# Discrete Element Modeling of Soils as Granular Materials

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### Outline



### Discrete Element Method (DEM)

- 2 Soil simulations liquefaction
- Granular materials: Are they simple?

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Discrete Element Method (DEM)	Background of DEM
Soil simulations — liquefaction	Coding and challenges
Granular materials: Are they simple?	Alternatives to DEM

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- Coding and challenges
- Alternatives to DEM
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- 3 Granular materials: Are they simple?

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## DEM assembly of 6400 particles



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### Discrete Element Method (DEM)

### Background

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

**DEM** Algorithm

Background of DEM Coding and challenges Alternatives to DEM

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

 Background of DEM
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With each time step

Via Newton's equations of motion

### **DEM Software**

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Commercial software

- PFC3D Itasca, Inc.
- EDEM DEM Solutions

Open source software

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

Background of DEM Coding and challenges Alternatives to DEM

# Coding Challenges

- Particle shapes
   Spheres = Easy
   Other shapes = Difficult
- Contact detection: an N<sup>2</sup> 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

Discrete Element Method (DEM)	Undrained loading & static liquefaction
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- Ocyclic liquefaction
- Severity measures

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## DEM assembly of 6400 particles



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# Particle shape



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## **DEM** model

Contact properties:

• Hertz-Mindlin (elastic-frictional) contact model

•  $\mu = 0.60$  friction coefficient

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# Verifying the DEM model

#### Undrained triaxial compression and extension tests



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# Verifying the DEM model

#### Undrained triaxial compression tests - range of densities



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### Undrained simple-shear results

#### Undrained simple-shear:



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## 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



Mean stress, p

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## Static liquefaction

Drained shearing followed by undrained shearing:



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# 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

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# Case I: Uniform cyclic shearing

Uniform shearing amplitude:



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

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### Case I: Uniform cyclic shearing

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



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# Case I: Uniform cyclic shearing

#### Liquefaction curves



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# Case II: Seismic shearing

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



Create CSR, cyclic shear record (Dr. Kramer)



Scale the CSR to prolong pre-liquefaction



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### Case II: Seismic shearing

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



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Severity measures

### Severity Measures for cyclic loading

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

KOCAELI CNA000 h2 2,392 CAPEMEND\_SHL090 2.262 CHICHI TCU107-N h2 1.965 ITALY A-BRZ000 1,923 LANDERS\_MCF000 1.883 COYOTELK G06320 1,876 WHITTIER A CAM009 1,859 WHITTIER A 116360 1.783 WHITTIER A WHD152 1.754 record GREECE E-PLK-NS 1.58 LOMAP TIB290 1.577 COYOTELK G04360 1 543 CSR MAMMOTH L-FIS090 1.517 LOMAP A02043 1.499 Severity of the WHITTIER A-RO3000 1.42 COALINGA H COH090 1.416 BIGBEAR HOS180 1.34 WHITTIER A-ALT090 1,261

CHICHI CHY088-N h2 2,398

MAMMOTH H-XMC207 0.553

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COALINGA D PVP360 1,227 PALMSPR MVH135 1.124

HECTOR 12543090 0 864 NORTHR VEN090 0,773 Discrete Element Method (DEM) Soil simulations — liquefaction Granular materials: Are they simple? Undrained loading & static liquefact Cyclic liquefaction Severity measures

### **Severity Measures**

"Severity Measure":

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



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# Severity Measures



Possible Severity Measures for the 24 stress records:

- Maximum shear stress,  $| au/p_o|_{\max}$
- 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.

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### **Severity Measures**

#### Efficiencies of four Severity Measures: 24 cyclic stress records



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### Severity Measures

Sufficiency of the Maximum Shear Stress as a Severity Measure:

 $| au/p_o|_{\mathsf{max}}$ 



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### **Severity Measures**

Sufficiency of a stress path scalar as a Severity Measure:

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



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  - Shear bands and non-classical continua
  - Strain gradient-dependent materials
  - DEM measurement of strain gradient effects

Shear bands and non-classical continua Strain gradient-dependent materials DEM measurement of strain gradient effects

# **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

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Shear bands and non-classical continua Strain gradient-dependent materials DEM measurement of strain gradient effects

# Shear bands in DEM simulation — free deformation



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### Shear bands in DEM simulation — free deformation



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### Non-classical continuum models

Continuum models with inherent length scale:

- Cosserat / micropolar continua
- Strain gradient-dependent material models
- Non-local material material models

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### Non-classical continuum models

#### Continuum models with inherent length scale:

- Cosserat / micropolar continua
- Strain gradient-dependent material models
  - $au = f(\epsilon, \dot{\epsilon})$  Simple material
  - $\boldsymbol{\tau} = f(\boldsymbol{\epsilon}, \dot{\boldsymbol{\epsilon}}, \nabla \boldsymbol{\epsilon}, \nabla (\nabla \boldsymbol{\epsilon}), \ldots)$  Gradient-dependent material
- Non-local material material models

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### Non-classical continuum models

#### Continuum models with inherent length scale:

- Cosserat / micropolar continua
- Strain gradient-dependent material models
   τ = f(ε, ė) Simple material
   τ = f(ε, ė, ∇ε, ∇(∇ε),...) Gradient-dependent material
   Does stress really depend upon the spatial gradients of strain?

   Non-local material material models

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### Strain gradient-dependent materials

Does stress depend upon the spatial gradients of strain?



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### Shear bands in DEM simulation — free deformation



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# Constrained deformation using body forces



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# Effect of the first strain gradient



An increasing first gradient,  $\gamma'$ , has a softening effect.

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### Effect of the second strain gradient



An increasing second gradient,  $\gamma''$ , has a hardening effect.

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## Shear bands

Shear bands and gradient-dependent behavior:

- Persistent bands develop near the peak stress state
- Shear strain  $\gamma$  is non-uniform within a shear band
- Shear stress depends upon  $\gamma$ ,  $\gamma'$ , and  $\gamma''$
- 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:



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### Questions?

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