Engineering sand: From the micro- to the macro-scale

Catherine O’Sullivan
Overall argument

From an engineering perspective, it is worthwhile to look at the behaviour of sand from the perspective of an individual grain.

Reigate Sand – PhD Research of Dr. Joana Fonseca

Leighton Buzzard Sand – PhD Research of Dr. Howard Taylor

DEM simulation of Gap Graded Sand
Dr. A. Sufian & Ms. M. Artigaut
Sand behaviour

Stiffness

Strength

Seepage
Sand behaviour

Contact behaviour

Collective behaviour

Coupled behaviour
Supporting research
Size matters in soil classification

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt (Fine, Medium, Coarse)</th>
<th>Sand (Fine, Medium, Coarse)</th>
<th>Gravel (Fine, Medium, Coarse)</th>
<th>Cobbles</th>
<th>Boulders</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.002 0.006 0.02 0.06 0.2 0.6 2</td>
<td></td>
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<tr>
<td>0.001</td>
<td>0.01 0.02 0.06 0.2 0.6 2</td>
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<tr>
<td>0.001</td>
<td></td>
<td>10 100</td>
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<tr>
<td>0.001</td>
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</tbody>
</table>

- Clay grains smaller than 2 μm (0.002 mm)
- Ratio of surface area to volume is large
- Surface charges influence behaviour

Figure 1.2 Knappett and Craig (2012)
Clay

2 μm (2 μm = 0.002 mm)

Clay


Sara Bandera
Size matters in soil classification

- Sand grains exceed 60 µm (0.06 mm)
- Ratio of surface area to volume is small
- Surface charges don’t influence behaviour

Figure 1.2 Knappett and Craig (2012)
Sand

Badger Sand
Image by F. Altuhafi

Leighton Buzzard Sand
Image by I. Cavarretta

Dunkirk Sand

https://www.imperial.ac.uk/safety/safety-by-topic/safety-signs/
Sand behaviour is important

WAC Bennett Dam
- High as a 60-storey building and two kilometres wide
- Holds back 360 kilometres of Williston Lake, the largest reservoir in North America

1996 Sinkhole at WAC Bennett Dam
(BC Hydro as cited by Muir Wood, 2007)
Sand behaviour is important

Minas Gerais – January 2019
157 fatalities, 182 people unaccounted for

Sand behaviour is important

Approx. location of the Hayward Fault
Sand behaviour is important

Earthquake-induced liquefaction at Onahama Port, Japan, 2011

Liquefaction in Maria District, San Francisco 1989 Loma Prieta Earthquake

Shortland Street in the suburb of Aranui, New Zealand, 2011
Fundamental research into sand behaviour

Laboratory element tests ➔ *How* sand behaves
Fundamental research into sand behaviour

Particle scale simulation and observation $\Rightarrow$ \textit{Why} sand behaves the way it does
Discrete Element Method (DEM)
DEM uptake

All disciplines
Application of DEM

Hanley (2011)
Application of DEM

Experiments

DEM Simulations

Al - Cu alloy

Push plate

Push plate

Push plate

Push plate

Low Solid Fraction

High Solid Fraction

Liquid expelled

Increased fluid pressure

Meniscus sucked in

Decreased fluid pressure

Change in liquid pressure (kPa)

-0.05

-0.05

https://www.mesinc.net/aluminum-die-casting/

Su et al. (2018)
DEM uptake

Geomechanics

Papers in 7 leading journals

No. of papers

Year

1999 2004 2009 2014 2018
How many particles in our models?

Sand with median particle diameter = 0.200 mm:

>150,000 particles


** DEM Calculation Cycle **

- Identify contacting particles
- Determine contact forces
- Calculate accelerations+velocities of particles
- Update positions

*Small timesteps are needed*
How many particles in our models?

Papers in 7 leading geomechanics journals

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>150,000 particles</td>
</tr>
<tr>
<td>2004</td>
<td>500 particles</td>
</tr>
<tr>
<td>2009</td>
<td></td>
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<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
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</table>
Density-dependent behaviour

\[ q = \sigma'_1 - \sigma'_3 \]

\[ q = \text{deviatoric stress:} \]

\[ \varepsilon_a = \text{axial strain (}\Delta L/L)\]

\[ e = \text{void ratio : measure of packing density} \]

Loose sands at risk of liquefaction
Initial $e = 0.65$

Periodic Boundaries

Cell Simulated

Ring size $\approx D_{50}$

Black regions – very low packing density

Volumetric strain

Cell Simulated

Periodic Boundaries

Initial $e = 0.65$

PB

Rigid Wall Boundaries

20,164 spheres

Periodic Boundaries

6,783 spheres

16,073 spheres

31,392 spheres

20,164 spheres

PB

$\epsilon_a = \text{axial strain } (\Delta L/L)$

$\epsilon_v = \text{volumetric strain}$

$e_a = \text{axial strain } (D_L/L)$

$e_a = \text{axial strain } (D_L/L)$

$V_{\text{cell}}$ = simulated

$V_{\text{periodic}}$ = simulated
How many particles in our models?

Papers in 7 leading geomechanics journals

No. of particles
Average for year
Research I have been involved with

PhD Liang Cui
PhD Geraldine Cheung
PhD Tom Shire
Adnan Sufian
PhD Catherine O’Sullivan
High performance computers
Microcomputed Tomography

Approx 10 mm in diameter
Microcomputed Tomography

X-ray source
Sample
Detector
Sand behaviour

Stiffness

Strength

Seepage
Stiffness

Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011
Stiffness

Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011

Building weight

Settlement

Slope = stiffness
Stiffness

\[ q = \sigma'_1 - \sigma'_3 \]

\[ \varepsilon_a = \text{axial strain } (\Delta L/L) \]

Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011
Stiffness

\[ q = \sigma'_1 - \sigma'_3 \]

\[ \varepsilon_a = \text{axial strain (}\Delta L/L\text{)} \]
Shear Stiffness, $G$ (kPa) vs. Average Pressure, $p'$ (kPa)

Stiffness

Shear Stiffness, $G$ (kPa)

Average Pressure, $p$ (kPa)

Stiffness

Shear Stiffness, $G$ (kPa) vs Average Pressure, $p$ (kPa)

Thanet Sand

Ventouras and Coop (2009)
Stiffness

Contact for smooth spheres

\[ N \propto \delta^{3/2} \]

Shear Stiffness, \( G \) (kPa)

Average Pressure, \( p \) (kPa)

Normal force

Contact normal deformation (\( \delta \))
Stiffness

Shear Stiffness, $G$ (kPa)

Average Pressure, $p$ (kPa)

- Theory: Slope = $1/3$
- Experiments: Slope = $1/2$

Normal force

- $N \propto \delta^{3/2}$

Contact for smooth spheres
Surface roughness effects on stiffness

Ballotini + Toyoura Sand

$S_q = 58 \text{ nm}$

$S_q = 612 \text{ nm}$

(Otsubo, 2017)
Quantifying stiffness via wave propagation

(Otsubo, 2017)
Quantifying stiffness via wave propagation

Asperity dominated
Transitional
Hertzian

Contact between rough spheres

$\delta$ (Otsubo, 2017)
Surface roughness and stiffness

- Smooth particles: Slope $\approx 1/3$
- Rough particles: Slope $\approx 1/2$

- Lab: $S_q \approx 60$ nm
- Lab: $S_q \approx 600$ nm
- DEM: $S_q = 70$ nm
- DEM: $S_q = 600$ nm
Sand behaviour

Stiffness

Strength

Seepage
Strength

Big Sur Landslide – California (2017)

Domestic foundation failure: Rehoboth Beach Delaware, 1962
Soil strength is stress-dependent

Strength = maximum stress or pressure that can be applied

\[ q = \sigma'_1 - \sigma'_3 \] (kPa)

\[ \varepsilon_a = \text{axial strain} \left( \frac{\Delta L}{L} \right) \]

Based on Figure 5.20 Knappett and Craig (2012)
Stress: strength relationship
Stress:strength relationship

Friction $\mu$

interface friction angle

$\phi = \tan \phi$

$\mu = \tan \phi$

$N$

$T$

$\phi$
Stress: strength relationship

Figure 5.8 Knappett and Craig (2012)
Stress:strength relationship

Figure 5.8 Knappett and Craig (2012)
**Stress:strength relationship**

\[ \tau = \frac{T}{A} \]

\[ \sigma = \frac{N}{A} \]

\( \phi = \text{angle of internal friction} \)

Figure 5.8 Knappett and Craig (2012)
Stress:strength relationship

Friction $\mu$
Effect of particle friction

\[ T = \mu N \]

\[ \mu = \tan (\phi_{\text{surface}}) \]

\[ \phi'_{cv} = \sin^{-1} \left( \frac{\sigma'_1 - \sigma'_3}{\sigma'_1 + \sigma'_3} \right) \]

\[ \phi'_{cv} : \text{relationship between normal stresses and shear strength} \]

Soil Friction Angle

Particle surface friction angle, \( \phi'_{\text{surface}} \) (Deg)
Contact Normal Forces (Normalized)

Global shear strain: %

Stress ratio $\tau / \sigma_n$

Vertical strain: %
Global shear strain: %

Vertical strain: %

Stress ratio $\tau / \sigma_n$

Contact Normal Forces (Normalized)
Global shear strain: %
Vertical strain: %

Stress ratio $\tau / \sigma_n$

Contact Normal Forces (Normalized)
Force chains

Photoelastic grains under shear
Photo/Behringer Group, Duke University

Force chains inferred from 3D microCT image
Fonseca et al. (2017)

Force chains in 3D DEM simulation
Shire (2011)
Stress:strength relationship
Stress:strength relationship

Vary FL to model varying $\sigma'_3$

Spring and rigid link model of single force chain

Hanley et al. (2015)
Stress: strength relationship

To find P that causes buckling
Minimize potential energy function

Spring and rigid link model of single force chain

Spring and rigid link model of single force chain

Hanley et al. (2015)
3D nature of soil strength

Axisymmetric stress conditions

Non-axisymmetric stress conditions

\[ \sigma'_1 > \sigma'_2 > \sigma'_3 \]
3D nature of soil strength

Lade failure criterion
Same average stress

\[ b = \frac{\sigma'_2 - \sigma'_3}{\sigma'_1 - \sigma'_3} \]

\( b=0 \) \quad \( b\approx 0.5 \) \quad \( b=1 \)

\( \sigma'_1 > \sigma'_2 > \sigma'_3 \)

O’Sullivan et al. (2013)
3D soil strength

4000 spheres
Narrow size distribution

Barreto (2008)
3D nature of soil strength

Spring and rigid link model of single force chain

$P / P_b = 0$

O’Sullivan et al. (2013)
3D nature of soil strength

Spring and rigid link model of single force chain

O’Sullivan et al. (2013)
Reigate sand

PhD Research of Dr. Joana Fonseca
Reigate sand – response in triaxial compression

Intact: $e_0 = 0.48$
Reconstituted: $e_0 = 0.49$

Cell pressure 300 kPa
Reigate sand – particle-scale analysis

Contact Index = \frac{\text{Contact area}}{\text{Particle surface area}}

Graph showing contact index versus percentage of smaller particles for intact material and reconstituted material.
Contact network and strength

Force chain stability significantly influences sand strength

Factors which contribute to stability

• Friction
• Rotational resistance at contact points
  Depends on shape and contact area
• Support provided by lateral contacts

Magnitude of contact force
Number of contacts

Interparticle friction angle, $\phi_{\text{surface}}$ (Deg)
Strength, dilatancy, fabric

Dense $\Psi < 0$

Loose $\Psi > 0$

Data for sand (Jefferies and Been)

DEM data
Strength: collective behaviour

Granular materials are complex networks of contacting particles

A reductionist approach that considers a single interaction will not explain the overall material behaviour

The collective behaviour of the system needs to be considered
Sand behaviour
Flood embankments
Flood embankments

Design aim:
- Reduce downstream hydraulic gradient, $i$
- $i$ is rate of energy loss in seeping water
- When $i = 1$, in soil $\sigma' = 0$, and shear strength is lost

Flood embankments

Construction completed in 2015

https://www.raitoinc.com/applications/cutoff-wall-1/
10% of particles by mass are smaller than $D_{10}$

15% of particles by mass are smaller than $D_{15}$

85% of particles by mass are smaller than $D_{85}$

Filter retention $D_{15F} < 4 \ D_{85B}$
Permeability

Permeability is a measure of resistance to flow – quantifies how much energy the water needs to exert to pass through the soil.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Degree of permeability</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean gravels</td>
<td>High</td>
<td>$&gt; 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sand and gravel mixtures</td>
<td>Medium</td>
<td>$1 \times 10^{-3} - 1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Very fine sands, silty sands</td>
<td>Low</td>
<td>$1 \times 10^{-4} - 1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Hazen (1892): $k = CD_{10}^2$

$k = \text{permeability}$

Empirical approach

Doesn’t consider void ratio

Uncertainty over choice of $C$
Seepage – samples considered

**Micro CT**
- Leighton Buzzard Sand $C_u=3$
- Leighton Buzzard Sand $C_u=1.5$
- Glass Beads $C_u=3$

**DEM Simulations**
- Spheres $C_u=1.2$
- Spheres $C_u=3.0$
- Spheres $C_u=6.0$

**CFD-DEM**
- Multi-flow (van Wachem et al.)

(Taylor, 2017) (Shire, 2014) (Knight, 2018)
Void space topology

Micro CT

Taylor et al. (2017)

http://www.christiani.biz/project/office-rooms-maze-illustration/

DEM

Shire (2014)
Fluid flow simulations

Sub-volume for CFD analyses

Micro-CT binary image

Finite volume mesh

OpenFOAM simulation

Pressures

Velocities
Fluid flow velocity

Velocity = \( V_{\text{discharge}} = \frac{Q}{A} \)

\( V_{\text{seepage}} = \frac{V_{\text{discharge}}}{n} \)  
\( n = \text{porosity} = \frac{\text{Volume of voids}}{\text{Total volume}} \)
Constrictions and seepage

Velocity maximum
(= Hydraulic constriction)

Constriction diameter / D

Passing, by number (%)

High velocity
Low velocity

Geometric Constriction
Tracing Flow along a Streamline

Sufian, Knight, et al. (2019)
Constriction size distributions (DEM)

Particle size distribution

% smaller

Normalised diameter \( \frac{D}{D_0} \)

---

Constriction size distributions (DEM)

- Spheres \( C_u = 1.2 \)
- Spheres \( C_u = 3.0 \)
- Spheres \( C_u = 6.0 \)

(Shire, 2014)
Constriction size distributions (DEM)

Particle size distribution

- Normalised diameter ($D / D_0$)
- % smaller

Delaunay triangulation of particles

Validity of geometric partitioning demonstrated in CFD analyses

Constriction size distributions (DEM) (Shire, 2014)

Delaunay triangulation of particles

Velocity maximum

(= Hydraulic constriction)

High velocity

Low velocity

Geometric Constriction

(Shire, 2014)
Constriction size distributions (DEM)

Particle size distribution

Constriction size distribution

Constrictions become larger to $\text{Cu} = 3$

Very similar constriction sizes for $\text{Cu} \geq 3$
Constriction size distributions (DEM)

Constriction size distribution

Normalised diameter ($D / D_0$)

% smaller

$CSD Cu = 1.2$
$CSD Cu = 1.5$
$CSD Cu = 2$
$CSD Cu = 3$
$CSD Cu = 4.5$
$CSD Cu = 6$

$D_{10} = \text{characteristic diameter}$

Gives indication of constriction sizes in soil

Hazen: $k = CD_{10}^2$
Embankment dams

Schematic cross section

- Reservoir
- Shell
- Clay core
- Shell
- Filter
- Drain

- Downstream protection
- Core
- Sandwich filter

Paraperios dam - May 26 2010
Filters

Schematic cross section

Reservoir
Shell
Clay core
Shell
Filter
Drain

Seeping water can move particles in the embankment

(FEMA, 2011)
Filters
Filters

Schematic cross section

Reservoir
Shell
Clay core
Shell
Filter
Drain

Seeping water can move particles in the embankment

When a filter works:

Fine core particles get trapped in constrictions in void space

Water flows so there is no build up of pressure

(FEMA, 2011)
Terzaghi’s filter rule / Sherard & Dunnigan (1989):

- $D_{15F}$ of filter
- $D_{85B}$ of base
- For retention $D_{15F} < 4D_{85B}$

(ICOLD, 2015)

(FEMA, 2011)
Constriction size distributions (DEM)

Filter PSD

Filter CSD

Constrictions become larger to Cu = 3

Very similar constriction sizes for Cu ≥ 3

Shire and O’Sullivan (2016)
Constriction size distributions (DEM)

Shire and O’Sullivan (2016)
Filtration – Network model

- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles
### Filtration – Network model

- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles

**Likelihoods**
- \( p(A) = 0.3 \)
- \( p(B) = 0.6 \)
- \( p(C) = 0.1 \)

**Base particle movements**
- Moves through constriction
- Retained + constriction blocked
- Retained in void

---

Shire and O’Sullivan (2017)
Filtration – Network model

- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles

Node (void)
Edge
Three entrances and three exits per void

Base Particles

\[ p(A) = 0.3 \]
\[ p(B) = 0.6 \]
\[ p(C) = 0.1 \]
Controlling constriction size

Kenney et al. (1985): Base-Filter tests: Base-filer tests

\( D^* \) = controlling constriction diameter = largest particle that can pass through filter

Largest base particle eroded agrees with experimental data for range of base material sizes \( D_{50B} \) and filter \( Cu = 1.2, 3, 6 \)

\( D_{50B} \) = median base (clay core) diameter
\( D_{0F} \) = smallest filter diameter

\( (K\)enney et al., 1985)
Filtration – Network model

- $D_{15B} =$ base diameter 15% smaller
- $D_{85F} =$ filter diameter 85% smaller

Terzaghi’s filter rule / Sherard & Dunnigan (1989):
- $D_{15F}$ of filter
- $D_{85B}$ of base
- For retention $D_{15F} < 4 \times D_{85B}$

(FEMA, 2011)

Shire and O’Sullivan (2017)
• In gap graded materials erosion can happen at low hydraulic gradients
Skempton and Brogan permeameter experiments

Prof. Skempton

Sample A

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

i=0.2:

- "strong general piping of fines throughout"
- permeability twice initial value

Skempton and Brogan (1994)
Géotechnique

Prof. Skempton

Piezometers

Rigid wall transparent cylinder

Inflow

\( v \text{ cm/s} \)
Flood embankments

Design aim:

• Reduce downstream hydraulic gradient, $i$

• $i$ is rate of energy loss in seeping water

• When $i=1$, in soil $\sigma' = 0$, and shear strength is lost

Skempton and Brogan permeameter experiments

Sample A

- "strong general piping of fines throughout"
- permeability twice initial value

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

i=0.2:

- permeability twice initial value

Prof. Skempton

Skempton and Brogan (1994)

Géotechnique
\( \alpha \): proportion of stress carried by finer grains

- Larger particles transfer most of stress
- Finer grains carry reduced effective stress
- \( \alpha \) is proportion of stress carried by finer fraction

\[
\sigma'_{\text{fines}} = \alpha \times \sigma'
\]

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

Skempton and Brogan (1994)  
Géotechnique
DEM simulations to investigate instability

Shire et al. (2014) ASCE JGGE

Range of gap graded materials
Density varied for all samples

Shire et al. (2014) ASCE JGGE
Variation in $\alpha$ with fines content ($F_{\text{fine}}$)

$\alpha$: proportion of stress carried by finer fraction

Shire et al. (2014) ASCE JGGE
Variation in $\alpha$ with fines content ($F_{\text{fine}}$)

Shire et al. (2014) ASCE JGGE
Permeameter test simulations

- Simulate water flow through packed bed
- To establish link between $\alpha$ and erosion likelihood

DEM
- For soil particles
- Porosity
- Drag force

CFD
- For fluid
- Fluid velocity in each cell
- Fluid pressure gradient at cell-scale

Coarse grid method proposed by Tsuji

MPhil research of Kenichi Kawano
Particle stress and movement

**Gap 25 Loose**

**Gap 25 Dense**

Displacement (mm)

Normalized particle stresses $\alpha$

Normalized particle stresses $\alpha$
Fluid particle interaction force - verification

Coarse Grid Approach:
- Fluid properties averaged in cell
- Fluid-particle interaction force calculated using empirical equation

Immersed Boundary Method:
- Fully resolved flow
- Fluid-particle interaction force can be directly determined
- Smaller samples – computational cost high (Knight, 2018)
Fluid particle interaction force - verification

Multi-flow (van Wachem et al.)

Fully resolved flow

Fluid-particle interaction force can be determined

Sample: Cu=2.5, e=0.425

(Knight, 2018)
Fluid particle interaction force using local void ratio

Forces normalized by Stoke’s Drag

Tenneti et al. polydispersity correction also applied

Forces calculated from CFD DEM
Prediction using local void ratio

Drag force on particles

$D / D_{\text{min}}$

Knight (2018)
Network based approach to determine forces

Sufian, Knight, et al. (2019)
Sand behaviour

- Stiffness
- Strength
- Seepage
Sand behaviour

Contact behaviour

Collective behaviour

Coupled behaviour
Conclusions: Stiffness

Stiffness – Contact behaviour

Increasing particle surface roughness reduces stiffness and influences the stress:stiffness relationship

Models agree with physical experiments
Conclusions: Strength

Strength – Collective behaviour

Chains of particles carrying relatively large stress transmit pressure through sand

Failure is associated with buckling of these chains

Friction, confining pressure and contact geometry contribute to force chain stability
Conclusions: Seepage

Seepage – Coupled behaviour

Most of the energy in seeping water is lost at the constrictions in the void space.

Constriction sizes determine filtration properties.

Can link constriction sizes to characteristic diameters ($D_{10}$, $D_{15}$).

Accurate prediction of the forces imparted by seeping water is important to advance understanding of seepage induced instabilities.
From an engineering perspective, it is worthwhile to look at the behaviour of sand from the perspective of an individual grain.

Reigate Sand – PhD Research of Dr. Joana Fonseca

Leighton Buzzard Sand – PhD Research of Dr. Howard Taylor

DEM simulation of Gap Graded Sand
Dr. A. Sufian & Ms. M. Artigaut
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