Discrete Element Modeling of Soils as Granular Materials

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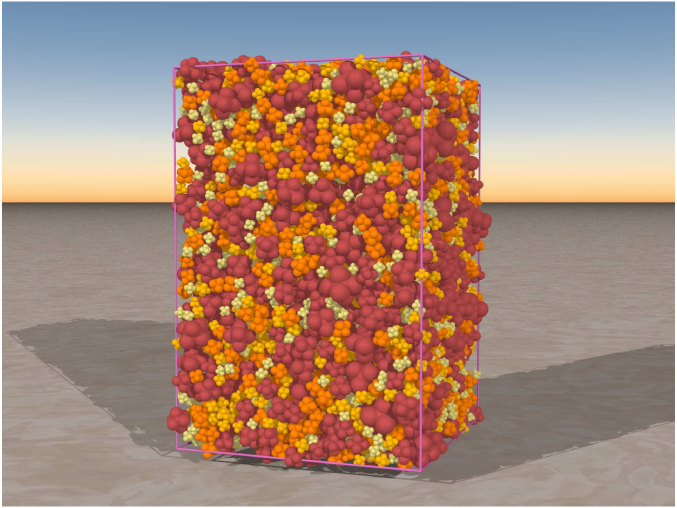
Outline

Contents

DEM assembly of 6400 particles



Discrete Element Method (DEM)

Background

- Granular media are modeled with individual particles
- Peter A. Cundall (1971)
  1979 *Geotechnique* paper

DEM Algorithm

A finite difference (time-stepping) algorithm, in which

Elemental particles (spheres, polyhedra, etc.)

- Interact in a pair-wise manner (contacts), such that the
  - Imbalances in the forces on each particle
  - Impel the particles to new positions
    - With each time step
    - Via Newton's equations of motion

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DEM Software

Commercial software

- PFC3D — Itasca, Inc.
- EDEM — DEM Solutions

Open source software

- Yade — yet another dynamics engine
- ESyS
- LAMMPS
- OVAL

Coding Challenges

- Particle shapes
  - Spheres $=$ Easy
  - Other shapes $=$ Difficult
- Contact detection: an N^2 problem
- Contact force models
  - Linear springs $=$ Easy
  - Hertz-Mindlin springs $=$ Difficult
  - Real (soil) particle interactions $=$ Not yet attempted
- Problem types
  - "Element" tests
  - Field problems (realistic boundaries)

Modeling real soil problems $=$ Very difficult

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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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Alternatives

Alternative computational methods:

- Discontinuous Deformation Analysis (DDA)
  G.-H. Shi and Y. Kishino
  $[K][u] + [C][\dot{u}] + [M][\ddot{u}] = 0$
- Contact Dynamics
  M. Jean and J.-J. Moreau
  Inequality constraints, non-linear programming
- Event-driven Models
  Instantaneous collision-based

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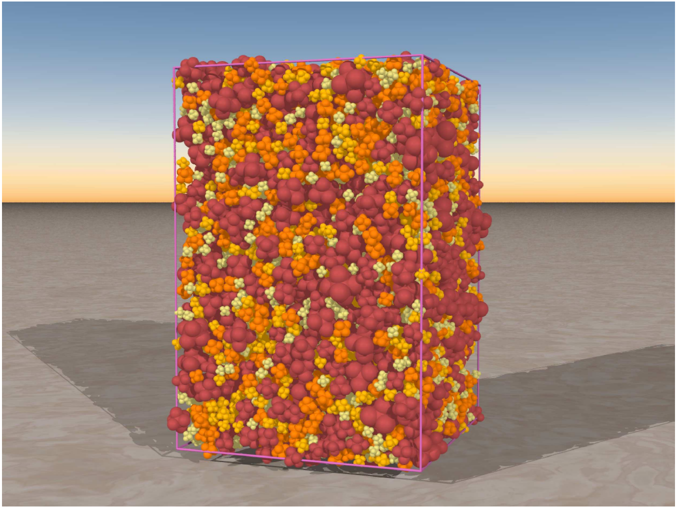
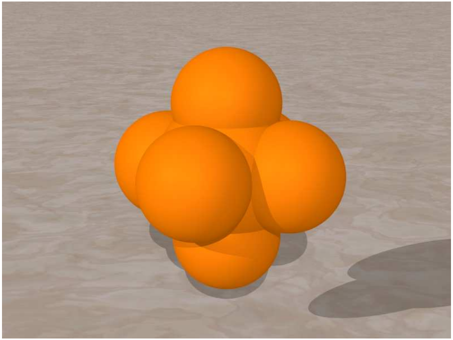


Particle shape



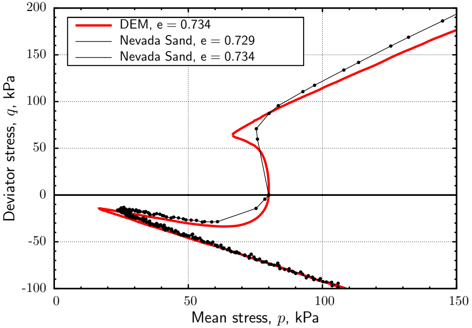
DEM model

Contact properties:

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

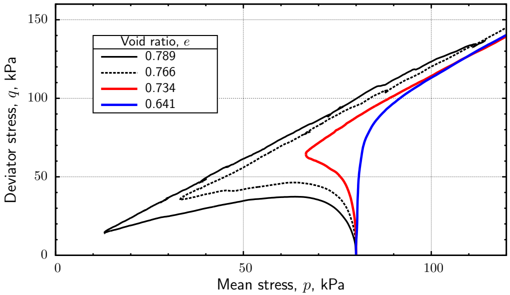
Verifying the DEM model

Undrained triaxial compression and extension tests



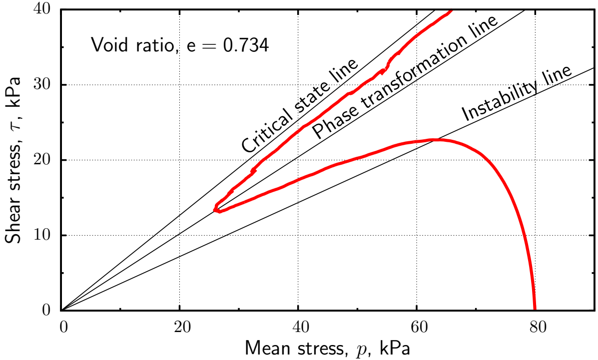
Verifying the DEM model

Undrained triaxial compression tests — range of densities



Undrained simple-shear results

Undrained simple-shear:



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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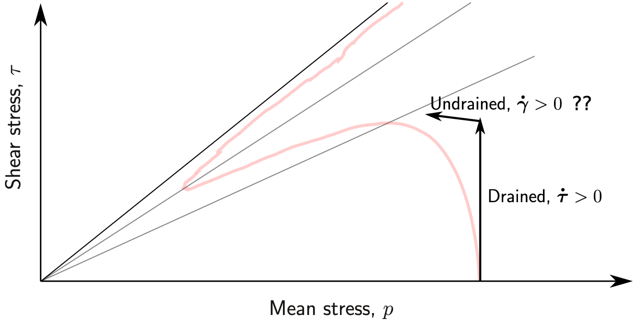
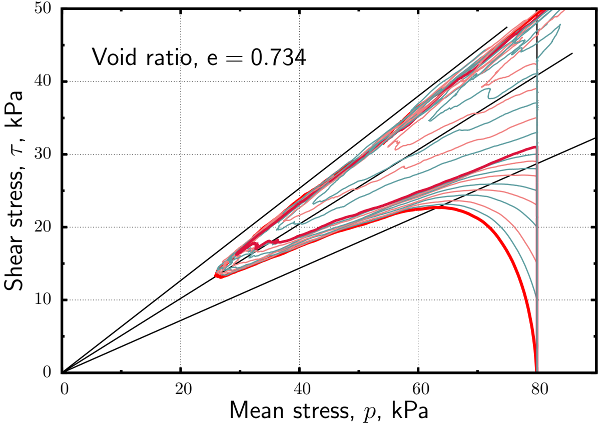
Static liquefaction

Stress path for inducing static liquefaction



Static liquefaction

Drained shearing followed by undrained shearing:



Cyclic liquefaction

Cyclic liquefaction simulations:

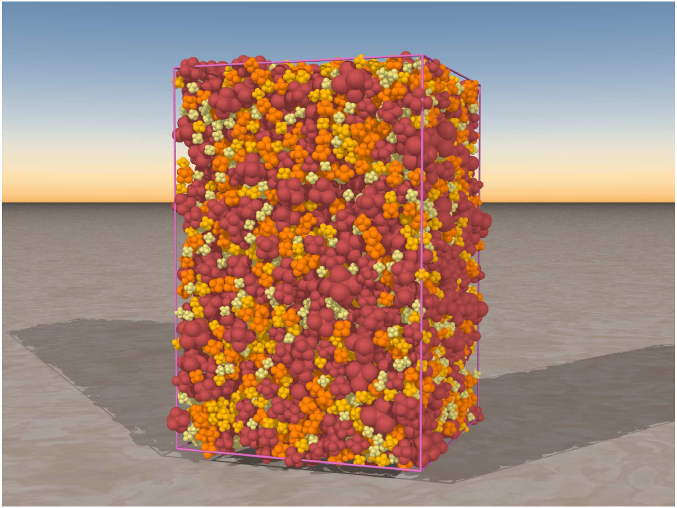
- Two loading cases

  Case I Uniform amplitude cyclic shearing

  Case II Erratic, seismic shearing

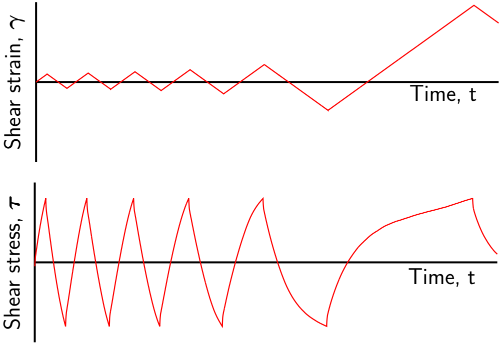
- “Severity Measure” for predicting initial liquefaction

DEM assembly of 6400 particles



Case I: Uniform cyclic shearing

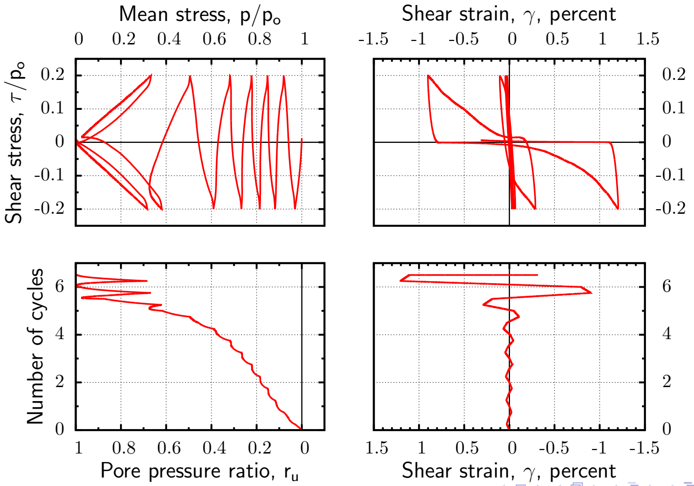
Uniform shearing amplitude:



Control strain rate $\dot{\gamma}$ in a sawtooth pattern until the targeted shear stress τ is attained.

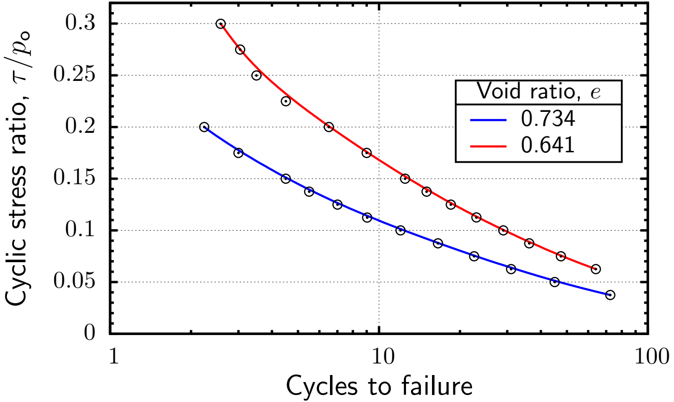
Case I: Uniform cyclic shearing

Conditions: $\tau = \pm 16$ kPa, $p_o = 80$ kPa



Case I: Uniform cyclic shearing

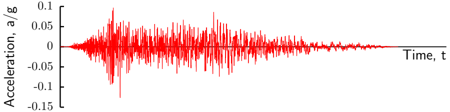
Liquefaction curves



Case II: Seismic shearing

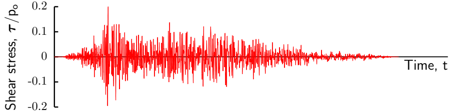
Select 24 sequences of seismic loading (Dr. Steven L. Kramer)

1. Earthquake ground accelerations from PEER data base



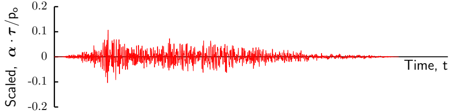
Landers, 1992
M = 7.3
MCF000

2. Create CSR, cyclic shear record (Dr. Kramer)



SHAKE91

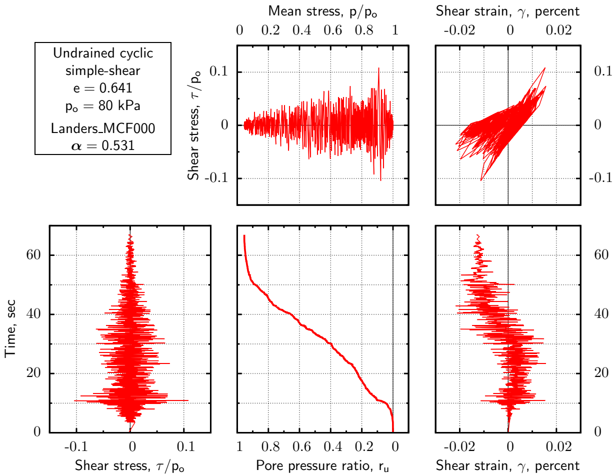
3. Scale the CSR to prolong pre-liquefaction



Scale factor:
α = 0.531

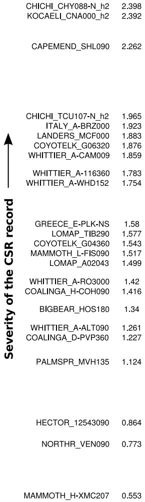
Case II: Seismic shearing

Landers 1992 CSR record, scaling factor $\alpha = 0.531$



Severity Measures for cyclic loading

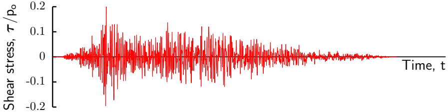
Ranking the severities, $1\,/\,\alpha$,
of 24 stress records,
as surmised from DEM simulations



Severity Measures

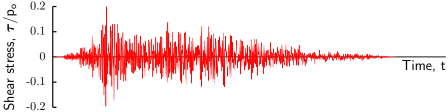
"Severity Measure":

- a scalar predictor of initial liquefaction
- computed from a cyclic stress (or strain) record



$\Longrightarrow$ Scalar value at initial liquefaction

Severity Measures



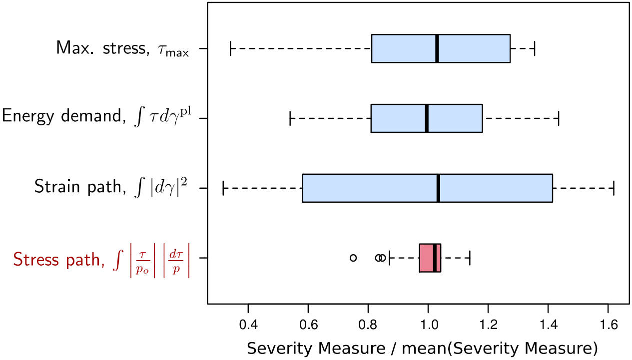
Possible Severity Measures for the 24 stress records:

- Maximum shear stress, $|\tau / p_o|_{\text{max}}$
- Energy demand, $\int \tau \, d\varepsilon^{\text{plastic}}$
- Strain path, $\int |d\varepsilon|^2$
- Stress path, $\int \left| \frac{\tau}{p_o} \right| \left| \frac{d\tau}{p} \right|$

Use DEM results to test the efficiency and sufficiency of each Severity Measure.

Severity Measures

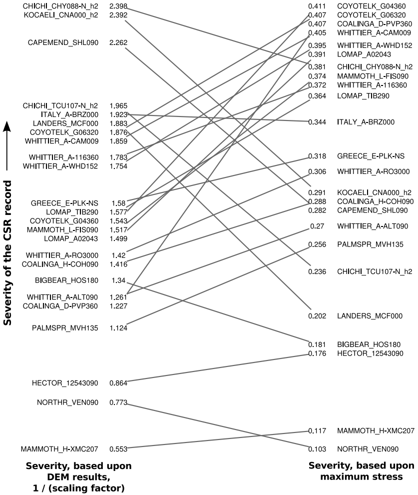
Efficiencies of four Severity Measures: 24 cyclic stress records



Severity Measures

Sufficiency of the Maximum Shear Stress as a Severity Measure:

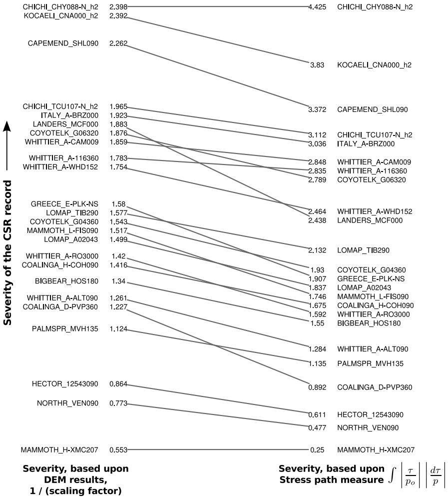
$|\tau / p_o|_{\max}$



Severity Measures

Sufficiency of a
stress path scalar
as a Severity Measure:

$$\int \left|\frac{\tau}{p_o}\right| \left|\frac{d\tau}{p}\right|$$



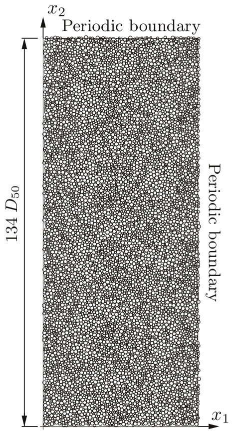
Contents

Granular Mechanics

Shear bands and non-classical continua

- Shear bands have a characteristic thickness
- Granular materials have an “inherent length scale”
- This scale is not acessible via classical continuum mechanics

Shear bands in DEM simulation — free deformation



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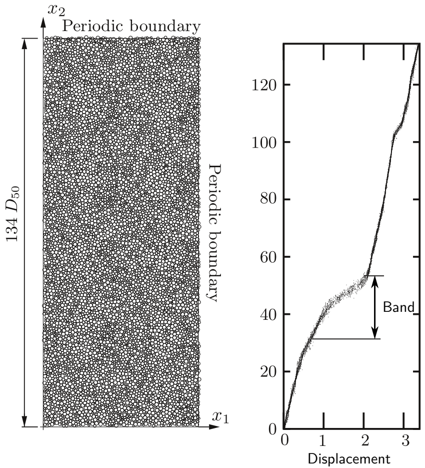

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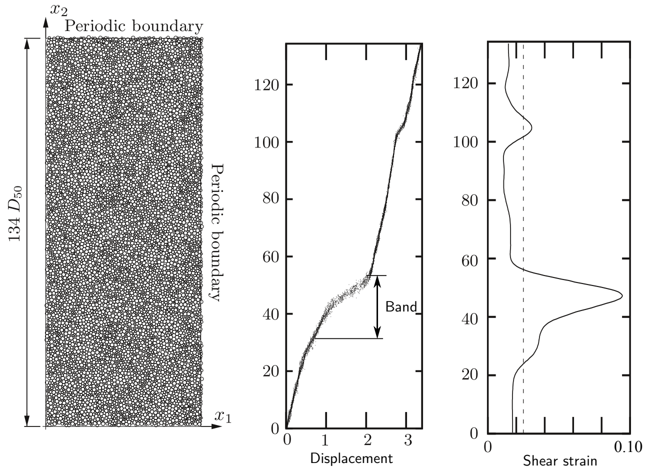

Non-classical continuum models

Continuum models with inherent length scale:

1. Cosserat / micropolar continua
2. Strain gradient-dependent material models
3. Non-local material material models

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2. Strain gradient-dependent material models

   $\boldsymbol{\tau} = f\,(\epsilon, \dot{\epsilon})$ Simple material

   $\boldsymbol{\tau} = f\,(\epsilon, \dot{\epsilon},\ \nabla\epsilon, \nabla(\nabla\epsilon), \ldots)$ Gradient-dependent material
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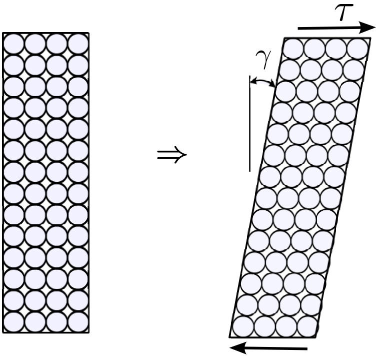
   Does stress really depend upon the spatial gradients of strain?
3. Non-local material material models

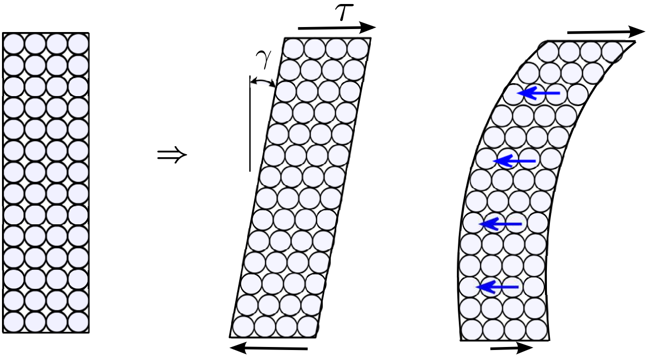
Strain gradient-dependent materials

Does stress depend upon the spatial gradients of strain?



Strain gradient-dependent materials

Does stress depend upon the spatial gradients of strain?



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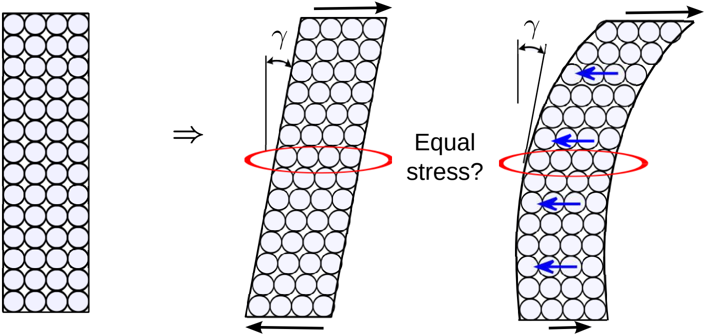
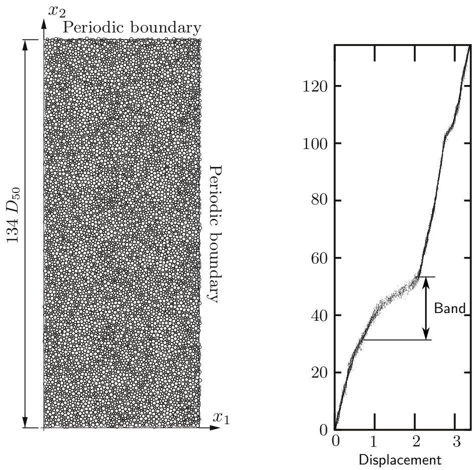
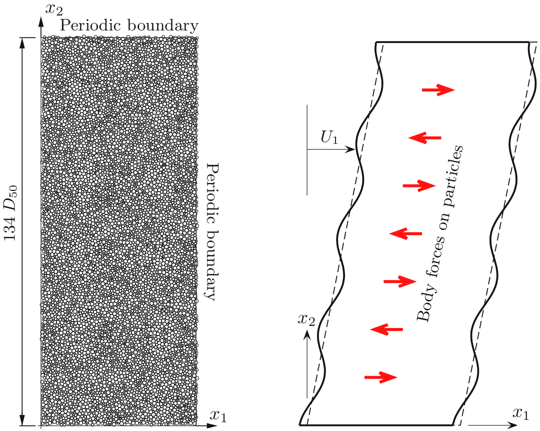


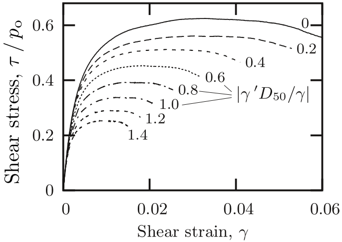
Shear bands in DEM simulation — free deformation



Constrained deformation using body forces

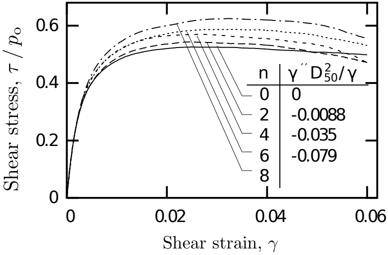


Effect of the first strain gradient



An increasing first gradient, γ', has a softening effect.

Effect of the second strain gradient



An increasing second gradient, γ'', has a hardening effect.

Shear bands

Shear bands and gradient-dependent behavior:

- Persistent bands develop near the peak stress state
- Shear strain γ is non-uniform within a shear band
- Shear stress depends upon γ, γ', and γ''
- In incremental form, $d\tau = f(d\gamma, d\gamma', d\gamma'')$
- Shear stress is constant within a shear band: $d\tau / dx_2 = 0$
- Can an incremental model explain the profile of strain within a shear band?

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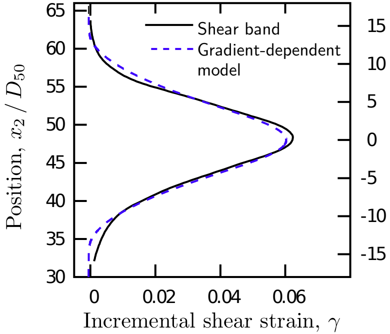
Solution of the incremental model:



Questions?