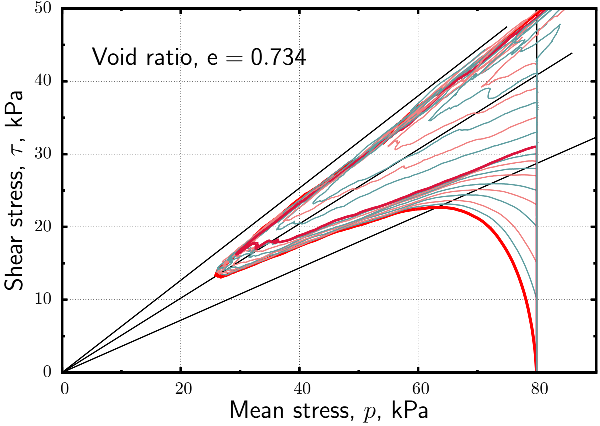
Static liquefaction

Drained shearing followed by undrained shearing:



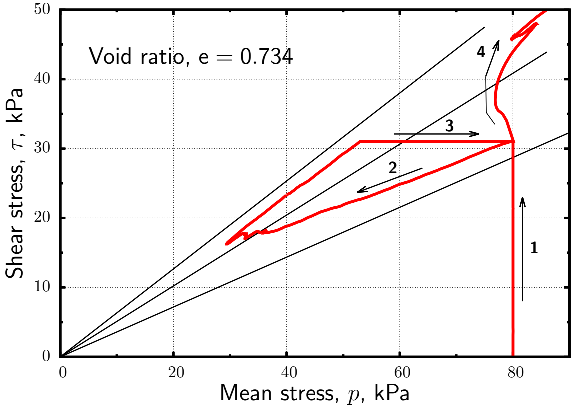
Static liquefaction

Drained shearing followed by undrained shearing:



Post-liquefaction

Static liquefaction followed by consolidation and by undrained shearing:



Summary

- DEM “element” tests can be used to simulate both drained and undrained behaviors of sand.
- Realistic simulations require proper selection of particle shapes and sizes.
- Assemblies with densities “above” the critical state line have not yet been created.
- DEM test can simulate both static and dynamic liquefaction phenomena.

Questions?