Wave propagation and fluid transport: linking measurements and modelling

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Cundall and Strack (1979)

Force vector plots obtained by De Josselin de Jong and Verruijt (1969) in photoelastic experiments

\[ \frac{F_H}{F_V} = 0.39 \]

Force vector plots obtained in Cundall and Strack’s DEM simulation

\[ \frac{F_H}{F_V} = 0.43 \]
Validation tests and simulations: steel rods

I want to present some examples that show that:

1. DEM simulations can help us design new testing approaches.
2. DEM simulations can inform how we can interpret element test data to infer fabric.
3. PIV opens the possibility for us to better understand how to use CFD to study flow in the pores of soil.
Outline:

I want to present some examples that show that:

1. **DEM simulations can help us develop new testing approaches.**
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Laboratory Geophysics

\[ G = \rho V_S^2 \]

- \( G \) = shear stiffness
- \( \rho \) = material density
- \( V_S \) = shear wave velocity

Alvarado & Coop (2012)
Cubical cell apparatus.

Cubical Cell Apparatus
University of Bristol

Allows independent control of three principal stresses

(Sadek, 2006)

T-shaped bender/extender elements

Sealing grommet to prevent loss of vacuum

Layers of latex adhesive solution
DEM simulations of wave propagation

- Simulated using PFC 3D
- Flexible membrane boundaries
- Simplified Hertz-Mindlin contact model – input $G$ and $\nu$ for particle
- Bender/extender elements modelled as point sources
Signal comparison: Time domain

*Isotropic stress of 100 kPa*

*Sinewave pulse with frequency of 15 kHz*

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O’Donovan et al. (2016) [https://doi.org/10.1007/s10035-015-0599-4](https://doi.org/10.1007/s10035-015-0599-4)
Shear stiffness vs confining pressure

O’Donovan et al. (2016) https://doi.org/10.1007/s10035-015-0599-4
Bender element testing
Influence of transmitter connectivity

Local fabric tensor:

- $\Phi_{yz} = 0.207$
- $\Phi_{yx} = 0.407$
- $\Phi_{yy} = 0.386$
Shear plate technology

Bender elements

Shear plates

Otsubo et al. (2020) DOI: 10.1520/GTJ20180146
Shear plate technology

Experimental data

DEM data

Otsubo et al. (2020) DOI: 10.1520/GTJ20180146
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Internal instability in gap-graded soils

Piezometers

Rigid wall transparent cylinder

Inflow

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

$i=0.2$:
- “strong general piping of fines throughout”
- permeability twice initial value

Sample A

Skempton and Brogan (1994) Géotechnique

Robert Negri MSc
Effect of Fc on Shearing response

Undrained stress-strain behaviour
(Modified from Yang and Wei, 2012)

Toyoura sand (coarser grains)
Crushed silica (finer grains)

\[ q = \sigma_1 - \sigma_3 \]

Critical state locus
(Modified from Yang and Wei, 2012)

Increasing Fc leads to a downward shift to the critical state line (CSL) (in e-logp’ plane)

Increase in Fc leads to an increase in undrained strain-softening

Variables:
- \( q \): undrained shear strength
- \( \sigma_1 \): maximum principal stress
- \( \sigma_3 \): minimum principal stress
- \( e \): void ratio
- \( p' \): effective confining pressure

Mathematical Expressions:

- \( p' = \frac{\sigma_1' + 2\sigma_3'}{3} \)

Graphs show:
- Graph 1: Relationship between q and \( \varepsilon_a \) for different Fc levels.
- Graph 2: Relationship between \( p' \) and e for different Fc levels.

Legend:
- Fc=0%
- Fc=5%
- Fc=10%
- Fc=15%

Note: All graphs are modified from Yang and Wei, 2012.
Variation in void ratio with Fc

Collation of published experimental studies

Zuo and Baudet (2015)
Soils and Foundations

Otsubo et al. (2021) https://doi.org/10.1680/jgeot.19.P.334
Sufian et al. (2021) doi.org/10.1061/(ASCE)GT.1943-5606.0002487
Stress transmission in gap-graded soils

Shire et al. (2014) https://doi.org/10.1061/(ASCE)GT.1943-5606.0001184
Cubical cell apparatus.

O’Donovan et al. (2016) [https://doi.org/10.1007/s10035-015-0599-4]
**Signal comparison: Time domain**

*Isotropic stress of 100 kPa*

*Sinewave pulse with frequency of 15 kHz*

Transmitted signal

Received signal

**O’Donovan et al. (2016)** [https://doi.org/10.1007/s10035-015-0599-4](https://doi.org/10.1007/s10035-015-0599-4)
Signal Comparison: Frequency domain

Isotropic stress of 100 kPa
Sinewave pulse with frequency of 15 kHz

Transmitted signal
Received signal

O’Donovan et al. (2016) https://doi.org/10.1007/s10035-015-0599-4
Influence of $e$ and stress on $f_{\text{low-pass}}$

Random monodisperse sample: 35,201 particles

Moving along sample from source to receiver

$f_{\text{low-pass}}$ depends on particle diameter/layer spacing (Santamarina and Klein; Mouraille and Luding)

Influence of $e$ and stress on $f_{\text{low-pass}}$

Gain factor: the ratio of the frequency spectra (received / inserted)

Gap-graded samples considered

GW samples

GN samples

Up to 2.29 million particles in samples

GN: SR=3.4
GW: SR=8.8

Otsubo et al. (2021) https://doi.org/10.1680/jgeot.19.P.334
Influence of FC on $V_s$

GN: SR=3.4  
Fc=20%

GW: SR=8.8  
Fc=20%

Otsubo et al. (2021)  https://doi.org/10.1680/jgeot.19.P.334
Influence of $F_c$ on $f_{lp}$

Otsubo et al. (2021) https://doi.org/10.1680/jgeot.19.P.334
Relating Fc to $f_{lp}$ and $V_s$

Otsubo et al. (2021) https://doi.org/10.1680/jgeot.19.P.334
Bulk density

Bulk density: $\rho = \frac{M_s}{V}$

$V$ total volume = $V_v + V_{sol}$

$M_s$ mass of soil grains

Mechanical bulk density:

$\rho_m = \frac{M_s - M_s^{0 \text{ or } 1}}{V}$

$M_s^{0 \text{ or } 1}$ mass of grains with 0 or 1 contact
Macro-scale, continuum stiffness

\[ G = \rho V_s^2 \]

\[ G = \text{Shear stiffness} \]

\[ V_s = \text{Shear wave velocity} \]

\[ G = \rho V_s^2 \quad \text{or} \quad G = \rho_m V_s^2 ? \]

Measuring shear wave velocity using laboratory geophysics
Gradings considered in DEM study

**Linear specimens**

\[ C_u = \frac{d_{60}}{d_{10}} \]

Measure of polydispersity

60% of particles by volume are smaller than \(d_{60}\)

10% of particles by volume are smaller than \(d_{10}\)

Liu et al. (2021)  [doi/10.1061/ASCE/GT.1943-5606.0002466](https://doi.org/10.1061/ASCE/GT.1943-5606.0002466)

**Bimodal specimens**
Density and mechanical density

$\rho_m$ considers only stress-transmitting particles

$C_u = \frac{d_{60}}{d_{10}}$

Bimodal, SR 8

Liu et al. (2021)  doi/10.1061/%28ASCE%29GT.1943-5606.0002466
Approaches to measure stiffness

\[
G_{sta} = \frac{\delta q}{3\delta \varepsilon^e_q}
\]

\[
\delta \varepsilon^e_q = 2 (\delta \varepsilon_1 - \delta \varepsilon_3)/3
\]
Density, mechanical density and G

Medium-dense DEM specimens

PhD Thesis Deyun Liu
Density, mechanical density and G

DEM sample: Dense SR=8, p=500 kPa

PhD Thesis Deyun Liu
Density, mechanical density and G

Experimental data on sand

PhD Thesis Deyun Liu
Variation in void ratio with Fc

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Sheffield Permeameter Experiments

Solid and fluid with same refractive index

Fluorescent dye in fluid

≈1 micron thick laser sheet illuminates plane

Particles dark against bright background

Model soil – crushed borosilicate

Sheffield Permeameter Experiments

Sanvitale et al. (2021) https://doi.org/10.1680/jgeot.20.P.432
Sheffield Permeameter Experiments

Sanvitale et al. (2021) https://doi.org/10.1680/jgeot.20.P.432
Sheffield Permeameter Experiments

Results: velocity magnitude (m/s), d=7.5mm, i=0.028

Sanvitale et al. (2021) https://doi.org/10.1680/jgeot.20.P.432
Sheffield Permeameter Experiments

Sanvitale et al. (2021) https://doi.org/10.1680/jgeot.20.P.432
Sheffield Permeameter Experiments + CFD

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CFD to study fluid – particle interactions

Shape no significant effect on tortuosity or flow field

Shape does affect permeability and drag

Conclusions:

I hope I have shown that:

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