Membrane Particle Interaction in Triaxial Testing: FEM-DEM Coupling and CT Imaging Insights

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27.09.24

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Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation
FWF Österreichischer Wissenschaftsfonds

Motivation

Triaxial testing of granular soils/materials

General focus of triaxial testing in geotechnics
Determination of material parameters such as cohesion c, friction angle φ', volume change, …

Geotechnical focus of project

- Vision of a virtual lab
  - Predict shear-strength of material with less experimental effort and less uncertainties of the material parameters
  - High physical accuracy especially given through resolving particles

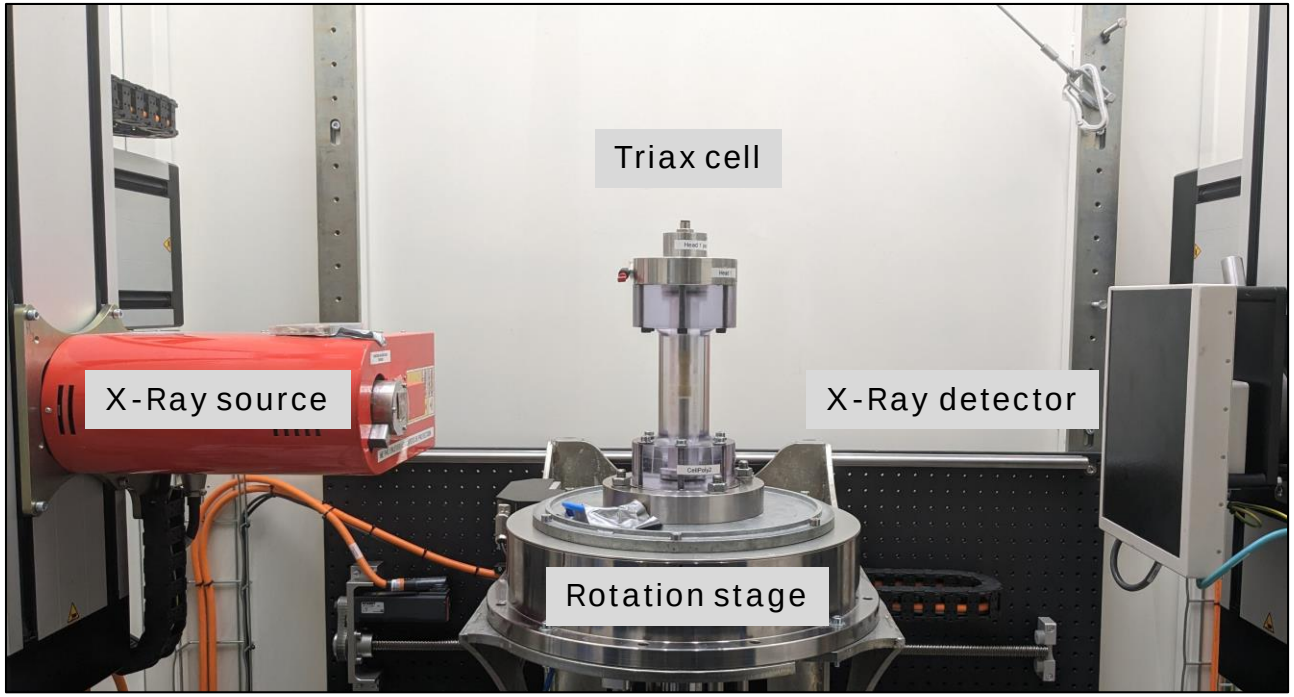
Numerical focus of project

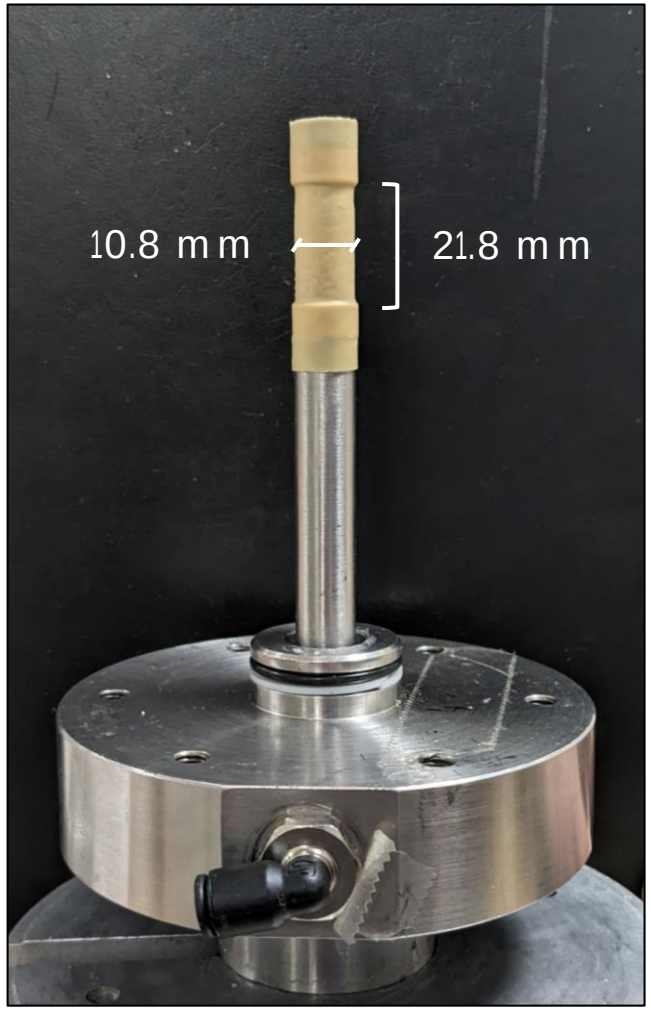
- Membrane-Particle Interaction (FEM-DEM coupling)
  - Membrane Modelling: FEM
  - Particle Modelling: DEM

Experimental Campaign

- CT-Imaging Setup
- Triaxial testing

Experimental setup





Triaxial Compression

Material

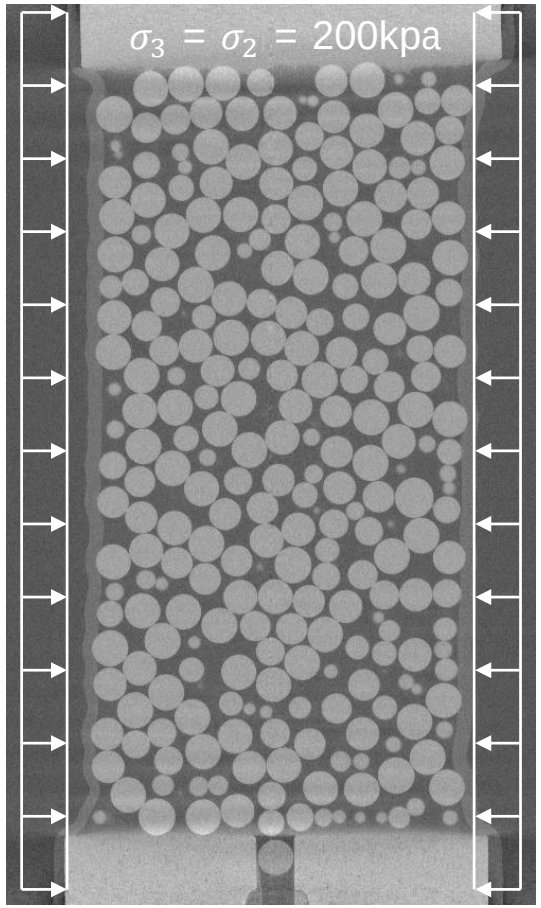
- Dry 1p00mm sodium lime glass beads

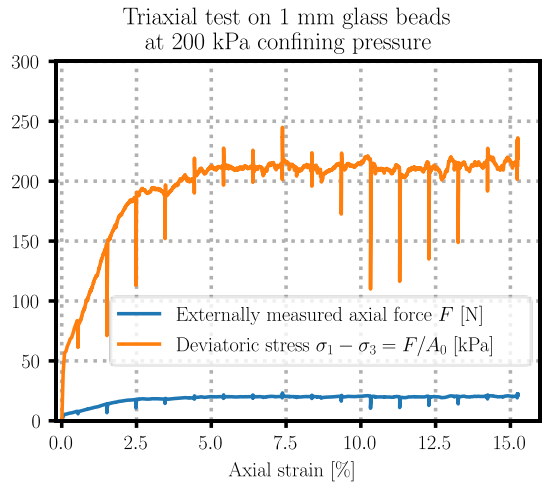
Specimen Size

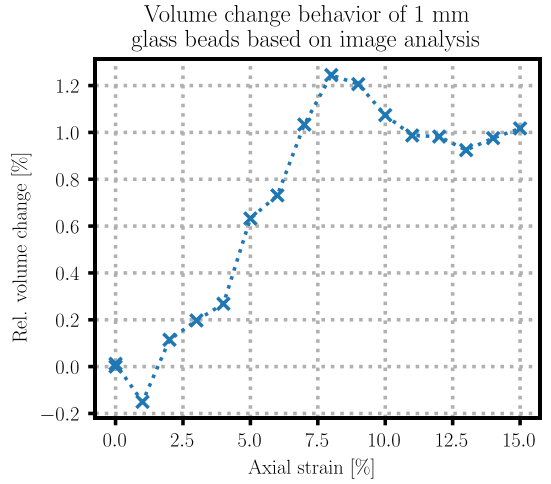
- Start: 21.8 mm
- End: 18.5 mm
- Diameter (start): 10.8 mm

Experimental boundary conditions

- Confining cell pressure 200 kPa
- Strain-controlled 0 – 15 % with increments of 1 %, where experiment is halted and tomography acquired

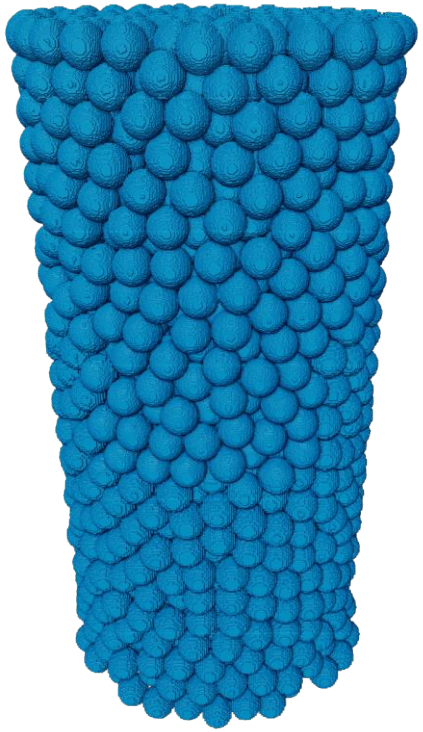






Particle Extraction

Filled membrane volume



Solid phase

Split solid phase (particles)

Input for …

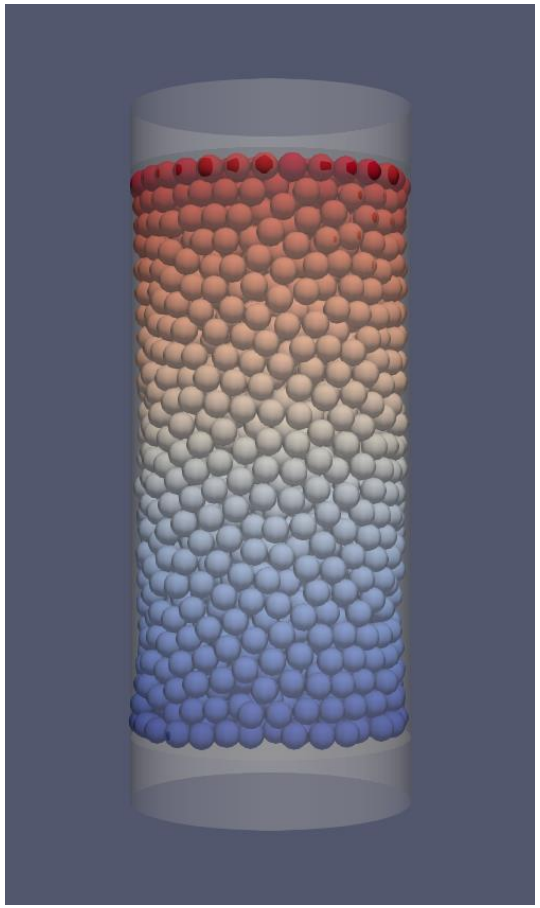
- Numerics
- Discrete Digital Image Correlation (DDIC)

Numerical Setup

Numerical setup of triaxial test

Init Phase 1

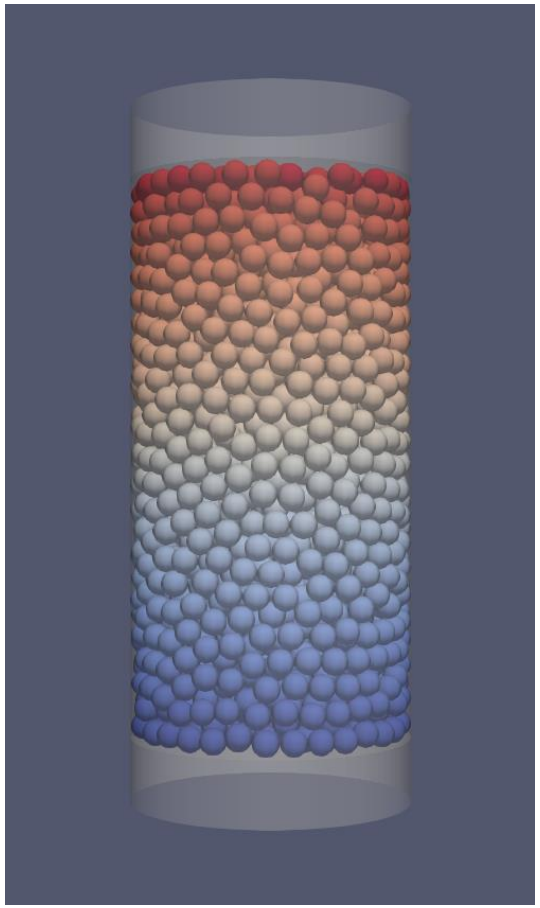
- Initialise container for particles
  (Young's-Modulus E → ∞)
- Insert particles as spheres in Aspherix®



Numerical setup of triaxial test

Init Phase 1

- Initialise container for particles
  (Young's-Modulus E → ∞)
- Insert particles as spheres in Aspherix®
- Settle particles and „straightening" of specimen



Numerical setup of triaxial test

Init Phase 1

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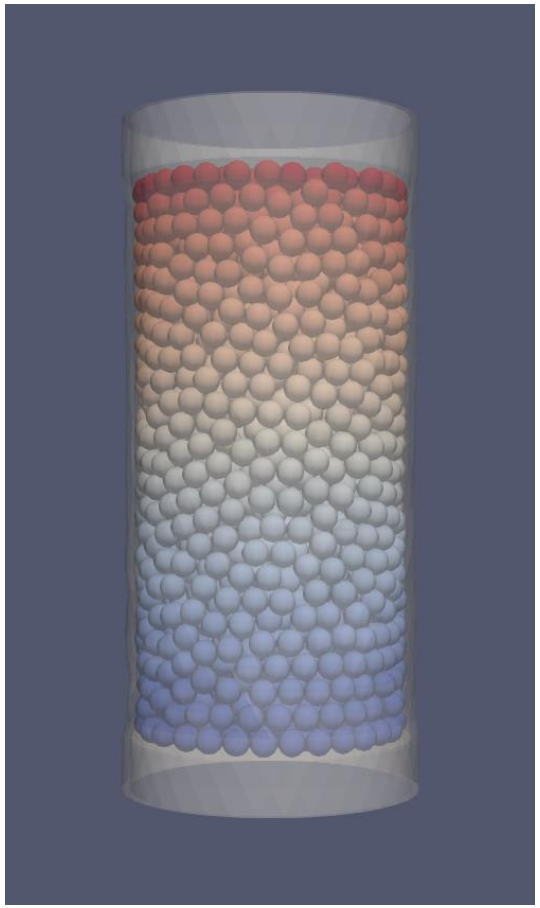
Init Phase 2

- Initialise membrane
  (Young's modulus E → 1400 kPa [Rubber])
- Increase cell pressure from σ_3 = 0 kPa to σ_3 = 200 kPa



Numerical setup of triaxial test

Init Phase 1

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Init Phase 2

- Initialise membrane
  (Young's modulus E → 1400 kPa [Rubber])
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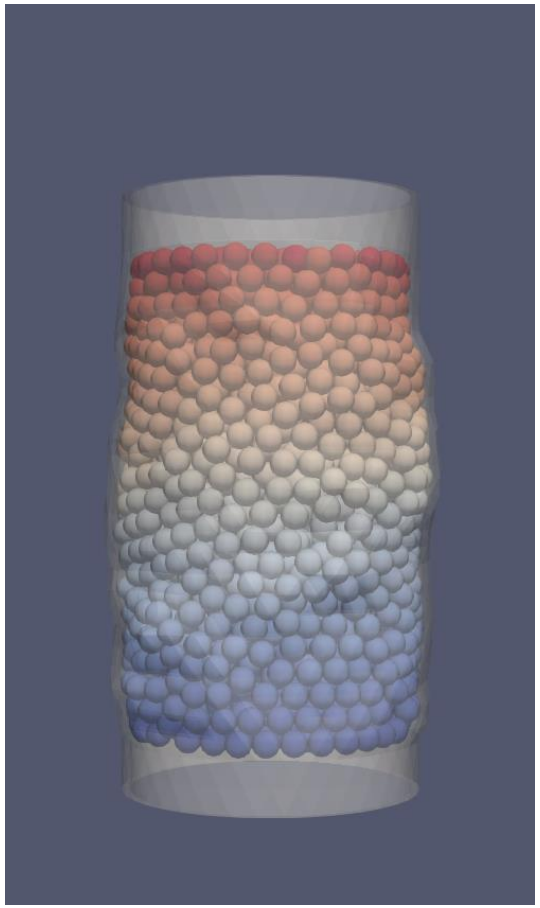
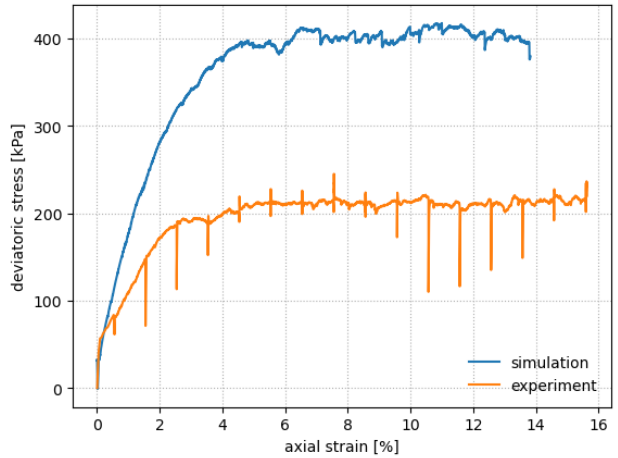
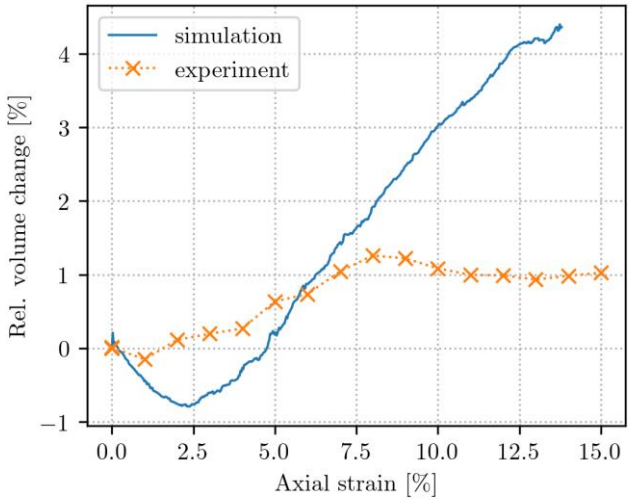
Simulation phase

- Start axial compression of specimen



Comparison of measurements





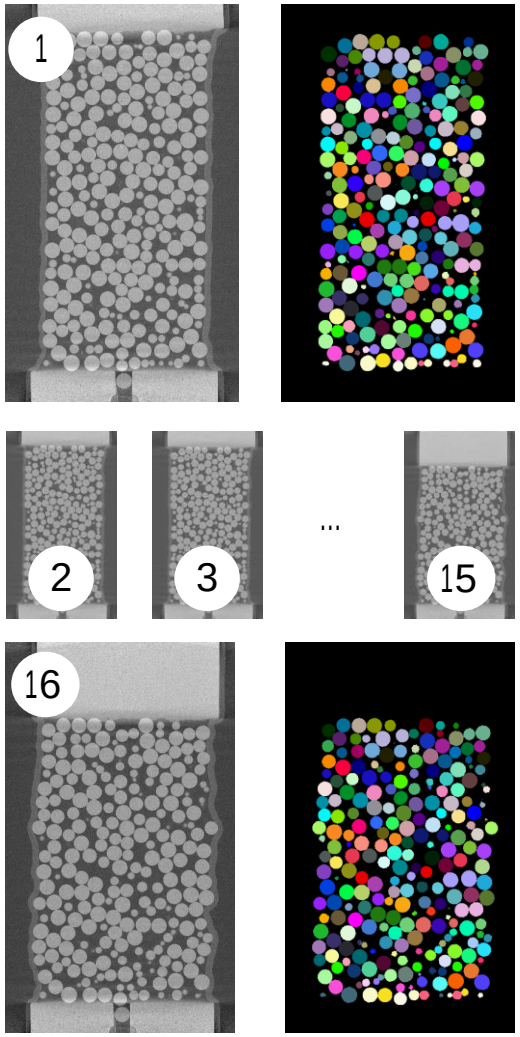
How to calibrate / modify the numerical model?

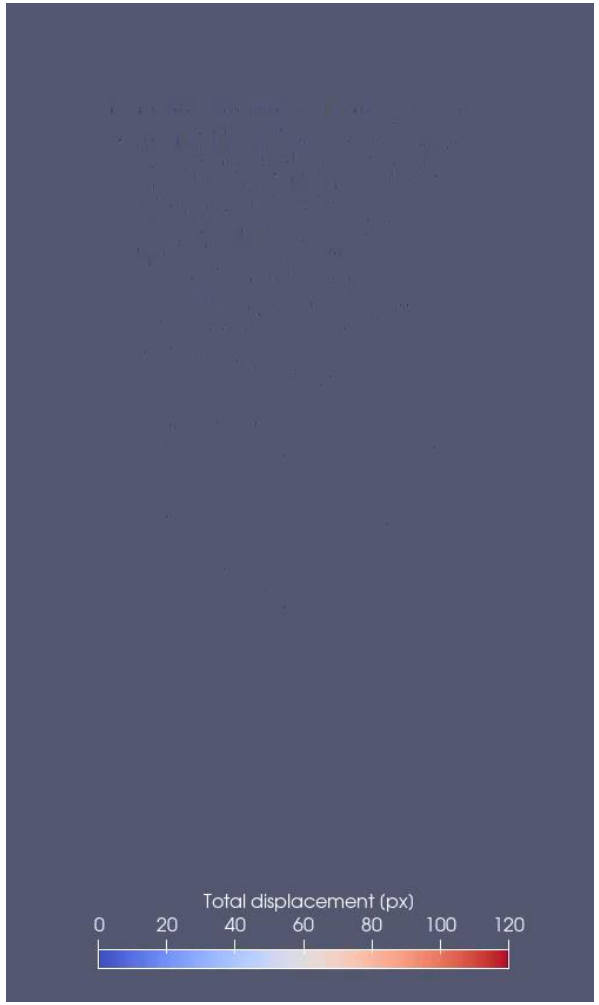
- Change (rolling) friction of particles?
- Change membrane stiffness?
  - Parameter issue or numerical issue?
- ...

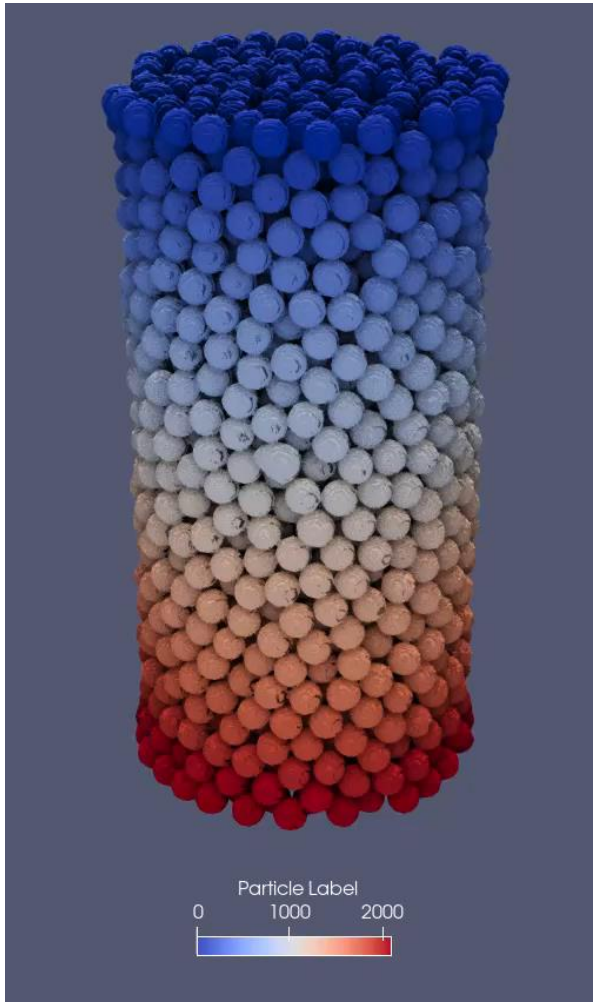
Image Analysis

- Discrete Digital Image Correlation

(Discrete) Digital Image Correlation

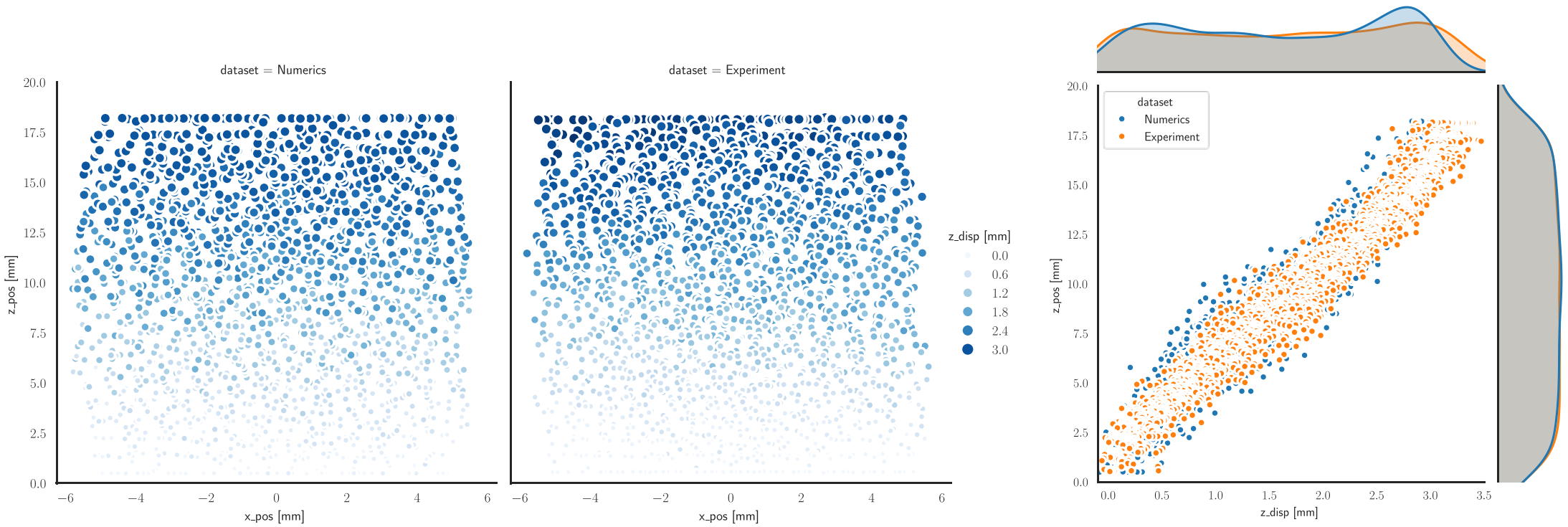




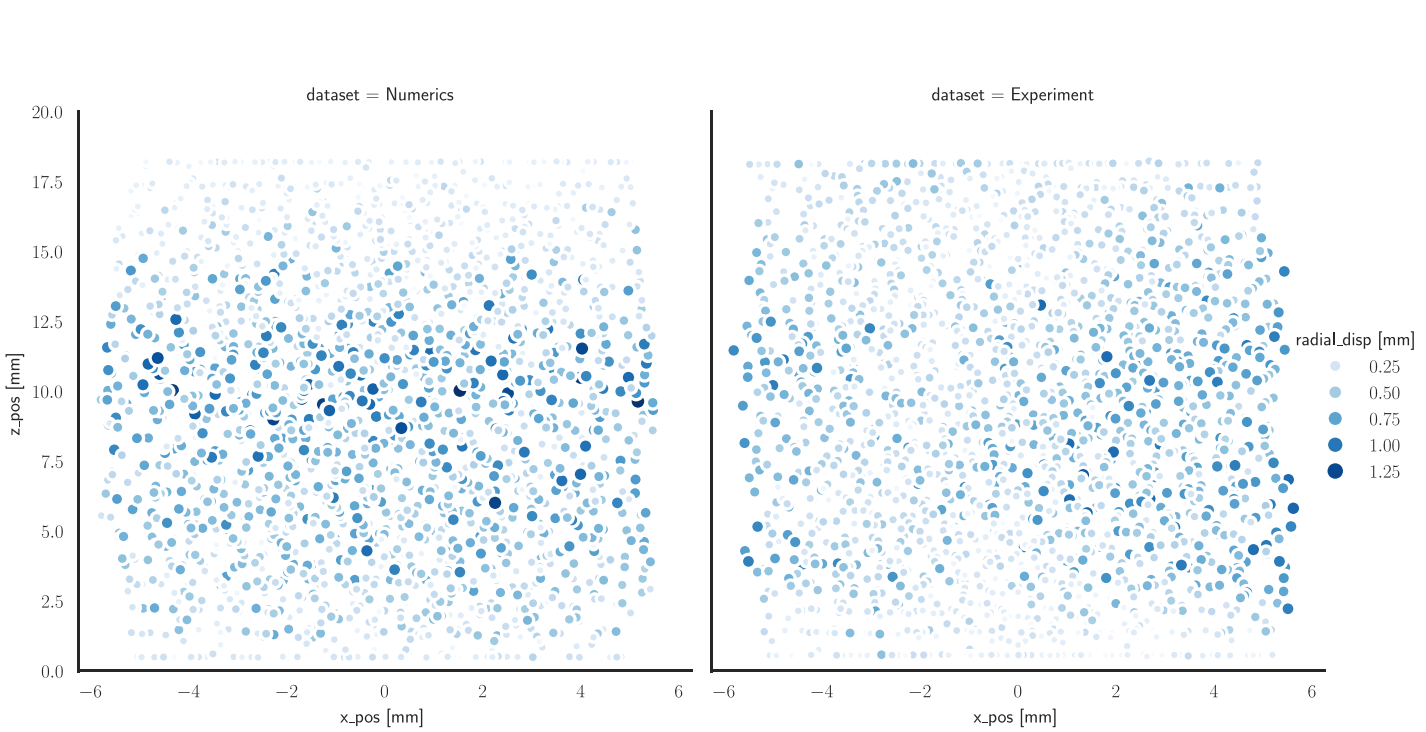


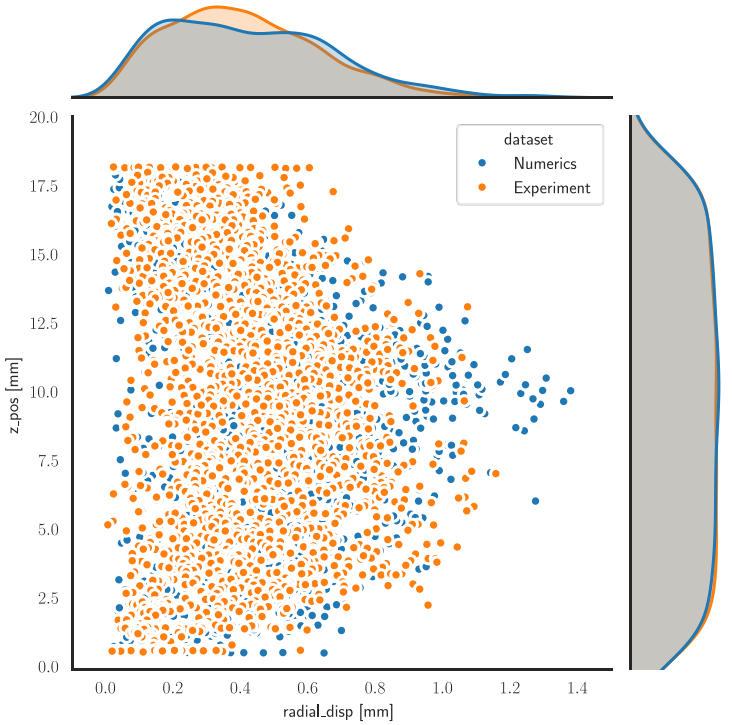
Comparison & Results

Comparison of results for 1 mm glass beads



Comparison of results for 1 mm glass beads





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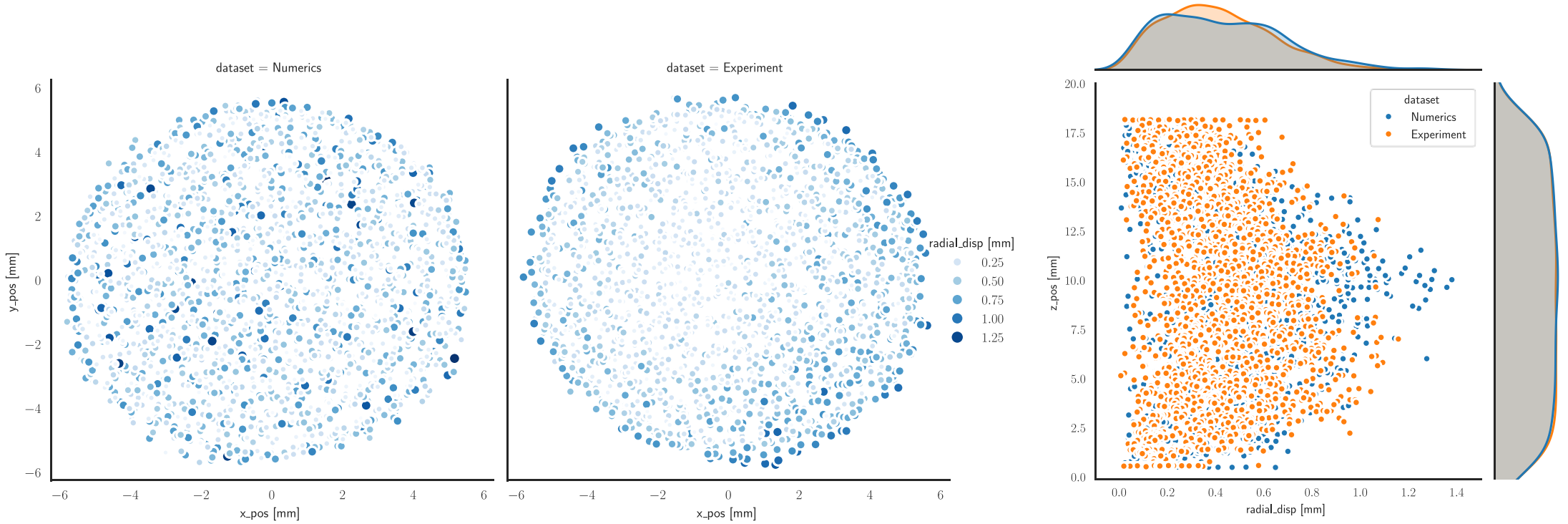


Summary & Conclusion

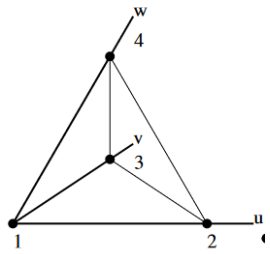
Summary & Conclusion

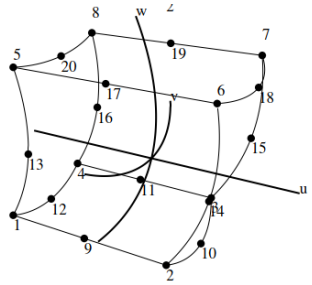
Visualisation of deformation pattern from imaging results

- A valuable addition to measured sensor data
- enables spatial comparison with numerical results
  - **vertical displacements** of particles show a **good match**
  - **radial displacements** indicate **optimization potential** with membrane modelling

Potential of optimization of numerical model

- Membrane modelling
  - Transition from linear tetrahedron (504) elements to 20-node (820) hexahedron elements
- FEM-DEM coupling
  - Optimize determination of damping factor to account for heavily diverging Young‘s moduli of membrane and particles





Outlook

- Extension to a FEM-CFD-DEM coupling to account for additional fluid interaction

Images taken from ElmerFEM User Manual

Thank you for your attention!

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Funded by
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References

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DFG-Project (461859082)
„Micro-mechanical modelling of unsaturated particle packings using CFD-DEM and computed tomography (MIME-UP)“

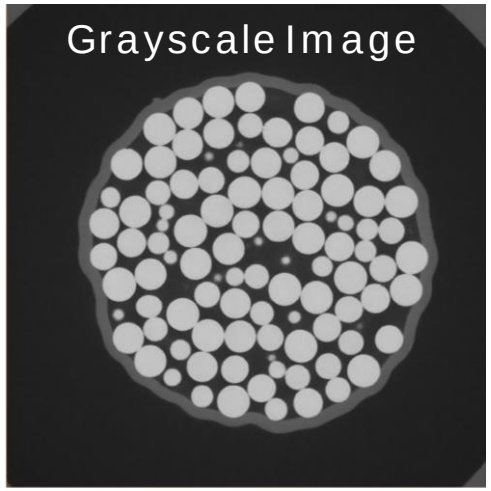
FWF Österreichischer Wissenschaftsfonds

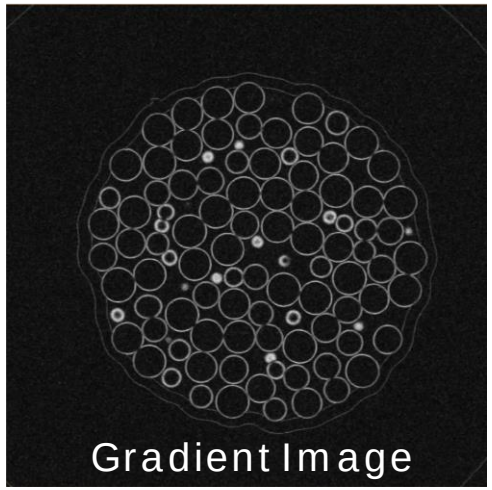
FWF Project (I 5374)
„Micro-mechanical modelling of unsaturated particle packings”

spam practical analysis

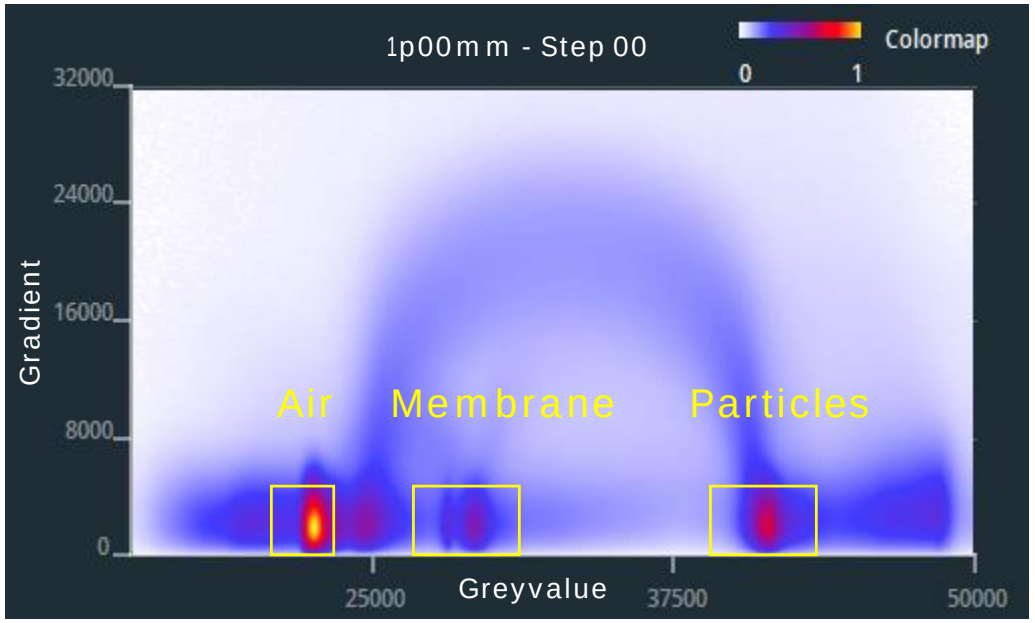
Software for Practical Analysis of Materials (SPAM)
https://www.spam-project.dev/

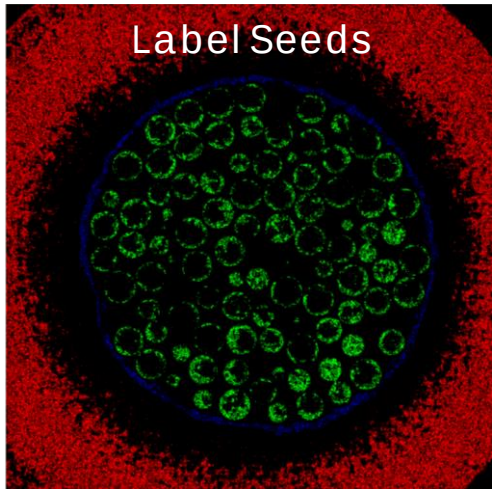
Appendix: Image Segmentation with Avizo®

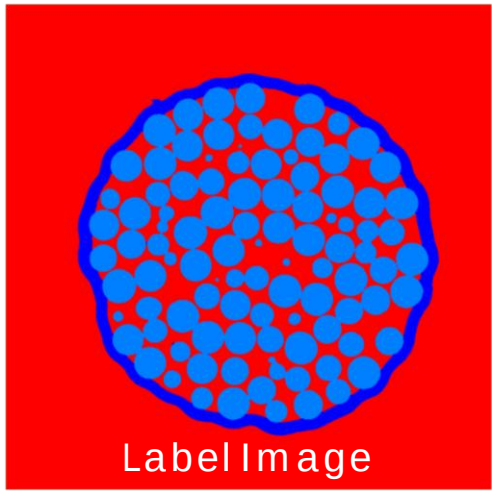




Correlation Histogram







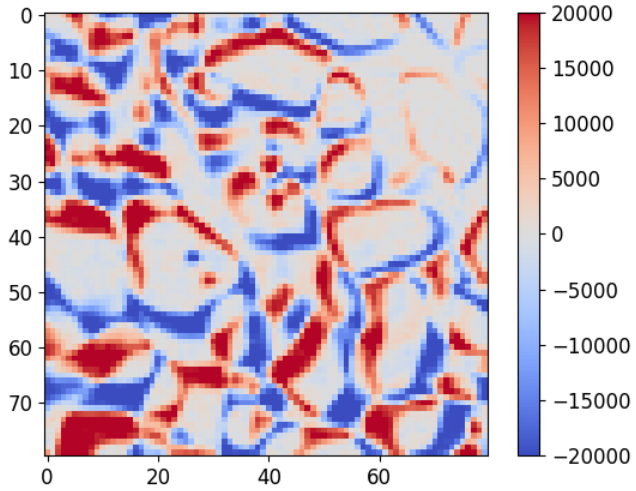
Appendix: Image Correlation Theory

$$x = (x, y, z) \qquad x = \begin{bmatrix} z \\ y \\ x \\ 1 \end{bmatrix} \qquad \Phi.x = x' = \begin{bmatrix} z + t_z \\ y + t_y \\ x + t_x \\ 1 \end{bmatrix}$$

$$\text{im1} = \text{im2}(\Phi.x)$$

or

$$\text{im1} - \text{im2}(\Phi.x) = 0$$



Translation

$$\Phi = \begin{bmatrix} 1 & 0 & 0 & t_z \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_x \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation

$$\Phi = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & sin(\theta) & 0 \\ 0 & -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Zooming/Shear

$$\Phi = \begin{bmatrix} F_{zz} & 0 & 0 & 0 \\ 0 & F_{yy} & 0 & 0 \\ 0 & 0 & F_{xx} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

General

$$\Phi = \begin{bmatrix} F_{zz} & F_{zy} & F_{zx} & t_z \\ F_{yz} & F_{yy} & F_{zy} & t_y \\ F_{xz} & F_{xy} & F_{xx} & t_x \\ 0 & 0 & 0 & 1 \end{bmatrix}$$