Geomechanical Performance of Hydrate-bearing Sediments in Offshore Environments

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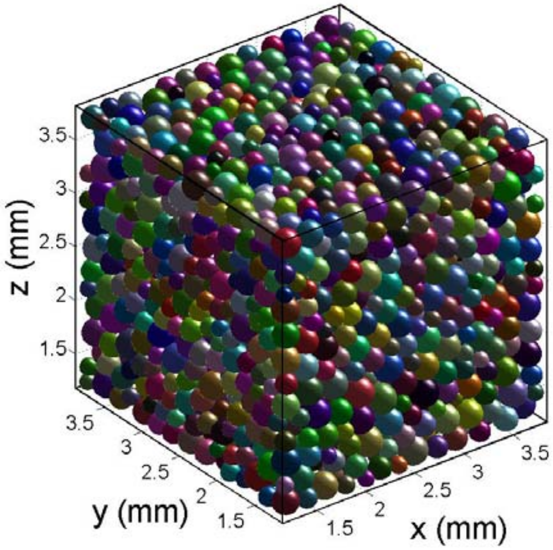


Objectives

- ***Motivation***: Quantify the impact of hydrate dissociation on the strength and elastic properties of hydrate-bearing sediments

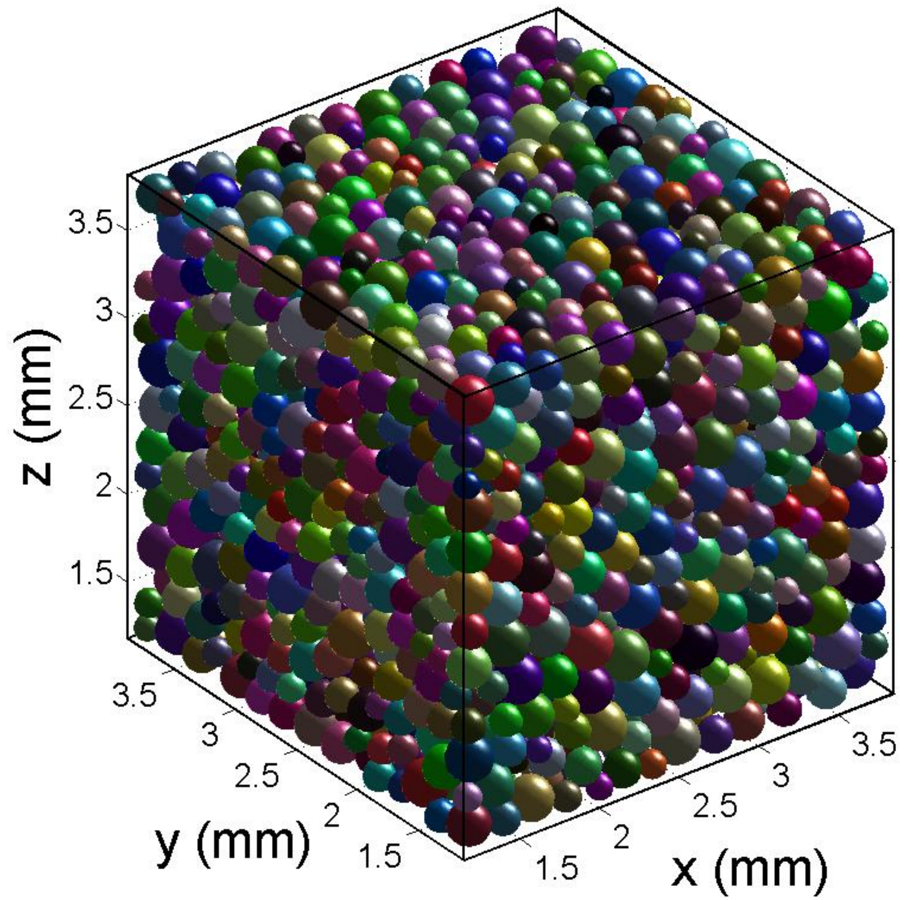
- ***The Task*****:** Estimate the changes of elastic moduli in order to populate the grid blocks for coupled TOUGH Fx/HYDRATE- FLAC3D simulations
  - **Inputs:** initial elastic moduli, variable pore pressure and hydrate saturation
  - **Tool**: Pore-scale quasi-static equilibrium model
  - **Method:** Verification of the model against available experiments and numerical simulations

Approach

- Saturated sediment is modeled as a granular medium
- The skeleton can be either unconsolidated or cemented
- Some of the pores are filled with gas-hydrates
- Consequences of hydrate dissociation:
  - Increased pore pressure and reduced effective stress
  - Decrease of the skeleton strength by losing hydrate support
  - Possibly, thermal contraction/expansion

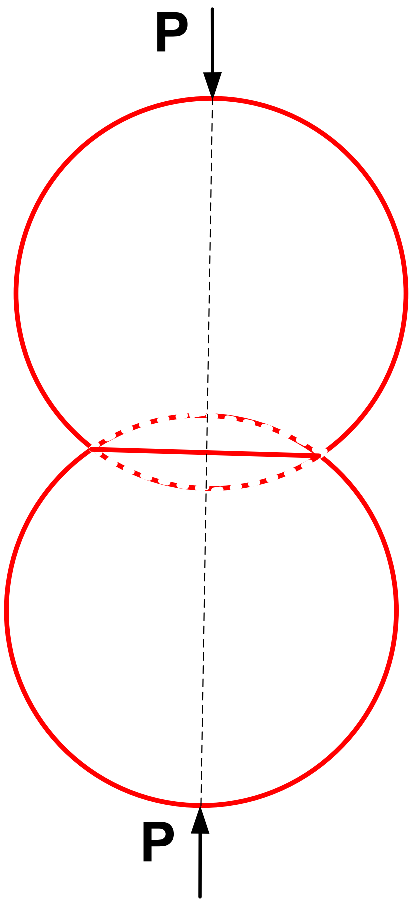
Grain Pack Properties

- 3D random heterogeneous grain packing
  - Spherical grains, differ in radii and mechanical properties
  - Each grain is homogeneous, isotropic, and linearly elastic
- To be implemented
  - Adhesion or cement at grain-to-grain contacts
  - Different grain shapes



Contact-Mechanics Model

- Hertz-Mindlin theory of elastic interaction of a grain pair
  - Small deformations localized around a small neighborhood of the contact area
  - Planar circular contact surface
  - Forces and moments at the contact



Normal Contact: Hertzian Model

Contact force:

$$P_{ij} = \frac{4}{3} E_{ij}^{*} \sqrt{R_{ij}^{*}} h_{ij}^{3/2}$$

Elastic strain energy:

$$U_{ij} = \frac{8}{15} E_{ij}^{*} \sqrt{R_{ij}^{*}} h_{ij}^{5/2}$$

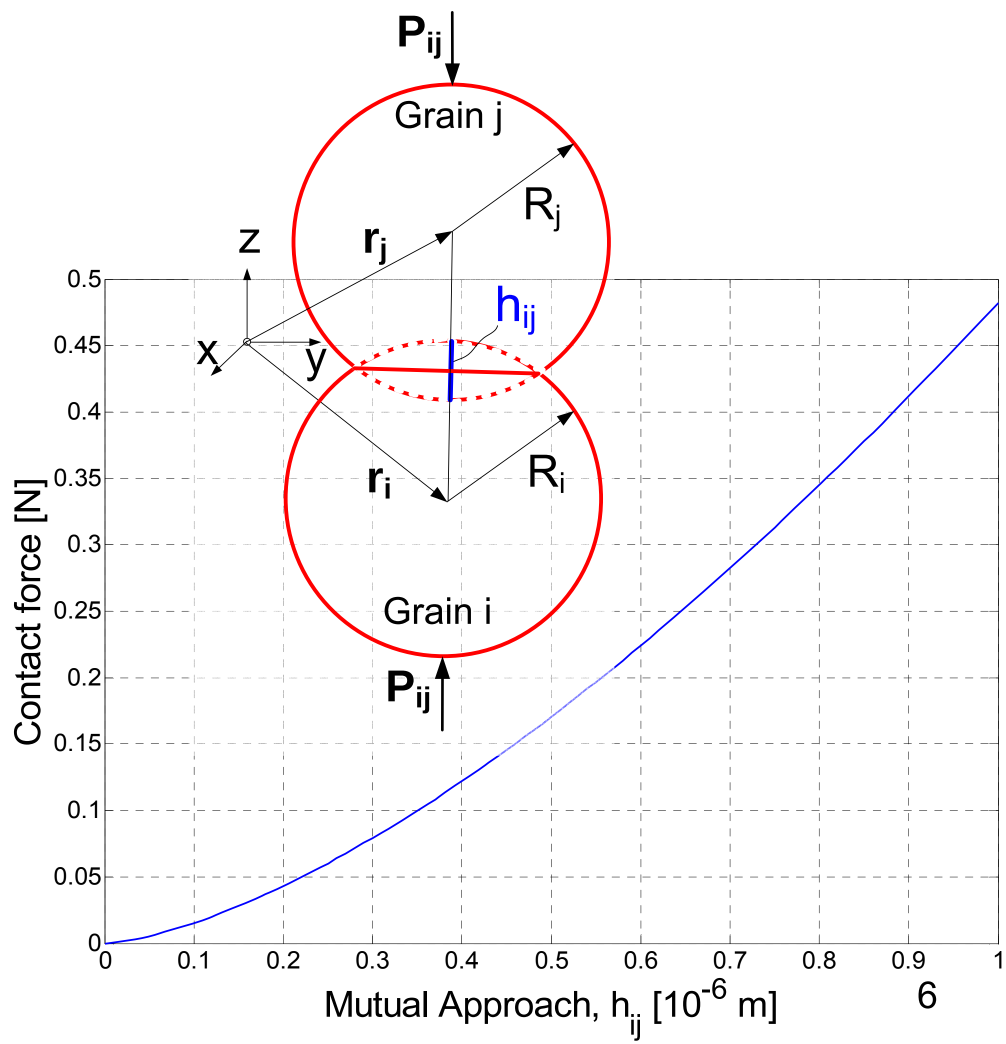
where

$$\frac{1}{E_{ij}^{*}} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_j^2}{E_j}$$

$$\frac{1}{R_{ij}^{*}} = \frac{1}{R_i} + \frac{1}{R_j}$$

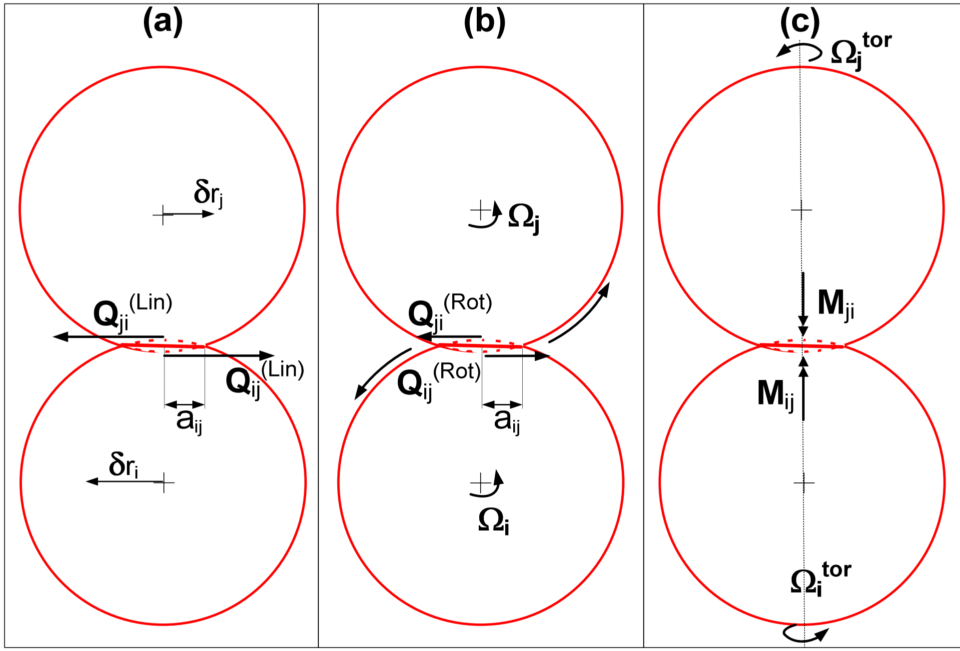
$$h_{ij} = R_i + R_j - \left\| \mathbf{r}_{ij} \right\|$$

$$\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$$



Frictional Contact: Mindlin's Theory

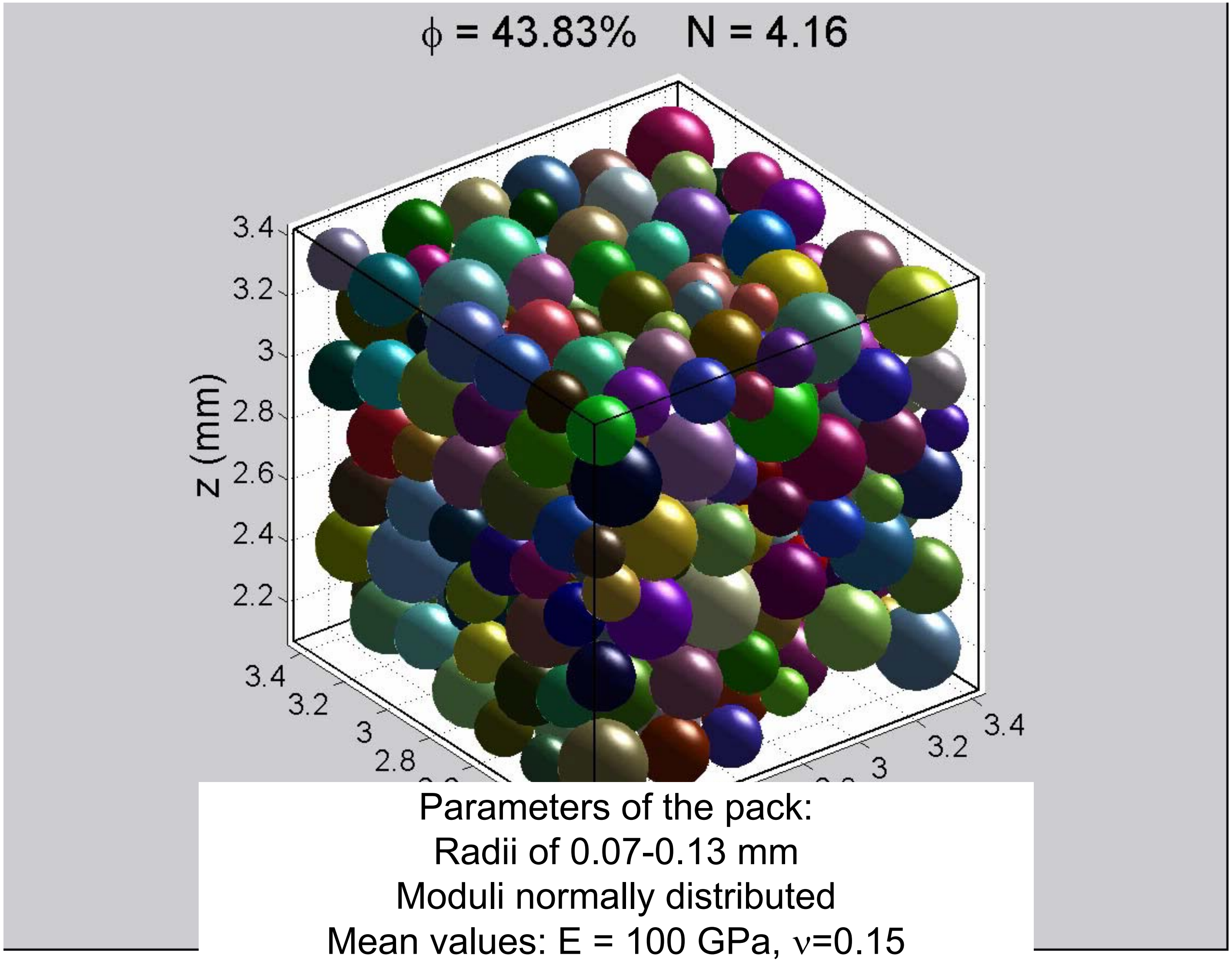
- Linear and rotational displacements introduce tangential tractions and moments
  - Tangential stiffness depends on normal pressure
  - Tangential tractions are path-dependent
  - Partial/complete slip can occur
  - Mindlin theory: normal tractions are not affected by the tangential components
- To eliminate some of these difficulties, we consider:
  - Pre-stressed pack
  - Small deformations
  - Static friction (no slip)



Effective Properties *via* Simulations

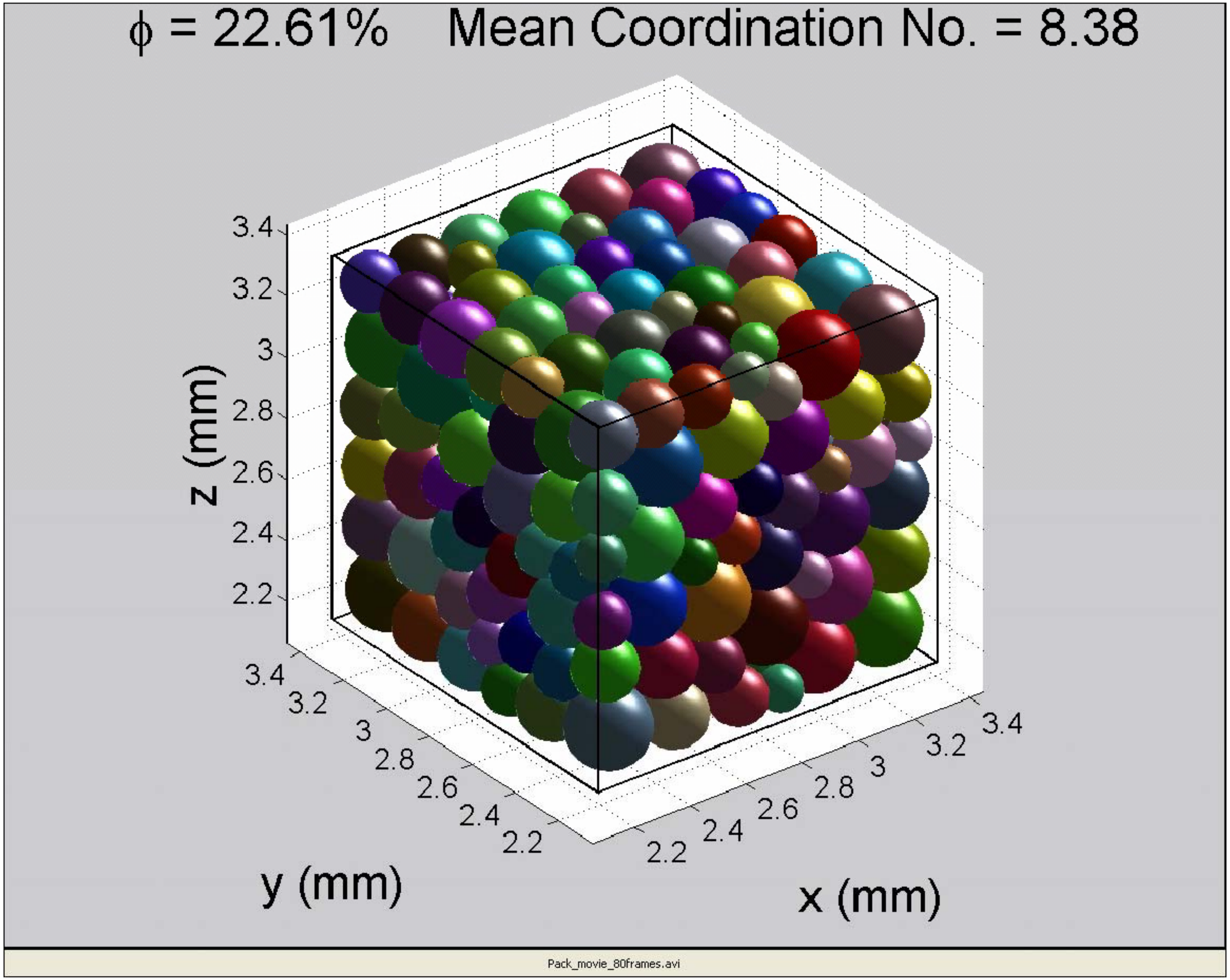
- A grain pack is enclosed in a semi-rigid container
- Boundary conditions = wall displacements
- Macroscopic stress is generated by contact forces
- Quasi-static model: equilibrium configurations
- Equilibrium = minimum total elastic energy
- Conjugate Gradient minimization algorithm
  - Functional to minimize = total energy of the pack
  - Dynamic list of contacts
- Effective moduli using Hooke’s law

Example of Simulation



Parameters of the pack:
Radii of 0.07-0.13 mm
Moduli normally distributed
Mean values: E = 100 GPa, ν=0.15
Number of grains: 306(small pack); 2,740 (large)

Example of Simulation



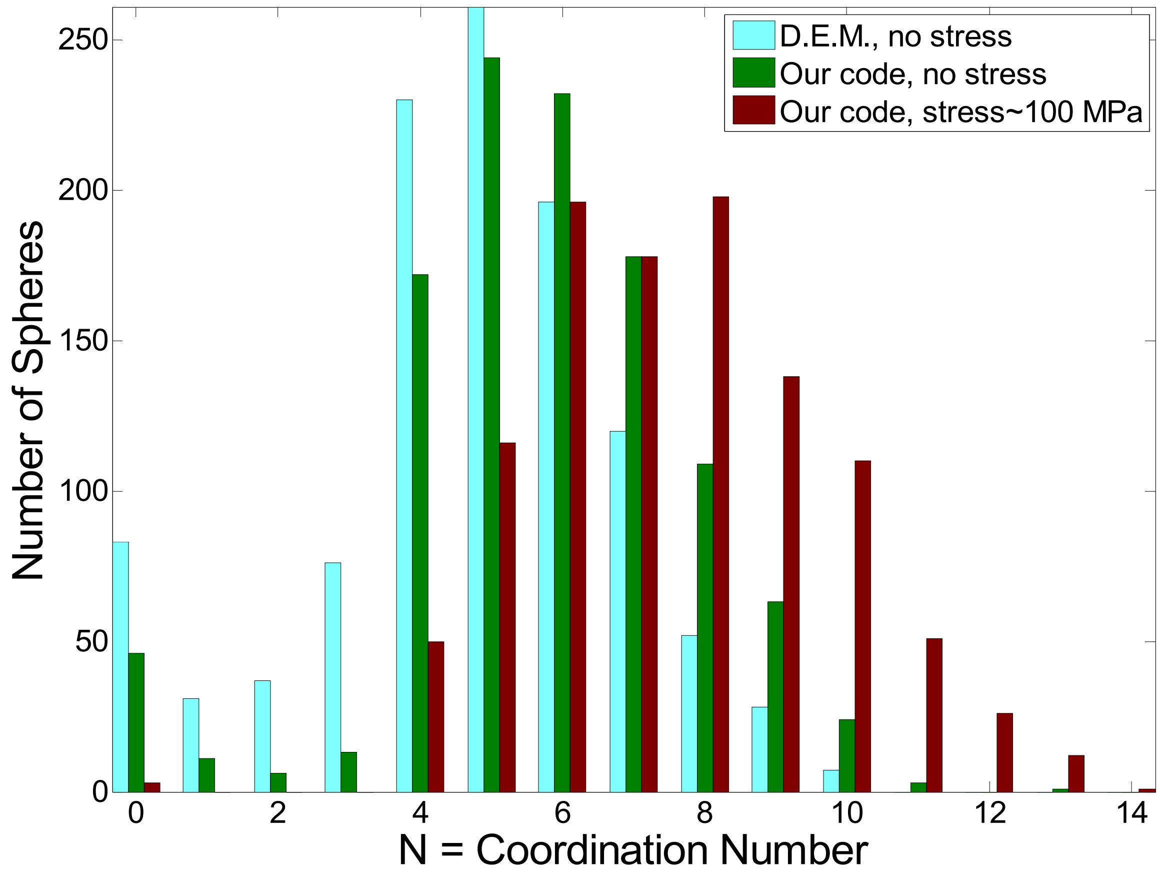
Modeling Challenges

Difficulties are in the modeling of grain pairs and packs

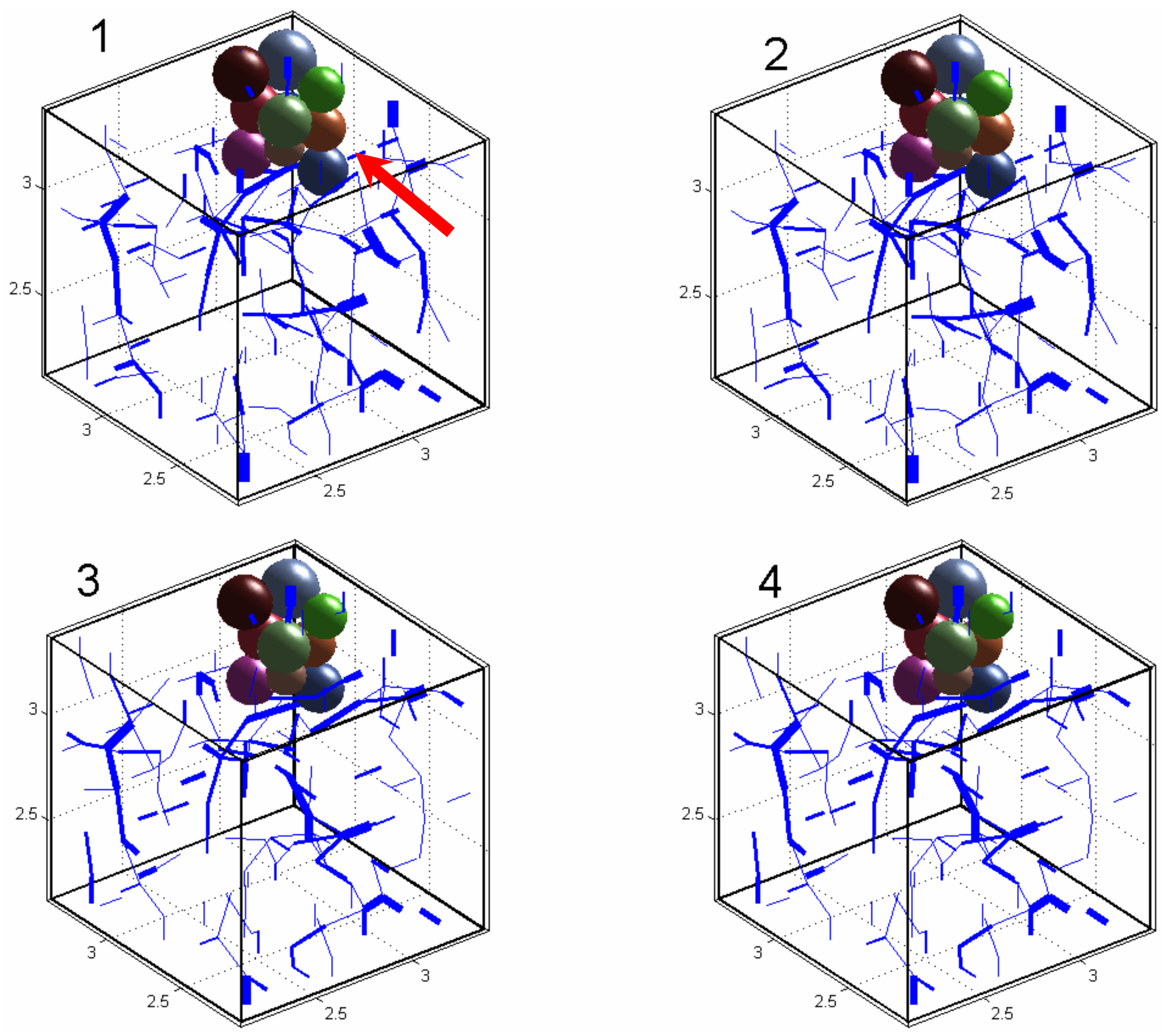
- Grain pairs
  - Nonlinearity of force-displacement relations
  - Stress depends on deformation history
  - Slip, partial or complete
- Grain packs
  - Complex contact geometry
  - Number of contacts, orientation and stiffness vary during the deformation
  - Deformation hysteresis even with fully elastic contacts

Creating a Stable Pack: Rearrangement *vs* Deformation

- The minimum coordination number for a stable pack is 3 (with gravity)
- Pack produced by D.E.M. simulations is unstable, i.e. not in equilibrium
- Our algorithm eliminates most unstable structures, by mere rearrangements (no grain deformations)
- As stresses increase, the pack gets more stable



Non-Linear Response



Local failure in a small pack (306 grains)

- Four consecutive configurations, similar macroscopic strains
- Force chains plotted are the top 10% contact forces
- Line width is scaled with the force magnitude
- Abrupt change from 2→3; brown grain is forced through a constriction

Non-Linear Response

- At a particular combination of contact forces, some grains experience large, irreversible (inelastic) displacements:
  - Macroscopic stress is reduced by rearrangements of grain clusters
  - Local phenomenon, affecting only a small neighborhood of each rearranged cluster
  - More pronounced in smaller packs
  - Local failure, followed by stiffening of the pack
  - Similar to strain-hardening in metals

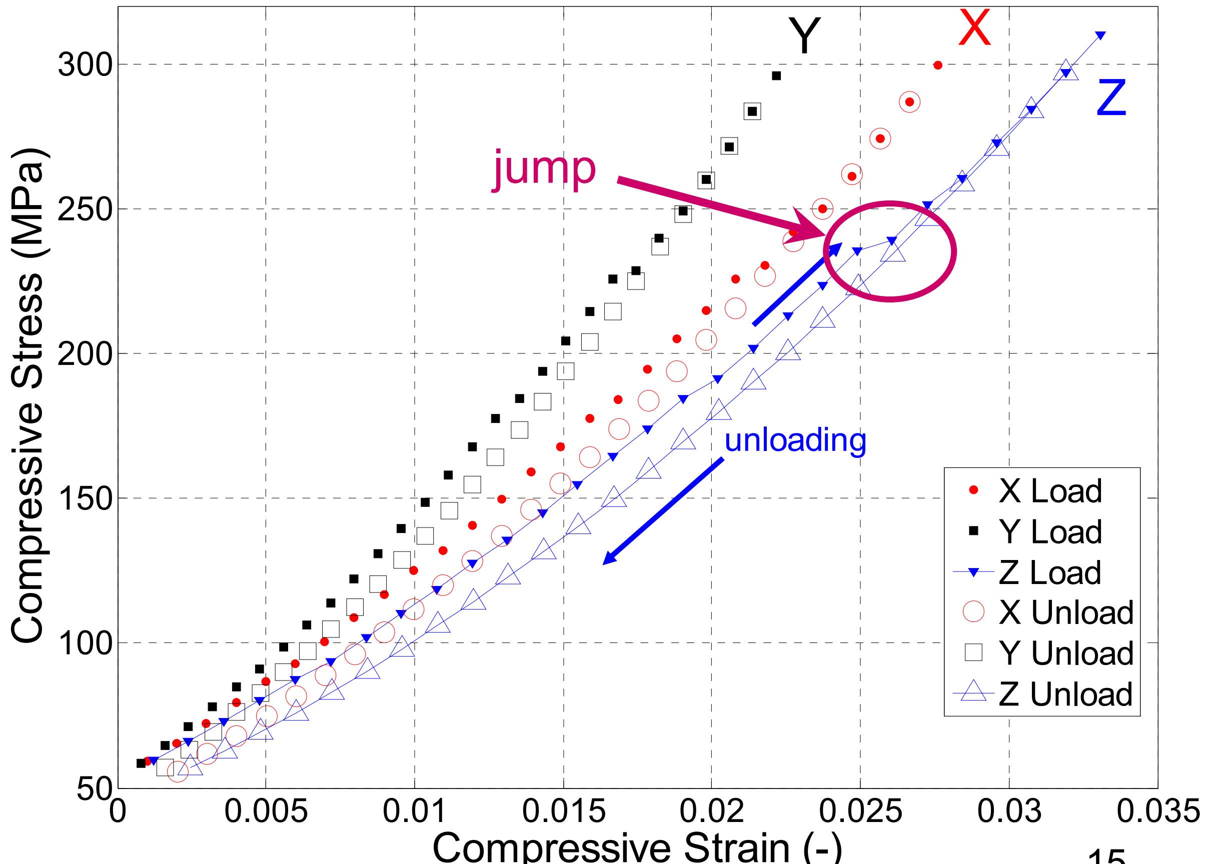
Loading/Unloading Hysteresis

- Elastic response of a single contact
- Inelastic behavior of a grain assembly

Triaxial compression test :

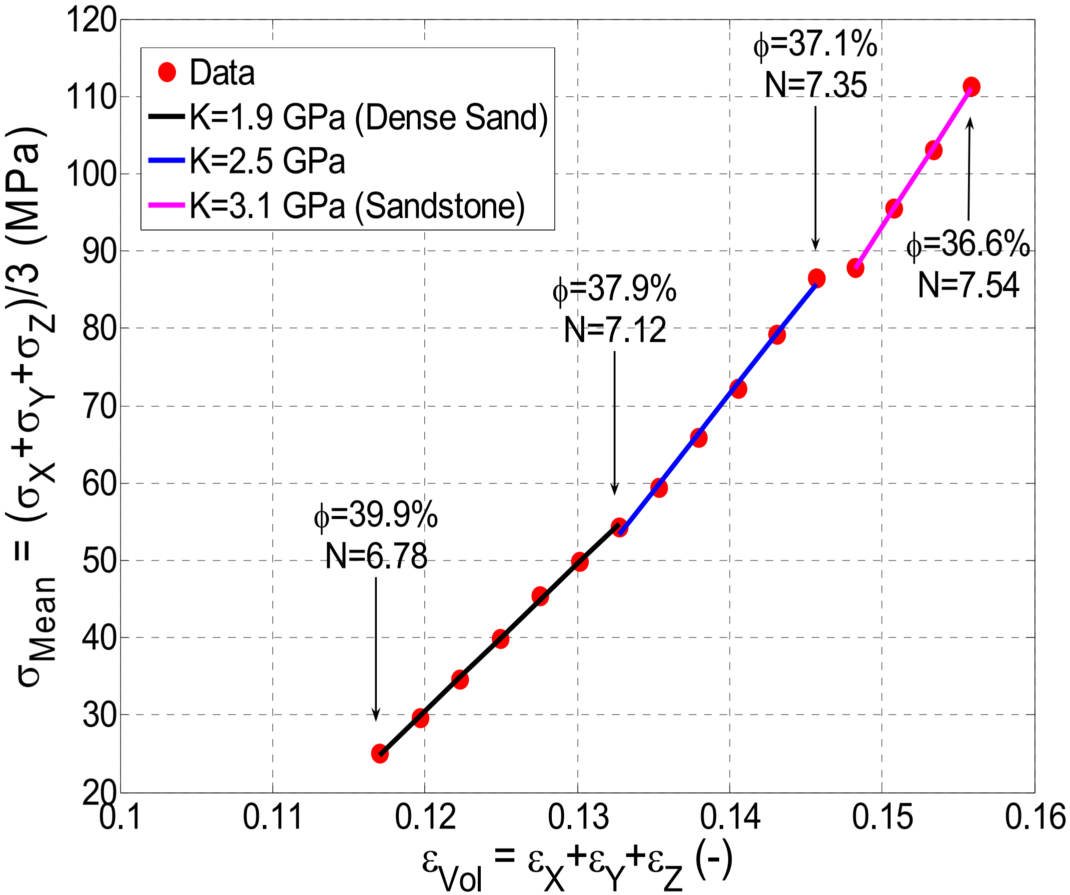
ϕ = 35.8~30.8 %;

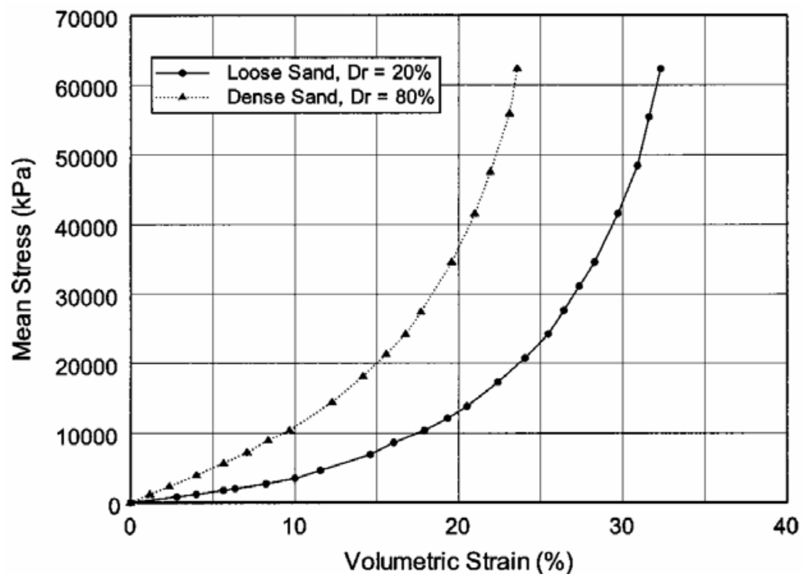
N = 7.2~8.3



Stiffness *vs.* Compaction

- Bulk modulus K increases with pack density
- Density increases as porosity ϕ decreases and coordination number N increases





Hydrostatic compression tests:

Left: Simulations;

Right: Experiment Vesic & Clough, 1968)

Conclusions

- Granular media exhibit non-linear, path-dependent behavior, even for a frictionless contact model
- Because of grain rearrangement, macroscopic deformation is possible with little deformation of grains
- Hysteretic effects are more pronounced when grain ‘jumps’ occur
- Introduction of frictional contacts increases the path-dependency (hysteretic effects)

Summary: Phase I

- A grain-scale model of rock
  - ✓Hertz-Mindlin contact mechanics
  - ✓Stable equilibrium grain packs
  - ✓Simulation of loading-unloading hysteresis
  - ✓Matching published laboratory measurements
  - ✓Efficient numerical procedure

Summary

- Grain-scale model provides a tool to estimate effective moduli
  - Irreversibility of deformations is captured
  - Stiffening ($K\uparrow$) with compaction is evident
  - Values of K match physical experiments
  - Poisson's ratio high, due lack of friction, cement, and simplified grain shapes
  - Efficient algorithm based on conjugate gradient method

Next...

- Use the already developed model to
  - Incorporate gas-hydrates and investigate
    - Solid skeleton support
    - Pore pressure and effective stress changes
  - Perform ensemble-averaging and investigate sample size effects
- Enhance the existing model by adding
  - Cementation/adhesion between grains
  - Failure criterion for cement
  - More complex grain shapes
  - Large strains

Thank You!