DEM, dams and dikes

Catherine O’Sullivan
DEM8 recognises dikes
The boy with his finger in the dike
Kinderdijk

742 years old

To drain the polder, a system of 19 windmills was built around 1740

UNESCO world heritage site

https://www.kinderdijk.com/
Dutch Dikes

Total land area Netherlands: 41,528 km²

26% below mean sea level (NAP)

66% of the area is flood prone

9 million people live in these low areas

70% of GNP is earned in flood-vulnerable area

The Dutch dike network extends for over 22,000 kilometres

http://dutchdikes.net/dike-map/
Dikes near here

University Campus

FC Twente Stadium

Strengthening of Twente Canal (Twentekanaal)

The International Levee Handbook - 2013

• Joint research project of CIRIA (UK), French Ministry for Ecology and US Army Corps of Engineers

• Funding from France, UK, USA, Ireland and the Netherlands
International perspective: US

30,000 documented miles of levee in the US

Breach in 17th Street Canal levee in New Orleans, Louisiana, on August 31, 2005

American River Levees California
http://www.watereducation.org/tour/bay-delta-tour-2018-0
International perspective: United Kingdom

UK Environment Agency responsible for 9,000 km of flood embankment

580 homes in the Wainfleet area were evacuated after the River Steeping burst its banks this June

https://www.bbc.co.uk/news/uk-england-lincolnshire-48646801
https://www.bbc.co.uk/news/uk-england-lincolnshire-48707396
Design issues requiring a particulate perspective

1. Base – filter compatibility
2. Internal instability / suffusion

(FEMA, 2011)

After Slangen and Fannin
Filters: Dikes

Engineered levee

Retrofit of existing levee

(International Levee Handbook, 2013)
- 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
- In the US there are about 90,580 dams
Filters: Embankment dams

(FEMA, 2011)

Paraperios dam - May 26 2010
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.

Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (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 (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)

Empirical rules used in design:

- Consider particle size distribution
- Terzaghi’s filter rule / Sherard & Dunnigan (1989)
  - $D_{15F}$ of filter
  - $D_{85B}$ of base
  - For retention $D_{15F} < 4 \times D_{85B}$
- Controlling constriction size – largest particle that can pass through filter

(FEMA, 2011) (ICOLD, 2015)
15% of particles by mass are smaller than $D_{15}$

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

Filter retention $D_{15F} < 4D_{85B}$
Research questions: Filter retention

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

• Does particle scale analysis support use of the ratio $D_{15F}/D_{85B}$ in design?
Retention

Gradient

Void

Constriction
Retention

Fine core particles get trapped in constrictions
Quantifying constriction size & frequency

- Ability to image pore space is a recent advancement
- Pore space topology is complex
- Pore space is continuous
- Division between individual voids / pores is subjective
Analytical approach to quantify constriction sizes

Coplanar spheres

Kenney et al. (1985)

Silvera et al. (1985)

Used to justify design criteria
Real constrictions from microCT data

Taylor et al. Géotechnique (2019)
Determining constriction size distribution

Generate particle scale data

Apply void partitioning algorithm

Calculate Constriction Size Distribution

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</tbody>
</table>

PSD
CSD

By number
By volume

Particle
Constriction

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 $C_u=3$

*Taylor, 2017*

**DEM Simulations**

- Spheres $C_u=3.0$
- Spheres $C_u=6.0$
- Spheres $C_u=1.2$

*Shire, 2018*

*Do not consider possibility of filters containing fines*
Coefficient of uniformity, $C_u$

10% of particles by mass are smaller than $D_{10}$

60% of particles by mass are smaller than $D_{60}$

Cumulative distribution by volume / mass
Samples considered to study retention

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

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

*(Taylor, 2017)*

*Do not consider possibility of filters containing fines*

*(Shire, 2018)*
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

User decides magnitude of overlap
Experimental approach

- **Sample**: Perspex cell walls, Latex membrane, O-ring, Nylon tubing, Glass reservoir, Epoxy resin
- **Axial loading system**: Aluminium cell
- **Drainage line from top cap**, **Resin**, **Feed lines to the base of specimen**
- **Suction (1kPa, air)**, **Cell Pressure (30kPa, air)**

**PhD Research of Dr. Howard Taylor**
Experimental approach

Fonseca et al. (2014)
Géotechnique
Micro Computed Tomography (microCT)

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

X-ray source
Sample
Detector

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 filter particles

Voxelized DEM Sample:

Void space (black)

Shire et al. (2016)

$C_u = 4.5$

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

Percent passing (by number)

Constriction diameter, microns

MicroCT watershed

Delaunay, lower limit

Delaunay, upper limit

Contact triangulation

Shire et al. (2016)
Fluid flow simulations

INLET BOUNDARY:
\[ P_{\text{in}} = 0.001 \, \text{kPa} \]
\[ V_x = 0 \]
\[ V_y = 0 \]

OUTLET BOUNDARY:
\[ P_{\text{out}} = 0 \, \text{kPa} \]
\[ V_x = 0 \]
\[ V_y = 0 \]

"No slip" condition on particle surfaces
Slice, perpendicular to flow direction

"Symmetry" condition on all side boundaries

Pressures
Velocities
Comparison of CFD and permeameter data

Permeability $k$ (cm/s)

- Lab results
- CFD results
- Kozeny-Carman prediction for
- Hazen prediction for

Cu3

Cu1.5

75mm permeameter

9mm core

4mm CFD volume

38mm triaxial
Comparison of geometric and hydraulic constrictions

![Graph showing comparison between geometric and hydraulic constrictions.](image)

Taylor et al. (2017)
Particle Size Distributions

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

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

**Filter PSD**

**Filter CSD**

Constrictions become larger to Cu = 3

Very similar constriction sizes for Cu ≥ 3

Cumulative distribution by number

Cumulative distribution by volume
Constriction Size Distributions (DEM)

Narrow range of constriction sizes for \( \text{Cu} \leq 4.5 \)
Controlling constriction size


Dc* = controlling constriction diameter = largest particle that can pass through filter
Filtration – Constriction Density / Spacing

Estimated constriction spacing/D_{50}

Constriction spacing expressions proposed in literature
Research questions: Filter retention

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

• Does particle scale analysis support use of the ratio $D_{15F}/D_{85B}$ in design?
Retention of Base

Base material: clay or silt with small particle size

Filter – large particle size to achieve drainage

(FEMA, 2011)
Can’t judge a filter’s effectiveness simply by visual comparison of the CSD of the filter and the PSD of the base material to be retained.

CSD – cumulative distribution by number

PSD – cumulative distribution by volume
Filtration – Network model

- Network model – lattice topology
- Nodes = individual voids
- Edges = inter void connections
- Edge diameters = constriction diameters
Filtration – Network model

- Simulates migration of finer base particles through network
- Fluid flow not explicitly considered
- Simple algorithm means up to 400 million base particles could be considered on a desktop pc
Filtration – Network model

- Network model – lattice topology
- Nodes = individual voids
- Edges = inter void connections
- Edge diameters = constriction diameters

Three entrances and three exits per void
Area based random walk

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

Likelihood of selecting a target edge to move through depends on constriction area

Three entrances and three exits per void
“Random walk” of base particles through network

Base particle moves through constriction

Base particle retained + constriction blocked

Base particle retained in void
Filtration – Network model

Node (void)

Three entrances and three exits per void

Filter Cu =1.2, 3, 6, largest base particle eroded agrees with experimental data

$D_{50B} =$ median base diameter
$D_{OF} =$ smallest filter diameter

$D_{100,eroded} / D_0$

$m_{eroded}$

$m_{eroded} / m_0$

$m_{eroded} / m_0 > 0.26$

(Kenney et al., 1985)

$Cu = 6.0$

Flow Direction

Filter Cu =1.2, 3, 6, largest base particle eroded agrees with experimental data
Filtration – Network model

- Cu Filter = 1.5 and 3.0
- Network model that considers only constriction sizes and not full void space topology confirms experimental observation that filter characteristic diameter ($D_{15F}$) controls filtration
Filtration – Network model

- \( \text{Cu}_{\text{base}} = 1.5 \) and 3.0
- Network model that considers only constriction sizes and not full void space topology confirms experimental observation that filter characteristic diameter (\( D_{15F} \)) controls filtration

\[ \begin{align*}
D_{15B} &= \text{base diameter 15% smaller} \\
D_{85F} &= \text{filter diameter 85% smaller}
\end{align*} \]
Research questions: Filter retention

• Normalization of constriction size distributions by $D_{15F}$ gives a narrow set of curves, supporting idea that $D_{15F}$ is indicative or representative of the constrictions sizes in a filter.

• Network analyses support use of $D_{15F}/D_{85B}$ to judge retention capacity. Analyses also support idea that effective retention requires $D_{15F} < 4D_{85B}$ in line with recent ICOLD documents.
**Suffusion**

- **suffusion** is the selective erosion of the fine particles from the matrix of coarse particles under the action of a hydraulic gradient.

- **suffusion** is sometimes associated with lack of volume change, **suffosion** associated with volume change.

- **internally unstable soils** are susceptible to suffusion / suffusion – **internal instability**
  
  general term

\[
\begin{align*}
D_m &> 0 \\
\frac{D_V}{V} &> 0 \\
D_k &> 0 \\
\frac{D_V}{V} &< 0 \\
D_k &> 0
\end{align*}
\]

(a) Instability without volume change

(b) Instability with volume change

\[m - \text{mass}\]
\[V - \text{volume}\]
\[k - \text{hydraulic conductivity}\]

*After Slangen and Fannin*
Skempton and Brogan Permeameter Experiments

Piezometers

Rigid wall transparent cylinder

Inflow

Gap-graded material

Mixture of larger and smaller grains
Skempton and Brogan Permeameter Experiments

Piezometers

Rigid wall transparent cylinder

Inflow

Skempton and Brogan (1994) Géotechnique

Significant increase in permeability

Clear that complete failure is happening at a low hydraulic gradient

Variations in permeability will cause preferential flow

i = hydraulic gradient

Expect $v = ki$

Sample A

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

$0.2$ $0.4$ $0.6$

$v \text{ cm/s}$

$0$ $0.1$ $0.2$ $0.3$

$i$

$139 \text{ mm}$

Screen
Internal Instability

MSc student photo of internal instability
Flood embankments

Design aim:
- Reduce downstream hydraulic gradient, \( i \)
- Critical case \( i=1 \)

WAC Bennett Dam

- Located in British Columbia, Canada
- Owned by BC Hydro
- High as a 60-storey building and two kilometres wide
- Holds back 360 kilometres of Williston Lake, the largest reservoir in North America
Bennett dam transition

Blended “till-like” core
Transition
Filter
High capacity drain

BC Hydro as cited by Muir Wood (2007)

https://www.imperial.ac.uk/media/imperial-college/faculty-of-engineering/civil/public/geotechnics/Fannin_1Sept17_London.pdf
WAC Bennett Dam

1996 Sinkhole at WAC Bennett Dam
(BC Hydro as cited by Muir Wood, 2007)
Factors influencing internal instability risk

Venn diagram concept proposed by Fannin and Gardner

- Geometry
  - Particle size distribution
  - Size of constrictions in void space

- Hydraulics
  - Velocity of water in void space
  - Drag on particles

- Stress state
  - Applied macro-scale stress
  - Stress inhomogeneity
Factors influencing internal instability risk

Geometry

- Particle size distribution
- Size of constrictions in void space

Hydraulics

- Velocity of water in void space
- Drag on particles

Stress state

- Applied macro-scale stress
- Stress inhomogeneity
Empirical Filter Criteria: Kézdi (1979)

Split PSD into coarse and fine "PSDs"

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

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)
- Aluminium cell
- Perspex cell walls
- O-ring
- Latex membrane
- Sample
- Suction (1kPa, air)

Sample dimensions:
- 76 mm central core
- 38 mm axial loading system (not used)

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: μCT study materials

Post-doctoral Research of Dr. Joana Fonseca
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

Increasing Kézdi no.
Decreasing stability

$\mu$CT WG
$\mu$CT G1
$\mu$CT G2
$\mu$CT trendline

Coordinate Number, $Z$

Kezdi $D_{15}^{coarse}/d_{85}^{fine}$
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
Factors influencing internal instability risk

Geometry
- Particle size distribution
- Size of constrictions in void space

Hydraulics
- Velocity of water in void space
- Drag on particles

Stress state
- Applied macro-scale stress
- Stress inhomogeneity
Stress Partition - $\alpha$

- Hypothesis to explain erosion at low hydraulic gradients
- Based on observations of permeameter tests
- Coarse matrix transfers most of stress
- Finer grains carry reduced effective stress:

$$\sigma'_{\text{fines}} = \alpha \times \sigma'$$

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

Skempton and Brogan (1994) Géotechnique
Stress Partition - $\alpha$

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Skempton and Brogan (1994)
Geotechnique

PhD Research of Dr. Thomas Shire
Skempton and Brogan Permeameter Experiments

Skempton and Brogan (1994)
Géotechnique

Sample A

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

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

\[ \sigma'_{\text{fines}} = \alpha \times \sigma' \]
DEM Simulations to Investigate Instability

- DEM code granular LAMMPS with periodic boundaries
- Isotropic compression at to $p' = 50\text{kPa}$
- Sample density controlled using inter particle friction ($\mu$):
  - $\mu = 0.0$ (Dense)
  - $\mu = 0.1$ (Medium dense)
  - $\mu = 0.3$ (Loose)

Shire et al. (2014) ASCE JGGE
\[ \alpha = \frac{p'_{\text{fine}}}{p'} \]

- \( p' \) = overall mean effective stress
- \( p'_{\text{fine}} \) = mean effective stress in finer fraction
- \( p' \) and \( p'_{\text{fine}} \) can be directly obtained from a summation of contact forces in DEM
Skempton and Brogan Sample A: comparison of $\alpha$ values

Density | $\alpha_{DEM}$
---|---
Loose | 0.15
Medium | 0.06
Dense | 0.04

$\alpha_{experiment} = 0.18$

Experimental sample placed moist with no densification

Shire et al. (2014) ASCE JGGE
Link between $\alpha$ and particle size distribution

Looked at a range of gap graded materials

Density varied for all samples

Skempton and Brogan A
FR7
18% Fines
25% Fines
35% Fines
45% Fines
Variation in $\alpha$ with Fines Content ($F_{\text{fine}}$)

$\sigma'_{\text{fines}} = \alpha \times \sigma'$

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

Shire et al. (2014) ASCE JGGE
• Critical fines content where fines just fill voids: $F_{\text{fine}} = 24$-$29$

• Finer fraction separates coarse fraction particles: $F_{\text{fine}} = 35$

• Confirms hypotheses of Skempton and Brogan (1994)

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

Shire et al. (2014) ASCE JGGE
Variation in $\alpha$ with stress anisotropy

Proportion of stress in fines

- Loose
- Medium
- Dense

Stress ratio $q/p'$

Triaxial compression – constant $p'$

25% Fines loose
25% Fines dense
35% Fines loose
35% Fines dense

Axial Strain (%)

Volumetric strain

Compression
dilation
Variation in $\alpha$ with stress anisotropy

Proportion of stress in fines

- 25% Fines loose
- 25% Fines dense
- 35% Fines loose
- 35% Fines dense

Axial strain (%) vs. Proportion of stress in fines
Factors influencing internal instability risk

**Geometry**
- Particle size distribution
- Size of constrictions in void space

**Hydraulics**
- Velocity of water in void space
- Drag on particles

**Stress state**
- Applied macro-scale stress
- Stress inhomogeneity
Permeameter test simulations

- PFC 3D Coupled with CCFD
- Circa 30,000 particles
- Di Felice drag expression
- Particle assembly: 6.1 mm cube
- Fluid cell size: 1.2 mm

MPhil research of Kenichi Kawano
Virtual permeameter test samples

Current study:
PFC+CCFD
Rigid walls
LAMMPS
Periodic boundaries

Stress-reduction $\alpha$

$F_{\text{fine}}$ (%) 

Loose
Dense
Loose
Medium
Dense

Shire et al.
Permeameter test simulations

Combination of DEM (PFC3D) and CFD (CCFD)

- DEM for soil particles
- CFD for water seepage

Data exchange

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

Coarse grid method proposed by Tsuji

(Tsuji et al., 1993, Xu and Yu, 1997)
Permeameter test simulations

1. Create non-contacting cloud of spheres
2. Compress to 50kPa, Apply gravity
3. Create fluid mesh, Fix boundaries, Fix particle positions, Apply pressure gradient
4. Steady state fluid, Release particles, Monitor response
Permeameter test simulations

- Applied pressure differential across sample \((\Delta p)\)
- Increased hydraulic gradient \((i)\) in steps
- As samples small

\[ i = \frac{\Delta h}{\Delta z} \approx \frac{\Delta p}{\gamma_w \Delta z} \]

- \(\Delta h=\) head drop across sample
- \(\gamma_w =\) unit weight of water
- Simulation gives permeability \(k \approx 5 \times 10^{-3} \text{ m/s}\)

Kawano et al. (2017) Soils and Foundations
Particle displacements – for $i = 1$

Kawano et al. (2017) Soils and Foundations
Particle displacements – for $i = 1$

**Gap 25 Loose**

- **Mean**
- **Standard deviation**
- **Maximum**

**Gap 25 Dense**

- **Mean**
- **Standard deviation**
- **Maximum**

*Increase in density*
Particle displacements – for $i = 1$

Gap 25 Loose

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<th>Particle diameter (mm)</th>
<th>Displacement (mm)</th>
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Gap 35 Loose

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</table>

Just underfilled

Just overfilled
Particle displacements – for $i = 1$

\[ \alpha_{\text{particle}} = \frac{\sigma_{\text{particle}}}{\sigma_{\text{overall}}} \]

- $\sigma_{\text{particle}}$ = average stress in a particle
- $\sigma_{\text{overall}}$ = overall sample stress

Kawano et al. (2017) Soils and Foundations
Particle displacements – for $i = 1$

**Gap 25 Loose**

**Gap 25 Dense**

**Increase in density**
Particle displacements – for $i = 1$

Gap 25 Loose

Gap 35 Loose

Just underfilled

Just overfilled
Permeameter test simulations

- PFC 3D Coupled with CCFD
- Circa 30,000 particles
- Di Felice drag expression
- Particle assembly: 6.1 mm cube
- Fluid cell size: 1.2 mm

MPhil research of Kenichi Kawano
Immersed boundary method (IBM)

Allows simulation of fluid flow in void space (fixed, regular, Eulerian grid)

Fluid-particle interaction force can be determined

MultiFlow – B. van Wachem et al.
Verification simulations

Zick and Homsy – boundary integral method data

$\phi = \text{solids fraction} = \frac{V_{\text{solids}}}{V_{\text{total}}}$

$b = \text{radius retraction parameter}$

(retraction = $b\Delta x$)

$K = \text{fluid particle interaction force} / \text{Stokes drag}$

$D/\Delta x = 64$

$e=1.5$ $\phi$ $e=0.33$
Verification simulations

Body fitted mesh

Particles a boundary to fluid flow

Dense monodisperse sample
Low Re
IBM Simulations – linear gradings

% Smaller by Volume

Diameter (mm)

- $C_u = 1.01$
- $C_u = 1.20$
- $C_u = 1.50$
- $C_u = 2.00$
- $C_u = 2.50$

$C_u=1.01$
$N_p=629$

$C_u=1.2$
$N_p=629$

$C_u=1.5$
$N_p=491$

$C_u=2.0$
$N_p=497$
Simulation – configuration

Samples subject to laminar flow
Wide range of packing densities
Variation in permeability with $\phi$

$\phi = \text{solids fraction} = \frac{V_{\text{solids}}}{V_{\text{total}}}$

$k = \text{permeability}$
Variation in drag force with $\phi$

$\bar{F}_d$ = drag force normalized by Stokes drag
Assessment of semi-empirical expressions

\[ \frac{\sum F_d}{V_t} (m^{-3}) \]

Method A: pressure gradient across particles approximated using the global pressure gradient

Method B: \[ \langle F_d \rangle = (1 - \phi) \langle F_{f,s} \rangle \]

\( \overline{F_d} \) = drag force normalized by Stokes drag – total for sample

Method A/B – approach used to extract buoyancy

\[ \phi \]

\[ \phi \]

\[ Cu = 1.01 \]

\[ Cu = 2.0 \]

\[ x10^{11} \]

\[ x10^{10} \]
Assessment of polydispersity correction

\[ \sum F_d/V_t \: (m^{-3}) \]

\[ \times 10^{10} \]

- Tenneti correction with 8 bins
- IBM method A fit
- IBM method B fit
- IBM method A data
- IBM method B data

- Bimodal case
  - Size ratio 4
  - FC = 11%
Individual drag forces versus diameter

\[ \bar{F}_d = \text{drag force normalized by Stokes drag} - \text{total for sample} \]

Method A used to remove buoyancy

Method B used to remove buoyancy

Local packing fraction

\[ \text{IBM Cu}=2.5, \phi=0.64 \]

\[ \text{IBM fit.} \]
Fluid particle interaction force: local void ratio

Forces normalized by Stoke’s Drag

Forces calculated from CFD DEM
Prediction using local void ratio

Drag force on particles

Tenneti et al. polydispersity correction also applied

Knight (2018)

Cu=2.5, Solids fraction 0.701
Network based approach to determine forces

Force calculated using pore network model

Forces normalized by Stoke’s Drag

Force calculated using CFD-DEM

Sufian, Knight, et al. (2019)
Seepage Induced Instability

Discrete element method simulations at Imperial College London

Transparent soil at the University of Sheffield
Conclusions

- Considerations of filter compatibility and internal instability are important in dam and embankment design and maintenance.
- Geometry / particle scale topology of materials; stress state and fluid:particle interaction determine behaviour.
- Particle-scale simulation can improve understanding leading to more robust design guidance.
Conclusions

• Simulations with gap-graded materials are challenging – large numbers of particles are needed and low strain rates are required.

• Significant research effort needs to be put into developing accurate drag expressions to enable unresolved DEM-CFD to be used with confidence in geomechanics applications where polydispersity is always an issue.

• Combining network based approaches with DEM datasets can overcome some of the challenges associated with CFD-DEM
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