Micro-scale modelling of internally unstable soils

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Outline

• Internal instability

• Micro-scale modelling

• Hydromechanical criteria for erosion:
  • Stress reduction in finer particles
  • Coupled DEM-CFD Analysis
Internal Instability

Gap/broadly graded soils: Fine fraction preferentially eroded

Erosion of fines at low hydraulic gradients (i < 0.3)

Prerequisites:

• Cohesionless fines
• Load carrying matrix of coarse particles
• Fines under low stress
• Fines small enough to pass between coarse
Eurocode 7: Hydraulic Failure

“[Geometric] **Filter criteria** shall be used to limit the danger of material transport by internal erosion.”

“If the filter criteria are not satisfied, the **hydraulic gradient** should be well below the critical gradient at which soil particles begin to move.”
Aim of micro-scale analysis

Examine both elements of filter design:

- Geometric Filter criteria
- Pore constrictions in granular filters
- Critical hydraulic gradient
- Effective stress reduction in fine particles
- Coupled analysis of erosion
Aim of micro-scale analysis

Examine both elements of filter design:

Filter design (internal instability)

- Geometric Filter criteria
- Critical hydraulic gradient
- Effective stress reduction in fine particles
- Coupled analysis of erosion

- Pore constrictions in granular filters
Geometric Filter Criteria: Kézdi (1979)

Split Gap-graded PSD into coarse and fine “PSDs”

Stable if:  \( \frac{D_{15}^{\text{coarse}}}{d_{85}^{\text{fine}}} < 4 \)

\( (D_{15}^{\text{coarse}} / 4) \) proxy for ‘pore size’

\( D_c \approx D_{\text{coarse}} / 4-5 \)
Micro-scale modelling:
Discrete Element Modelling
Micro-scale modelling

• DEM: Discrete Element Modelling

• Each element is a single soil particle

• Generally used for coarse-grained soils >100μm: Body forces dominate

• Used for virtual laboratory experiments
Discrete element method (DEM)

• Rigid particles which can overlap at contacts
• Overlap proportional to force acting at contacts
• Particles move at each timestep and make / break contact with neighbours

Measure variables unavailable in lab:

Inter-particle force
Particle stress
Void size
DEM Particle
Constriction
Hydromechanical potential for erosion: Stress reduction in finer particles
Critical hydraulic gradient and stress

For internally stable soils:

\[ i_{\text{crit(heave)}} : \text{hydraulic gradient at which } \sigma_v' = 0 \]

\[ i_{\text{crit(heave)}} = \frac{\gamma'}{\gamma_w} \approx 1.0 \quad (\text{Terzaghi, 1925}) \]

For internally unstable soils:

\[ i_{\text{crit(unstable)}} < 1 \quad (\text{as low as 0.2}) \]

How to predict \( i_{\text{crit(unstable)}} ?? \)
Hydromechanical criterion

Skempton and Brogan (1994):

Coarse particles transfer overburden

Fines carry reduced effective stress:

\[ \sigma'_{\text{fine}} = \alpha \sigma' \]

Critical gradient to reach \( \sigma' = 0 \)

\[ i_{\text{crit(unstable)}} = \alpha i_{\text{crit(heave)}} \]

Micromechanical hypothesis
DEM Simulations

> 300,000 particles for large simulations

Servo-controlled **isotropic compression** to $p' = 50\text{kPa}$

**Periodic cell** – no boundary effects

Sample **density controlled** using interparticle friction:
$\mu = 0.0$ (Dense), $\mu = 0.1$ (Medium dense), $\mu = 0.3$ (Loose)
Gap-graded samples

Study effect of:

- PSD (gap-ratio + fine-content)
- Relative density

DEM: Measurement of $\alpha$-factor:

$$\alpha = \frac{p_{\text{fine}}'}{p'}$$

Mean stress in finer particles

Mean stress in all particles

Two experimentally tested PSDs

Increasing $D_{15}^{\text{coarse}}/d_{85}^{\text{fine}}$

Increasing fines %
**Effect of % fines and density**

Low fines (<25%);

\[ \alpha < 0.4 \]

Fines don’t fill voids

Intermediate: Influence of relative density

High fines (>35%);

\[ \alpha \approx 1 \]

Fines separate coarse particles

**Results**

**Effect of gap-ratio**

<table>
<thead>
<tr>
<th>Loose</th>
<th>Medium</th>
<th>Dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>35% fines</td>
<td>25% fines</td>
<td>18% fines</td>
</tr>
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</table>

\[ D_{15}^{\text{coarse}} / d_{85}^{\text{fine}} \]

**Stress-reduction**

\[ \alpha \]

\[ F_{\text{fine}} \]

\[ \% \]
All Results

Good agreement between experimental and DEM $\alpha$-values

Experimental: Permeameter

$\alpha = \frac{i_{\text{crit}(\text{unstable})}}{i_{\text{crit}(\text{heave})}}$

DEM: $\alpha = \frac{p'_{\text{fine}}}{p'}$
Three important factors:

- Fines content,
- Relative density
- Diameter ratio

Underfilled and transitional: $\alpha$ reduces with Diameter ratio ($D_{15}^{\text{coarse}} / d_{85}^{\text{fine}}$)

Fines content < 25%  
Underfilled: $\alpha \ll 1$

Fines content > 35%  
Overfilled: $\alpha \approx 1$
Hydromechanical potential for erosion:
Coupled DEM-CFD analysis
Coupled DEM-CFD

Aim: model permeameter at micro-scale

Large permeameter for studying suffusion:

- Can vary top stress and hydraulic gradient

- Macro-scale measurements:
  - Hydraulic gradient (local)
  - Change in permeability
  - Visual observation of suffusion

University of British Columbia
Coupling DEM + Computational Fluid Dynamics

Soil-fluid interaction
- DEM: soil particles
- CFD: water seepage

Data exchange
- CFD
  - Fluid velocity
  - Fluid pressure gradient
- DEM
  - Porosity
  - Drag force

Coarse grid method proposed by Tsuji

Fluid cells larger than particles

(Tsuji et al., 1993, Xu and Yu, 1997)
Coarse grid method

Averaged Navier-Stokes equation

\[ \frac{\partial n v_f}{\partial t} + v_f \nabla (n v_f) = \frac{u_f}{\rho_f} \nabla (n \nabla v_f) - \frac{n}{\rho_f} \nabla p + \frac{f_{\text{drag}}}{\rho_f} \]

- Inertia force
- Unsteady acceleration
- Convective acceleration
- Viscosity
- Pressure gradient force

\( f_{\text{drag}} \) calculated using empirical equation based on fluid velocity, porosity and particle diameter (Di Felice, 1994)

\( n \): porosity
\( v_f \): fluid velocity
\( \rho_f \): fluid density
\( \mu_f \): fluid viscosity
Simulating permeameter tests

- Virtual stress-controlled permeameter

Compress to 50kPa, Apply gravity
Create fluid mesh, Fix boundaries,
Apply pressure gradient, Monitor steady state response
Virtual permeameter simulations

- 4 Samples tested: Up to 35000 particles

- $D_{15}^{\text{coarse}} / d_{85}^{\text{fine}} = 4.6$ : Borderline unstable (Kezdi, 1979)

- 25% and 35% fines
  - Each Loose and Dense

- Hydraulic gradient, $i = 1, 2, 5, 10$

- $k \approx 1.0 \times 10^{-4}$ m/s to $2.3 \times 10^{-4}$ m/s
  Similar to experimental data from UBC
Coupled analysis: typical micro-scale result

Hydraulic gradient: \( i = 1 \)

Normalised particle stress \( = \frac{\sigma_{\text{part}}}{\sigma'} \)

Gap 25 Loose \( (\alpha = 0.11) \)

- Fines: low stress, erosion initiates
- Coarse matrix: high stress, no movement
- No matrix collapse

Gap 35 Loose \( (\alpha = 0.34) \)

- Stress transferring particles also eroded
- Some load-carrying matrix collapse
Coupled analysis: typical micro-scale result

Results point towards different behaviour / fabric types:

**Gap 25 Loose** \( (\alpha = 0.11) \)

Coarse matrix transfers stress.

Fines do not participate in stress transfer: Eroded *en masse*
Coupled analysis: typical micro-scale result

Results point towards different behaviour / fabric types:

Gap 35 Loose ($\alpha = 0.34$)

- Coarse particles dominate stress-transfer
- Understressed fines provide lateral support to coarse matrix

Fines harder to remove:
- But removal could cause matrix collapse and settlement
Coupled analysis: typical micro-scale result

Coupled study examined only small range of possible states (due to computational expense of simulations)
Summary

• DEM can be used to study internal instability at micro-scale

• Stress controls initiation of erosion and is linked to PSD and relative density

• Coupled DEM-CFD can be used to study fluid-particle interactions
Acknowledgements

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