Insight into granular materials from tomography:
(i) natural and engineered sands
(ii) semi-solid metals

Catherine O’Sullivan

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Chris Gourlay, Te-Cheng Su, Kristina Kareh, Fatin Altuhafi
Application: Embankment dams

- Dams can be over 100 m high
- Water seeps through dam continuously
- Seeping water can preferentially erode fines
- In the UK about 2,500 dams retain reservoirs exceeding 25,000 m³

Typical cross section

- Shells
- Clay core
- Filter
- Drain
Embankment dams

As a first effort, a number of conventional filter tests (with an initial hole in the base specimen) were made with compacted sand and sandy gravel filters using relatively thin (30-60 mm thick) base specimens of clay and silt. The specimens were compacted near Standard Proctor Optimum water content. In these tests, the water pressure acting across the base specimen was gradually increased to a maximum of about 6 kg/cm, giving a hydraulic gradient of about 1,000-2,000.

**Figure 2-3.** Typical embankment dam design elements found in a central core design. Components of a modern embankment dam illustrated in are:

- **Core**: Zone of low permeability soil that acts as the water barrier in the dam.
- **Cutoff Trench**: A cutoff trench to rock or other low permeability strata that is integrated with the overlying core.
- **Upstream Shell**: Zone of higher strength soil to support the upstream face of the core. The geometry of the upstream core is sometimes dependent on the rapid drawdown loading case.
- **Transition Zone**: A zone on the interior side of the upstream or downstream shells. Upstream transition zones can also function as seismic crack stoppers.
- **Chimney Drain**: Zone that carries away seepage coming through the chimney filter and delivers it to the blanket drain. It also acts as a transition zone between the chimney filter and the downstream shell. Usually, this zone is composed of gravel-size particles.
- **Downstream protection**: Paraperios dam - May 26 2010

(FEMA, 2011)
Application: Flood embankments (Levees)

• Levees – transient water levels, but can be very long.

• Concerned about seepage through embankment and foundations.

• 30,000 documented miles of levee in US

• 7,500 km of flood embankments in the UK

American River Levees California

http://www.watereducation.org/tour/bay-delta-tour-2018-0
Application: Flood embankments (Levees)

**Engineered levee**

- **Waterside**
  - Existing levee
  - Berm fill
- **Landside**
  - Geotextile
  - Existing grade
  - 300 mm drain rock
  - 150 mm filter layer
  - Ground surface after stripping

**Retrofit of existing levee**

- **Waterside**
- **Landside**

(International Levee Handbook, 2013)
Role of filters

Filters are designed and constructed to achieve specific goals such as preventing internal soil movement and controlling drainage (FEMA, 2011)

Five filter functions govern the capability of providing control for internal erosion.
1. Retention.
2. Self filtration or stability.
3. No cohesion
4. Drainage.
Role of filters

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Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (International Levee Handbook, 2013)
Micro Computed Tomography (microCT)

Micro Computed Tomography (Micro CT)
Experimental study

PhD Research of Dr. Howard Taylor
Experimental study

Fonseca et al. (2014)
Géotechnique
Role of filters

Filters are designed and constructed to achieve specific goals such as preventing internal soil movement and controlling drainage (FEMA, 2011)

Five filter functions govern the capability of providing control for internal erosion.

1. **Retention**.
2. Self filtration or internal stability.
3. No cohesion
4. Drainage (*permeability*).

Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (International Levee Handbook, 2013)
Retention

The voids in the filter should be sufficiently small to prevent erosion of the base soil (ICOLD, 2015)

Geometric criteria:
- Consider particle size distribution
- Terzaghi’s filter rule / Sherard & Dunnigan (1989)
  - $D_{15F}$ of filter
  - $D_{85B}$ of base
  - For retention $D_{15F} < 4D_{85B}$
- Controlling constriction size

(FEMA, 2011)
Key Particle Sizes

D_{15F}: 15% of filter particles are smaller than D_{15F}

D_{85B}: 85% of base or fine particles are smaller than D_{85B}
Research questions: Retention

• What is the relationship between the size of the constrictions and $D_{15F}$?

• What is the density of constrictions in a filter?

• Is there a fundamental basis to empirical correlations used to assess stability?
Retention – role of constrictions

Eroding soil from the crack has been caught at the filter face, and hydraulic fracturing from the high gradients between water in the crack and the adjacent filter has caused further widening of the filter cake until the gradient is reduced. The filter cake having a very low permeability covers the width of the crack and some distance on each side of the crack. The remaining filter is open for collecting seepage flow through the pores of the soil between cracks.

In Sherard’s June 1984 article, “Filters for Silts and Clays” (Sherard 1984b), the observation was made: As a first effort, a number of conventional filter tests (with an initial hole in the base specimen) were made with compacted sand and sandy gravel filters using relatively thin (30-60 mm thick) base specimens of clay and silt. The specimens were compacted near Standard Proctor Optimum water content. In these tests, the water pressure acting across the base specimen was gradually increased to a maximum of about 6 kg/cm, giving a hydraulic gradient of about 1,000-2,000.
Retention – role of constrictions

Constrictions trap fine core particles
Constrictions hard to identify

3D image of sand from micro CT

Void space from microCT
Analytical approach to quantify constriction sizes

(a) Constriction diameter $D_c$

(b) Soil particles

Coplanar spheres

Kenney et al. (1985)

Silvera et al. (1985)
Determining constriction size distribution

Generate particle scale data

Apply void partitioning algorithm

Calculate Constriction Size Distribution

% smaller

By number

CSD

By volume

PSD

Diameter (mm)
Samples considered to study retention

**Micro Computed Tomography**

- Leighton Buzzard Sand $C_u=3$
- Leighton Buzzard Sand $C_u=1.5$
- Glass Beads $C_u=3$
- Spheres $C_u=1.2$

*(Taylor, 2017)*

**DEM Simulations**

- Spheres $C_u=3.0$
- Spheres $C_u=6.0$

*(Shire, 2018)*

*Do not consider possibility of filters containing fines*
Determining constriction size distribution

- $D_{10}$: 10% of particles are smaller than $D_{10}$
- $D_{60}$: 60% of particles are smaller than $D_{60}$
- $D_{60} / D_{10}$: coefficient of uniformity $= Cu$
DEM simulations

- LAMMPS (Plimpton, 1995; Sandia National Laboratories)
- Development and testing by Dr. Kevin Hanley (formerly Imperial College, now Edinburgh)
- Validation using lattice packings / Benchmarking against PFC
- Periodic boundaries, Hertz-Mindlin contact model
- Used Imperial College HPC clusters
- Isotropic compression of to 60,000 spherical particles
DEM constrictions: Triangulation method

Triangulation of particle centres weighted by particle radii

Tetrahedra faces define void boundaries

Constrictions located on tetrahedra faces

Al Raoush et al. (2033); Reboul et al. (2010)
DEM constrictions: Triangulation method

- False identification of constrictions due to over-segmentation
- Delaunay triangulation based on particle centroids
- Identify spheres tangent to particles forming Delaunay cell
- Where tangent spheres overlap Delaunay cells are merged
- Valid constrictions

Ambiguity over magnitude of overlap
Micro Computed Tomography (microCT)

Nikon XT-H-224 scanner
Voxel size $\approx 10\times10\times10 \ \mu m^3$

Cu3 - Glass Beads $e = 0.46$
(medium $\rightarrow$ dense)

Cu3 - Sand $e = 0.51$
(medium density)
Segmentation of void space

Threshold to identify gray level differentiating void space and particles

Distance map
Centre locations
Watershed boundary

Performed using “Avizo Fire” software
Identifying constrictions in µCT

µCT image → Watershed Segmentation → Voids → Void Boundaries

Constrictions local maxima of distances to particles

Taylor et al. (2017)
Comparison of constriction size distributions

DEM Sample

Voxelized DEM Sample:

Void space (black)

Voxelized filter particles

$C_u = 4.5$

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

Shire et al. (2016)
Particle Size Distributions

\[ \frac{D_{60}}{D_{10}}: \text{coefficient of uniformity} = \text{Cu} \]

Lab (µCT)

\[ \% \text{ passing (by volume)} \]

DEM

\[ \% \text{ smaller} \]

Taylor et al. (2018)
Constriction Size Distributions (DEM)

**Filter PSD**

<table>
<thead>
<tr>
<th>Normalised diameter ($D / D_0$)</th>
<th>% smaller</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

**Filter CSD**

Constrictions become larger to $Cu = 3$

Very similar constriction sizes for $Cu \geq 3$

- CSD $Cu = 1.2$
- CSD $Cu = 1.5$
- CSD $Cu = 2$
- CSD $Cu = 3$
- CSD $Cu = 4.5$
- CSD $Cu = 6$
Constriction size distributions (CSDs) $\mu$CT

Filter PSD

Filter CSD
Constriction Size Distributions: $D_{15}$ normalization

Narrow range of constriction sizes for $Cu \leq 4.5$
Constriction Size Distributions: $D_{15}$ normalization
Filtration – Constriction Density / Spacing

Estimated constriction spacing $/D_{50}$

Constriction spacing expressions proposed in literature
Research questions: Stability

• Is there a fundamental basis to empirical correlations used to assess stability?
Empirical Filter Criteria: Kézdi (1979)

Split PSD into coarse and fine “PSDs”

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

i.e. if

\[ D_{15}^{\text{coarse}} / d_{85}^{\text{fine}} < 4 \]

Relates to Terzaghi filter rule
Microcomputed Tomography (µCT)

Glass reservoir
Epoxy resin
Nylon tubing
Cell
Pressure (30kPa, air)

Axial loading system (not used)
Perspex cell walls
O-ring
Latex membrane
Sample
Suction (1kPa, air)

Aluminium cell

Approximately 76 mm
38 mm
9 mm central core

76 mm
38 mm
9 mm central core

PhD Research of Dr. Howard Taylor
Internal Instability: μCT study materials

3 scan samples for each grading

- WG – Kézdi ratios 1.54-1.62
- G1 - Kézdi ratios 3.3 – 4.66
- G2 - Kézdi ratios 4.01 – 4.29
Internal Instability: sample preparation

Diagram showing the setup:
- **Load Cell**
- **Loading shaft**
- **Topcap**
- **O-rings**
- **Resin reservoir**
- **Resin feed lines to base of specimen**
- **Displacement Sensor**
- **Suction**
- **Cell Pressure**
- **Ram Pressure**
- **Ram**
- **Cell**
- **Topcap**
- **Membrane**

Image on the right shows the setup with the following labels:
- **Resin**
- **Feed lines to the base of specimen**
- **Drainage line from top cap**
- **Suction**
Internal Instability: stress path

K₀ consolidation

K₀ = 0.43

ϕ' = 35°
Well graded sample

WG Top

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}}=1.56$

WG Middle

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}}=1.62$

WG Bottom

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}}=1.54$
Internal Instability: Filter criterion Kézdi (1979)

Split PSD into coarse and fine “PSDs”

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

i.e. if

\[ \frac{D_{15}^{\text{coarse}}}{d_{85}^{\text{fine}}} < 4 \]
Well graded sample

WG Top
\[ D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 1.56 \]

WG Middle
\[ D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 1.62 \]

WG Bottom
\[ D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 1.54 \]
Sample G1

12%: 300mm > D > 150mm

G1 Top

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 4.66$

G1 Middle

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 3.90$

G1 Bottom

$D_{15}^{\text{coarse}}/d_{85}^{\text{fine}} = 3.30$
Sample G2

G2 Top
\[ \frac{D_{15}^{\text{coarse}}}{d_{85}^{\text{fine}}} = 4.01 \]

G2 Middle
\[ \frac{D_{15}^{\text{coarse}}}{d_{85}^{\text{fine}}} = 4.29 \]

G2 Bottom
\[ \frac{D_{15}^{\text{coarse}}}{d_{85}^{\text{fine}}} = 4.07 \]

(24%: 300\mu m > D > 150\mu m)
Coordination number

$N_c = \text{Coordination number}$

No of contacts per particle

Leighton Buzzard Sand Blue particle 20 contacts

Glass beads Blue particle 50 contacts

Leighton Buzzard Sand Blue particle 2 contacts

No of contacts gives indication of kinematic constraint

Images from H. Taylor
Variation in Coordination No. with Kézdi Ratio

Fonseca et al. (2014)
Géotechnique
Shire and O’Sullivan (2013)
Acta Geotechnica
Discrete element method simulations

Spherical particles
Simple contact models
Isotropic samples
Gravity neglected

Shire and O’Sullivan (2013)
Acta Geotechnica
Variation in Coordination No. with Kézdi Ratio

Increasing Kézdi no.

Decreasing stability

Fonseca et al. (2014)
Géotechnique
Shire and O’Sullivan (2013)
Acta Geotechnica
Internal instability

• microCT + DEM confirmed a link between the Kézdi criterion and the contact density within the samples

• DEM simulations confirmed a link between the proportion of stress carried by the finer grains and the fines content

• Coupled DEM + CFD simulations confirmed a link between the stress carried by the finer grains and the likelihood of grain migration under seepage flow

• Need to revisit how fluid-particle interaction is determined in poly-disperse samples
Role of filters

Filters are designed and constructed to achieve specific goals such as preventing internal soil movement and controlling drainage (FEMA, 2011)

Five filter functions govern the capability of providing control for internal erosion.
1. Retention.
2. Self filtration or internal stability.
3. No cohesion
4. Drainage (*permeability*).

Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (International Levee Handbook, 2013)
Drainage requirement is achieved by limiting the fines content (% passing 0.075mm), and in some design manuals relying on relationships between $D_{15F} / D_{15B}$ to ensure the filter is sufficiently more permeable than the base soil to perform the drainage function. (ICOLD, 2015)
Experimental study - Materials

- Solid
- Void

≈4 mm

Approximately 400 vox$^3$ sub-volume used for CFD analyses

≈6 mm

Sand-Cu3

Sand-Cu1.5

Beads-Cu3

Beads-Cu1.5
Fluid flow simulations

Sub-volume for CFD analyses

≈4 mm

≈9 mm

≈6 mm

Micro-CT binary image

Finite volume mesh

OpenFOAM simulation
Fluid flow simulations

micro-CT image (Cu3)

HIGH PRESSURE

LOW PRESSURE

≈6 mm

≈9 mm

CFD Analysis

INLET BOUNDARY:

\[ P_{in} = 0.001 \text{ kPa} \]
\[ V_x = 0 \]
\[ V_y = 0 \]

OUTLET BOUNDARY:

\[ P_{out} = 0 \text{ kPa} \]
\[ V_x = 0 \]
\[ V_y = 0 \]

“No slip” condition on particle surfaces

Slice, perpendicular to flow direction

“Symmetry” condition on all side boundaries

CFD output 18-24hrs

Pressures

Velocities
Comparison of CFD and permeameter data

Permeability $k$ (cm/s)

Lab results
CFD results
Kozeny-Carman prediction for 75mm permeameter
Hazen prediction for 9mm core

Cu3
Cu1.5

9mm core
4mm CFD volume
38mm triaxial
MicroCT: Constrictions in void network – geometrical identification

Particles

Voids

Void Boundaries

Constrictions local maxima of distances to particles

Taylor et al. (2017)
Comparison of geometric and hydraulic constrictions

- Particle
- Void

High velocity
Low velocity

Velocity maximum (= Hydraulic constriction)

- Geometric Constriction

Taylor et al. (2017)
Headloss and streamlines

Majority of head loss occurs at discrete locations (constrictions)

Relatively little head loss within large void spaces

Distance travelled (voxels)

Head (m)

Streamline

Particle

Velocity (m/s)

Head (m)
Headloss and streamlines

Velocity (m/s)

Head (m)

Particle

Streamline

Graph showing head loss and streamlines over distance.
Headloss and streamlines

<table>
<thead>
<tr>
<th>Material</th>
<th>Proportion of head loss in constrictions</th>
<th>Proportion of length in constrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-Cu3[1]</td>
<td>77% (12%)</td>
<td>37% (8%)</td>
</tr>
<tr>
<td>Sand-Cu3[2]</td>
<td>77% (11%)</td>
<td>37% (8%)</td>
</tr>
<tr>
<td>Sand-Cu1.5</td>
<td>76% (12%)</td>
<td>37% (8%)</td>
</tr>
<tr>
<td>Beads-Cu3</td>
<td>77% (12%)</td>
<td>39% (8%)</td>
</tr>
<tr>
<td>Beads-Cu1.5</td>
<td>77% (11%)</td>
<td>39% (7%)</td>
</tr>
</tbody>
</table>

Mean (Standard Dev.)
Fluid flow simulations with sub-particle scale resolution confirm the dependency of permeability upon constriction sizes – head loss predominantly occurs at the constrictions.
Conclusions – Part (i)

Considerations of filter compatibility (retention), internal instability and drainage (permeability) are important in dam and embankment design and maintenance.

MicroCT data:
1. Indicate it is plausible to use $D_{15}$ as a characteristic diameter to estimate constriction sizes.
2. Provide evidence of a fundamental basis to the Kezdi criterion for internal stability.
3. Enable the fundamentals of permeability to be explored.
Semi solid metals – examples of casting defects

High pressure die cast Al-9Si-4Cu
PhD thesis Kristina Kareh Imperial College London

Defect bands in commercial steering wheel
PhD thesis Te-Cheng Su Imperial College London
Semi solid metals – examples of casting defects

Key hypothesis: Semi-solid metals behave as a granular material

To prove this — aim to demonstrate shear induced volume change or dilatancy

High pressure die cast Al-9Si-4Cu
PhD thesis Kristina Kareh Imperial College London

Defect bands in commercial steering wheel
PhD thesis Te-Cheng Su Imperial College London
Semi solid metals - Radiographs

Globules of Al-15Cu at ~70% solid

Globular-Polygonal Fe-2C-1Mn-0.5Si at 88% Solid

Al-15Cu with equiaxed-dendritic morphology at 30% solid

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
DEM study of Al foundry alloys

Envelop fraction at coherency vs. solid fraction at coherency for a range of Al foundry alloys

Al–7 Si–0.3 Mg
$g_s = 0.25$, $g_{env} = 0.62$

Al–5 Mg
$g_s = 0.42$, $g_{env} = 0.67$

Yuan et al. (2011)
doi:10.1016/j.actamat.2011.11.042
DEM study of Al foundary alloys

Yuan et al. (2011)
doi:10.1016/j.actamat.2011.11.042
DEM study of Al foundary alloys

\[ g_s = 52.6\% \quad g_s = 61.2\% \quad g_s = 63.8\% \]

Yuan et al. (2011)
doi:10.1016/j.actamat.2011.11.042
Semi solid metals - Radiographs

Beamlines BL20XU and BL20B2 at the SPring-8 synchrotron, Japan

Yasuda et al.
Semi solid metals - Radiographs

Yasuda et al.
Semi solid metals - Radiographs

\[
\frac{L_S^0}{L_{alloy}^0} = \frac{\ln I_{SL}^0 - \ln I_L^0}{\ln I_S^0 - \ln I_L^0}
\]

\[
g_{S,A}^0 = \langle \frac{L_S^0}{L_{alloy}^0} \rangle_A
\]

Yasuda et al.
Al-15Cu Deformation

Globules of Al-15Cu at ~70% solid

Gourlay et al. (2014)  
DOI: 10.1007/s11837-014-1029-5

Al-15Cu Deformation

Globules of Al-15Cu at ~70% solid

Schematic of the thin-sample shear cell used for synchrotron radiography experiments on Al-Cu samples

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5

BL20B2 at the SPring-8 synchrotron in Hyogo, Japan
Al-15Cu Deformation

A movie of globular Al-15mass%Cu published as stills in Fig. 4 in Gourlay et al. (2014). JOM, 66(8), 1415–1424.

https://doi.org/10.1007/s11837-014-1029-5
Al-15Cu Deformation

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
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Al-15Cu Deformation

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
High carbon steel deformation

Fe–2.08C–0.87Mn–0.45Si (mass%) high-carbon steel

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
High carbon steel deformation

Fe–2.08C–0.87Mn–0.45Si (mass%) high-carbon steel

Reigate sand

Fonseca et al. (2013)
http://dx.doi.org/10.1016/j.actamat.2013.03.043
High carbon steel deformation

Fe–2.08C–0.87Mn–0.45Si (mass%) high-carbon steel

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
High carbon steel deformation

Stage 1 to Stage 2

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
High carbon steel deformation

Stage 1

Stage 2

Stage 4

Fonseca et al. (2013)
http://dx.doi.org/10.1016/j.actamat.2013.03.043
High carbon steel deformation

Fonseca et al. (2013)
http://dx.doi.org/10.1016/j.actamat.2013.03.043
High carbon steel deformation

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http://dx.doi.org/10.1016/j.actamat.2013.03.043

Gourlay et al. (2014)
DOI: 10.1007/s11837-014-1029-5
Equiaxed semi-solid steel

Kareh et al. (2016)
http://dx.doi.org/10.1016/j.actamat.2016.11.066
Equiaxed semi-solid steel

A movie of a carbon steel at high solid fraction published as stills in Fig. 3 in Kareh et al. (2017). *Acta Materialia, 125*, 187–195. [https://doi.org/10.1016/j.actamat.2016.11.066](https://doi.org/10.1016/j.actamat.2016.11.066)
Equiaxed semi-solid steel

Kareh et al. (2016)
http://dx.doi.org/10.1016/j.actamat.2016.11.066
Equiaxed semi-solid steel

Kareh et al. (2016)
http://dx.doi.org/10.1016/j.actamat.2016.11.066
Al-Cu alloys: CFD-DEM

Su et al. (2020)
https://doi.org/10.1016/j.actamat.2020.03.011
Al-Cu alloys: CFD-DEM

Su et al. (2019)
https://doi.org/10.1016/j.actamat.2018.10.006
Al-Cu alloys: CFD-DEM

Su et al. (2020)
https://doi.org/10.1016/j.actamat.2020.03.011
Al-Cu alloys: CFD-DEM

Su et al. (2019)
https://doi.org/10.1016/j.actamat.2018.10.006
Al-Cu alloys: CFD-DEM

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Su et al. (2019)
https://doi.org/10.1016/j.actamat.2018.10.006
Triaxial compression tests

Altuhafi et al. (2021)
https://doi.org/10.1007/s11661-021-06213-9

Al-15wt.%Cu

Microscope image following segmentation
Triaxial compression tests

Altuhafi et al. (2021)
https://doi.org/10.1007/s11661-021-06213-9
Triaxial compression tests

Altuhafi et al. (2021)
https://doi.org/10.1007/s11661-021-06213-9
Triaxial compression tests

Altuhafi et al. (2021)
https://doi.org/10.1007/s11661-021-06213-9

Sample 300kPa-549
Conclusions – Part (ii)

Improving understanding of semi-solid metal behaviour may reduce occurrence of casting defects.

Radiography + DEM have been used to:

1. Show that at higher solid fractions it is plausible to consider semi-solid metal as a fluid-saturated granular material.

2. Shear induced dilation takes place and stress deformation response can be linked to dilation/contraction.

3. Establish link between volumetric strain and fluid migration.
Acknowledgements

- Dr. Howard Taylor
- Dr. Joana Fonseca: https://www.city.ac.uk/about/people/academics/joana-fonseca
- Prof. Chris Gourlay: https://www.imperial.ac.uk/people/c.gourlay
- Dr. Fatin Altuhafi: https://www.ucl.ac.uk/civil-environmental-geomatic-engineering/people/dr-fatin-altuhafi

EPSRC