Bauhaus-Universität Weimar

Approaches to Determine the Constriction-Size-Distribution for Understanding Filtration Phenomena in Granular Material

K. Josef Witt, Eric Vincens

ISCE-6   27-31 August, 2012, Paris

Approaches to Determine the CSD for Understanding Filtration Phenomena in Granular Material

- Introduction
- Different approaches

    Experimental

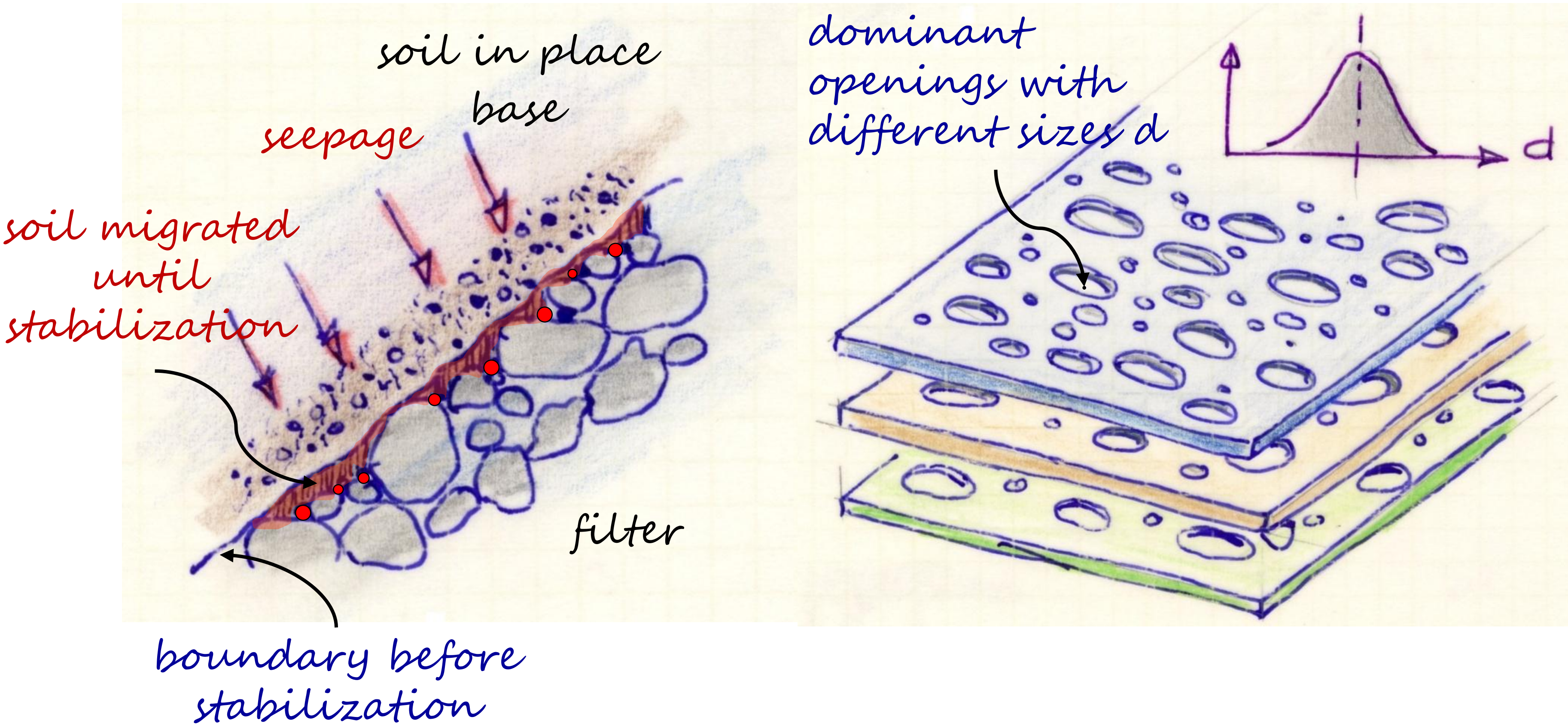
    Numerical

    Analytical

    $\Rightarrow$ Advantages and Limits

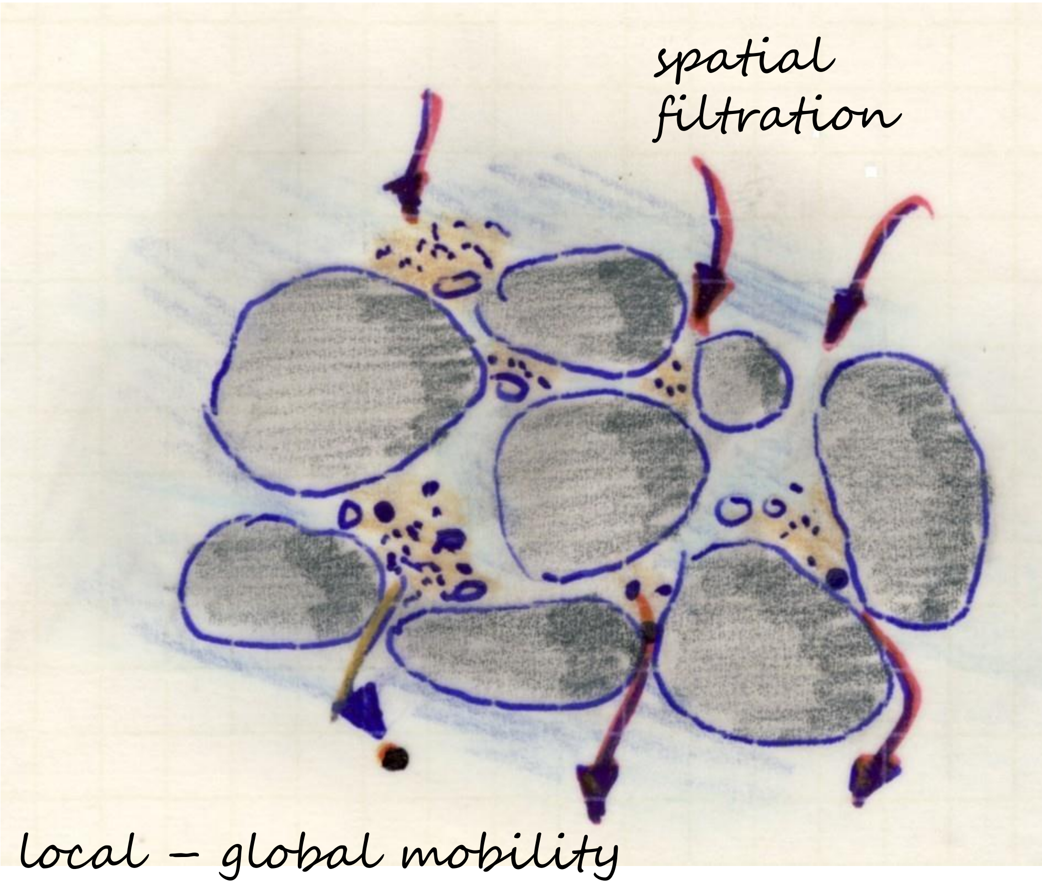
- Conclusion

Engineering context - Filtration



2D layered sieves with varying sizes of dominant openings

Engineering context - Suffusion

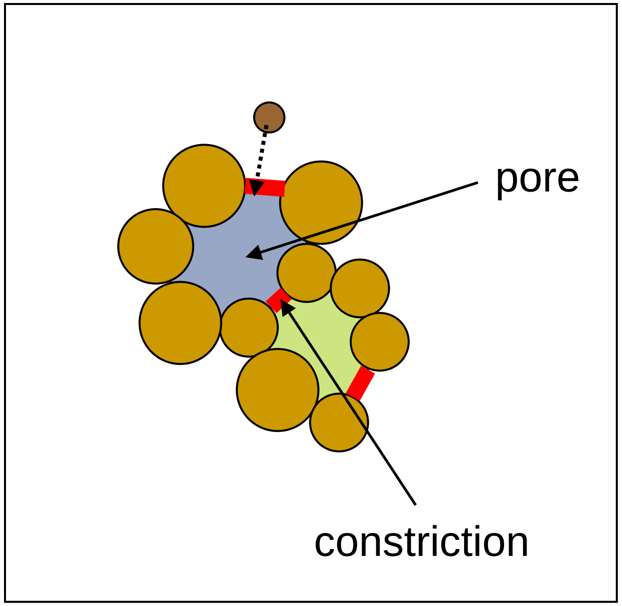


coarse grain structure and embedded fines
transported along pore paths

Pore Space – Single Pore – Constriction

- Pore

  three-dimensional body of the relatively wide part of a channel that is constricted by two or more throats



- Constriction

  throat along a void channel say a local minimum of width

  → narrowest obstacles for a particle to overcome along a pathway

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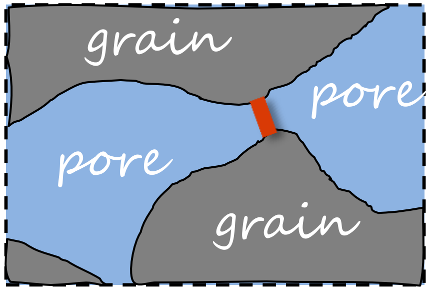

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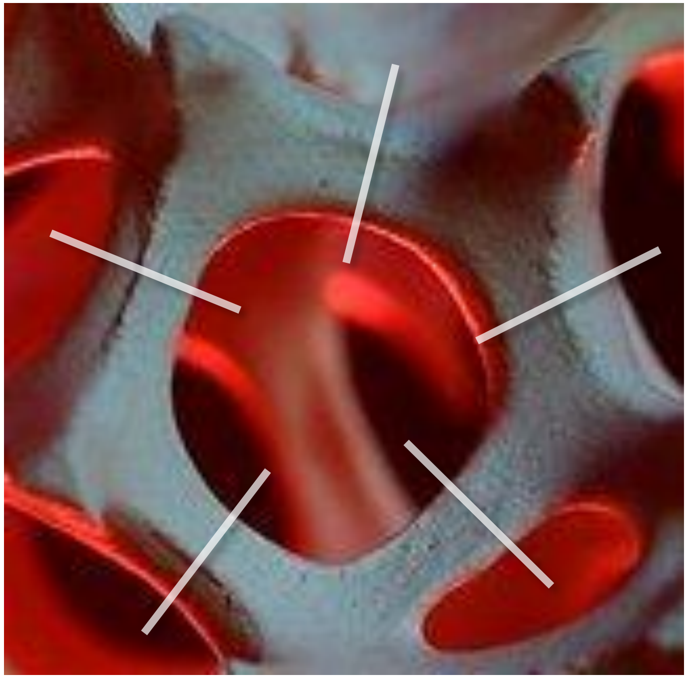

Imprint open-celled foam [Fraunhofer IKTS]

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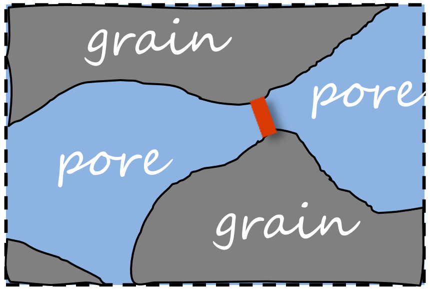

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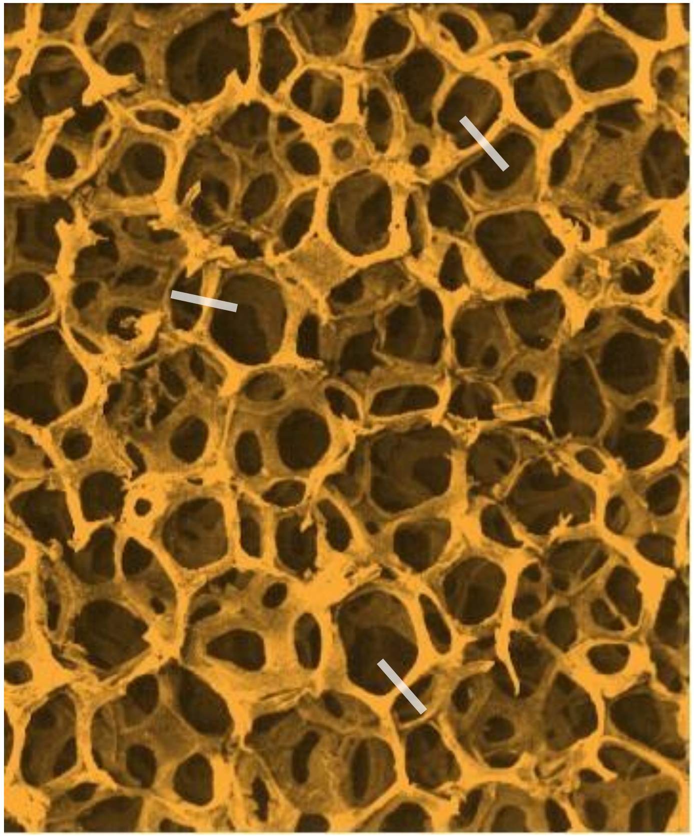

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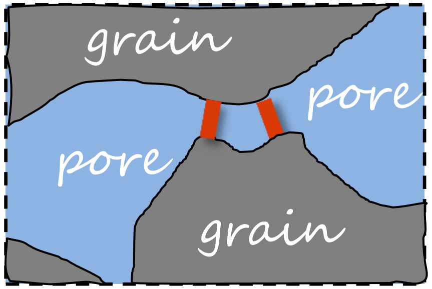

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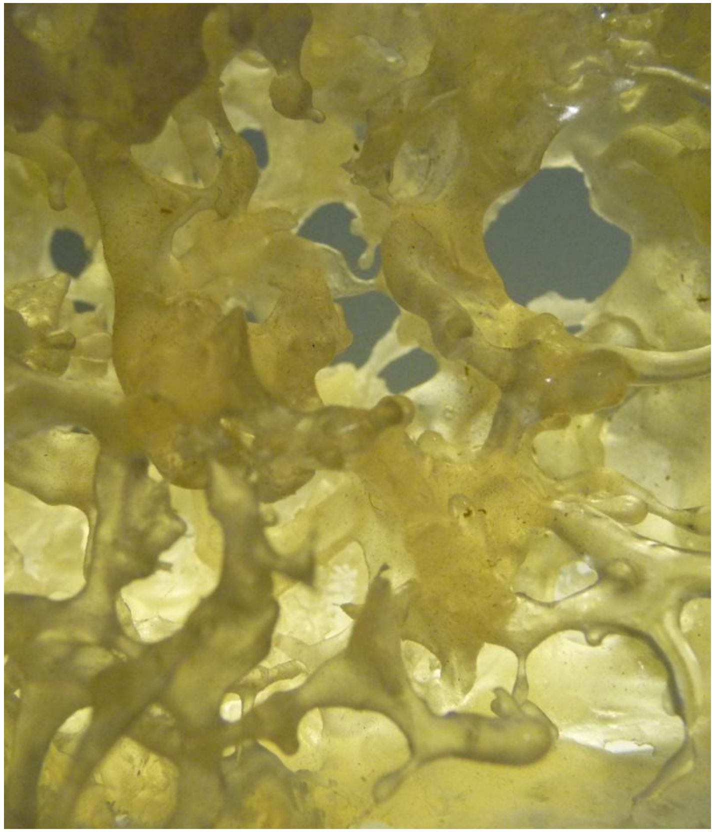
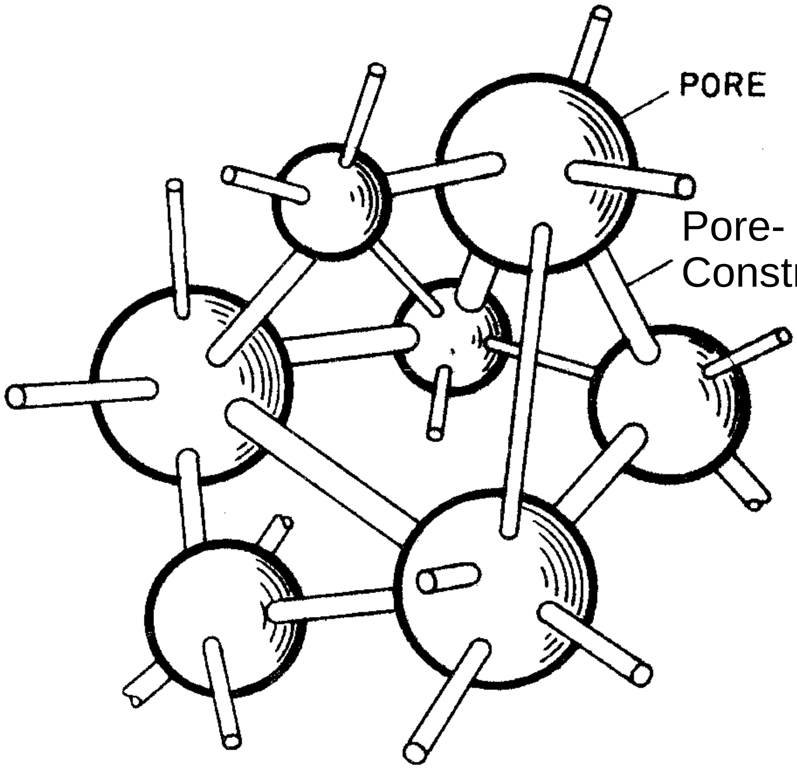


Imprint of a structure out of non spherical wax grains (R. Binner)

Model to simulate particle transport in soil



dynamic clogging rule

If there are mobile particles larger than the smallest constriction of a pathway then transport along this pathway will be stopped after a finite loss of mass

CSD = statistical distribution of the size of all constrictions between pores

EOS = statistical distribution of the ultimate width of possible pore paths

Witt, K. J. (1986)

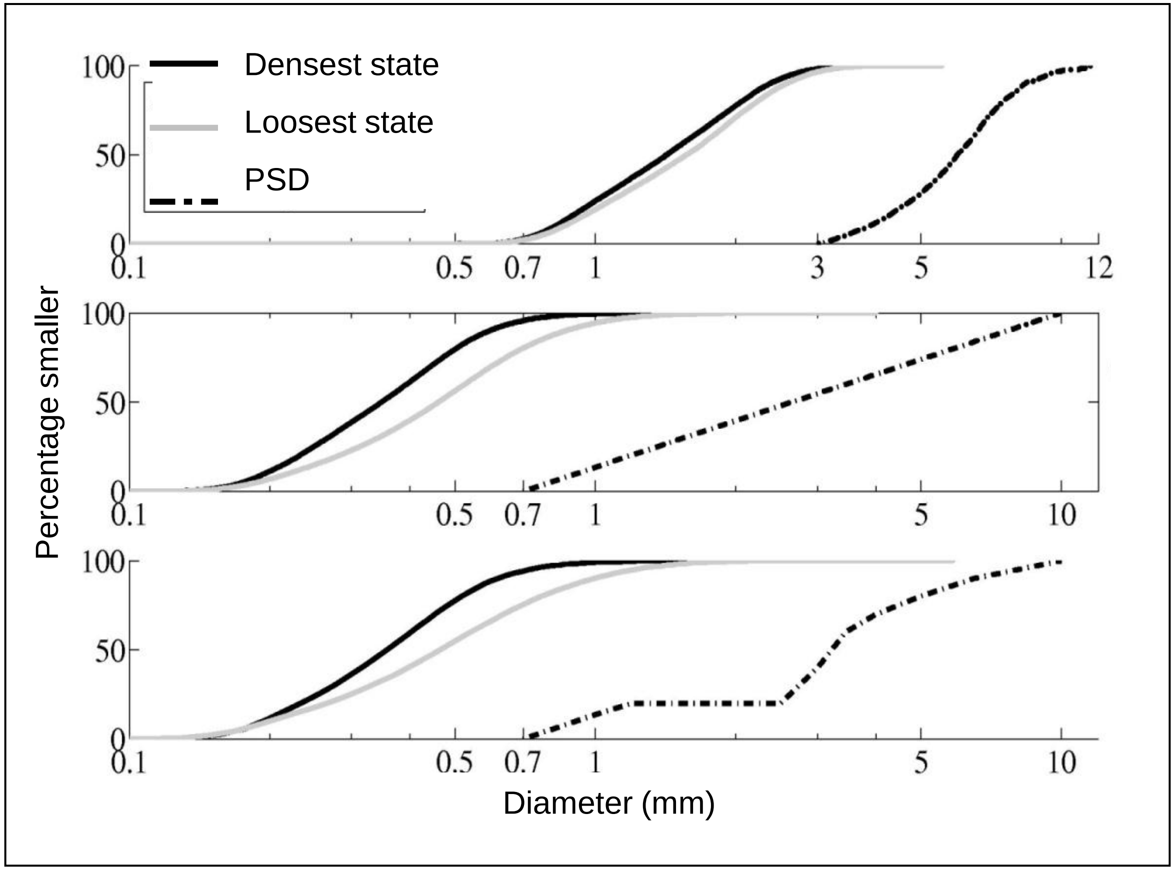
Constriction Size Distribution - CSD

A cumulative distribution in terms of number of constriction sizes

Shape depends on

Particle Size Distribution

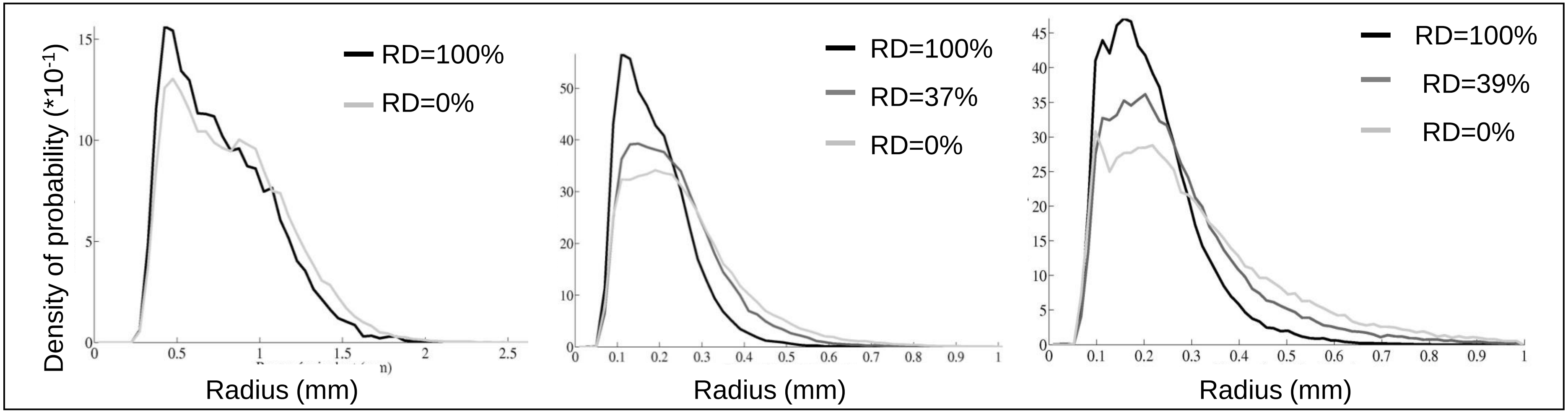
Density/Porosity



Assemblies of spherical material *[Reboul et al., 2008]*

Constriction Size Distribution - CSD

- Density distribution always gives more detailed information than the cumulative distribution
  → more numerous constriction sizes



Assemblies of spherical material *[Reboul et al., 2008]*

- The mode of the distributions only slightly shifts with density
  → Shrinkage of the distribution with densification

- For wide and gap-graded material: two modes may be noticeable (bimodal distribution)

Significance of CSD Related to Internal Erosion

pore space may be modelled as a 3D network of pathways with fluctuating width. To assess transport and blockage we need

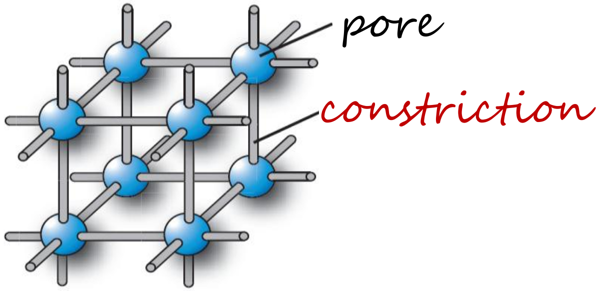
[Fraunhofer IKTS]

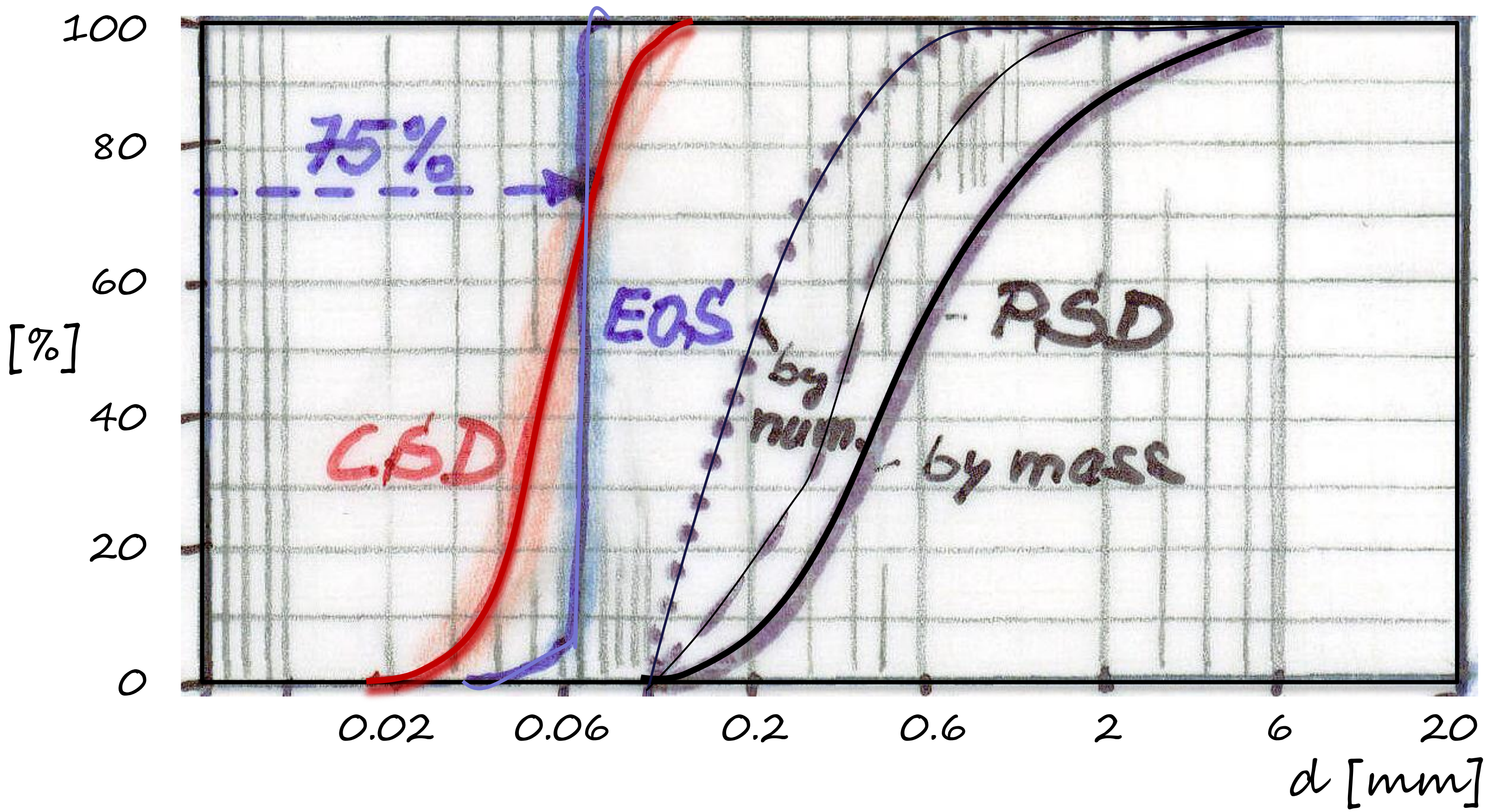
(i) the <u>overall distribution of pore constriction</u> sizes within the soil's structure and

(ii) the distribution of the smallest constriction size of a certain set of properly sequenced constrictions along a pathway, which corresponds to <u>the ultimate opening size of the pore paths</u> = EOS

⇒ CSD of a soil's structure is the most evident parameter to assess the ability of filtration, particle discharge and internal stability

Significance of CSD Related to Internal Erosion



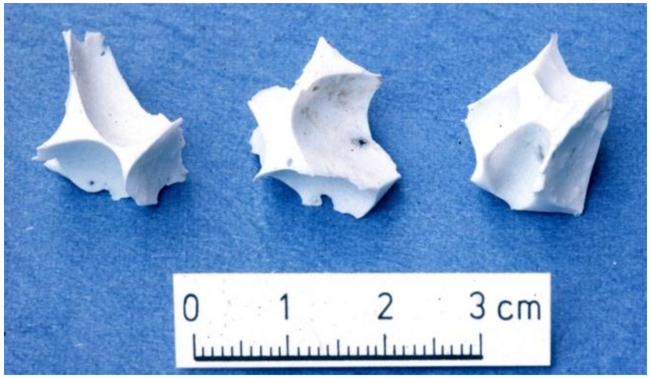


Silveira, 1965, Witt, 1986, Indraratna et al, 1990; Schuler, 1997; Locke et al, 2001; Indraratna & Raut, 2006; Reboul et al., 2007; Raut & Indraratna, 2008; Lőrincz et al, 2008, J. Sjah and E. Vincens, 2012

Replica technique

Imprint of the void space by injection of an elastic resin into a real soil or spherical structure.

Cutting and measurement of the narrowest sections



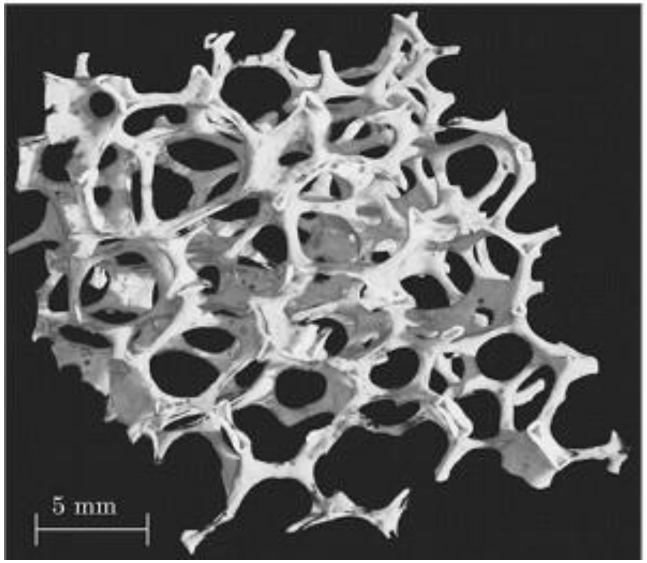
Individual pores [Witt, 1986]

Creation of an artificial, sacrificial solid structure - ceramic powder fills the pore space

Synthetic grains (wax, polymeric material)

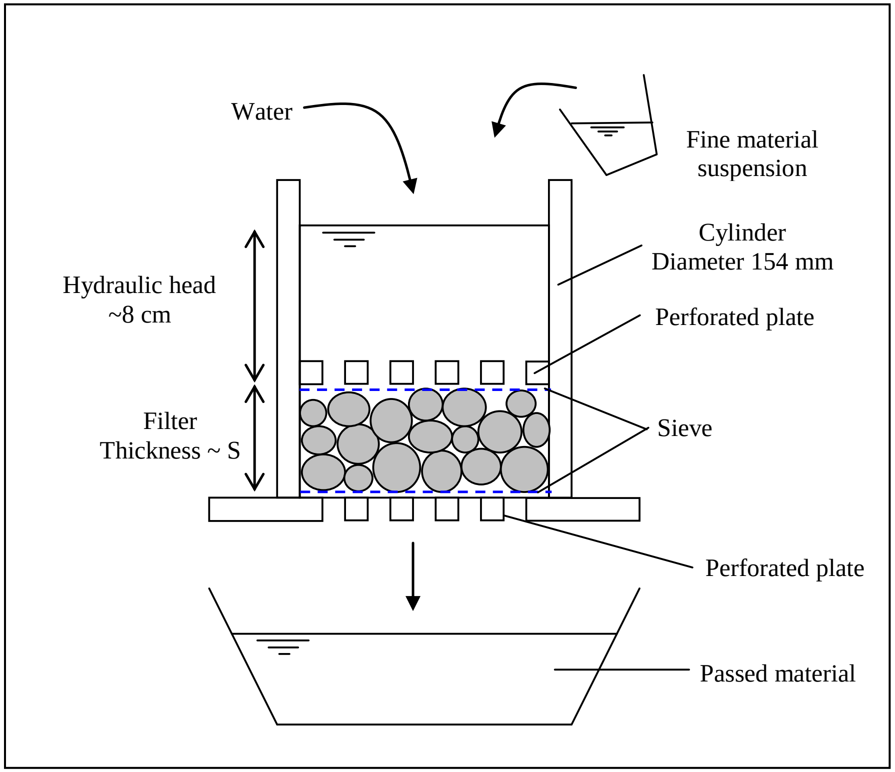
Fill the void space with a slurry or ceramic powder

Heating and curing → grain structure disappears, pore structure remains



Imprint of pore space
http://www.fhv.at

Base suspension method



[Soria et al., 1993]

Several filtration tests with suspended uniform base particles

same filter, same porosity

different thicknesses (RVE at minimum)

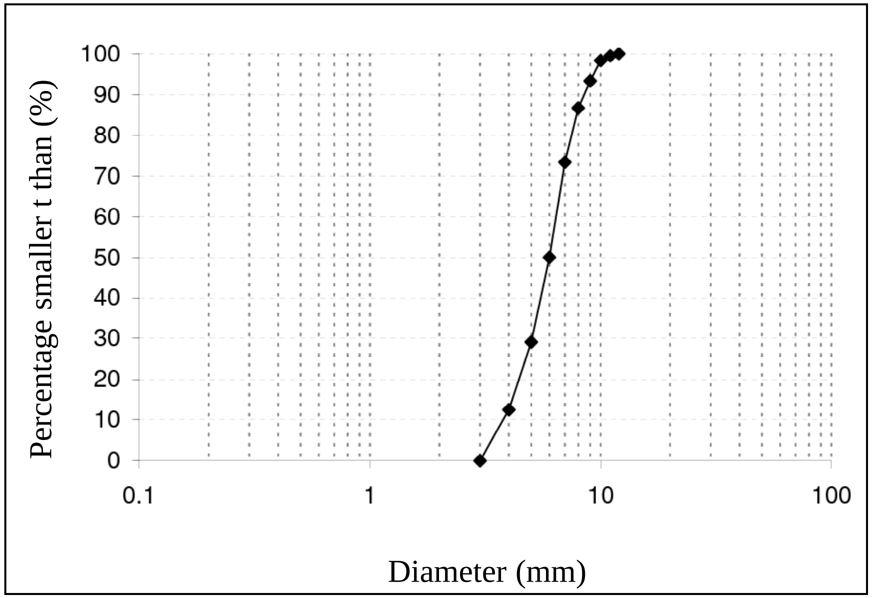
Passed base soil is collected

Grading of the passed material is related to the occurrence of the constriction sizes

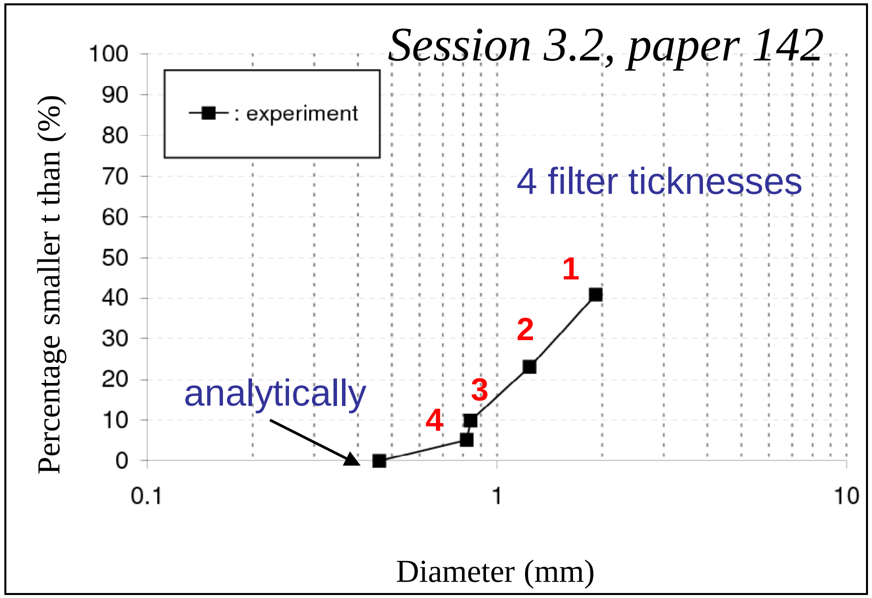
Probabilistic scheme is used to derive the CSD from the relation of applied and passed particles

$\Rightarrow$ *size of the largest particle that will pass through the soil structure*

Base suspension method



Filter with glass beads [Wu et al., 2012]



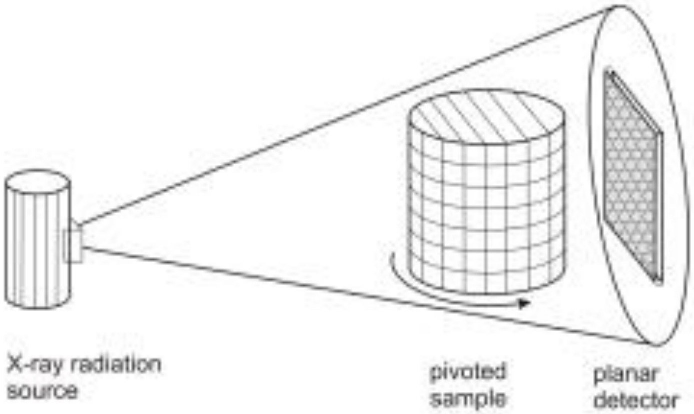
Computed CSD [Wu et al., 2012]

- The grading [d_0, d_{100}] of the base soil must reflect the filter void space
- Hydraulic head large enough to avoid meta stable rests
- Avoid bridging effect when pouring the base soil

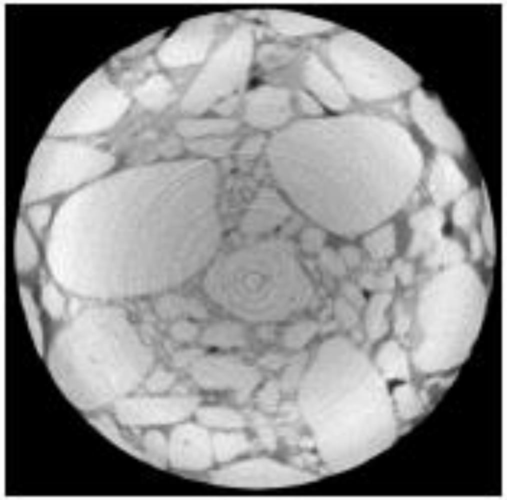
- *Result = EOS, performance curve of the soil structure acting as filter*
  = particle retention capacity of a soil

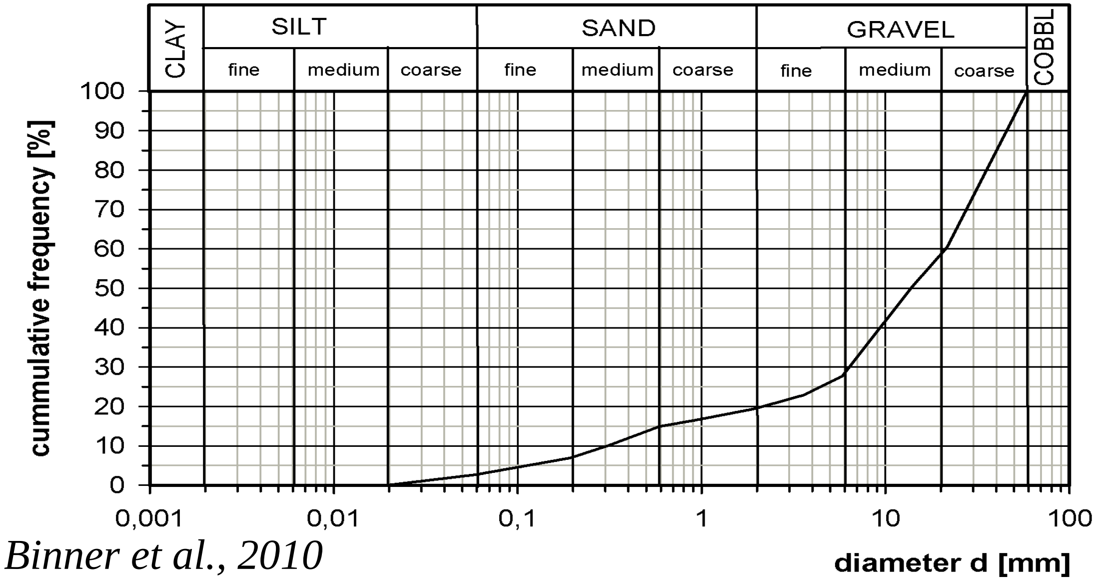
Micro CT-scan visualization

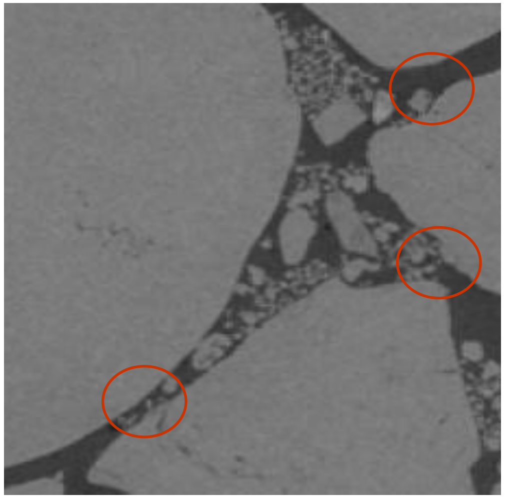
Infiltration of epoxy resin into the sample



RotatingParticles.avi





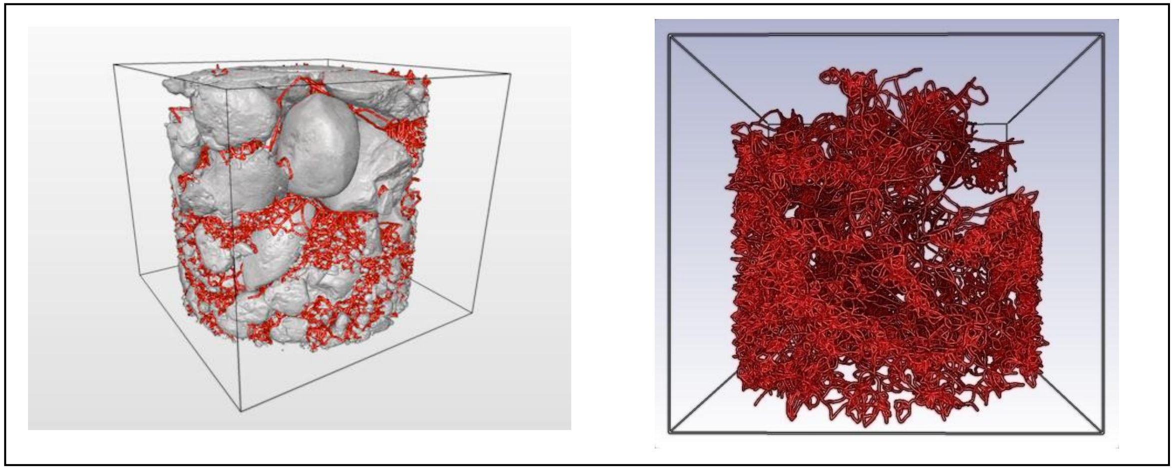


Binner et al., 2010

Micro CT-scan visualization

- CT-Scan of the specimen
- 3D visualisation of the solid structure and the void space due to a high contrast between the resin and the grains
- Different local analysis with different resolutions + recombination
- Voxelisation of the solid and pore space

Different properties of the soil-structure geometry can be derived

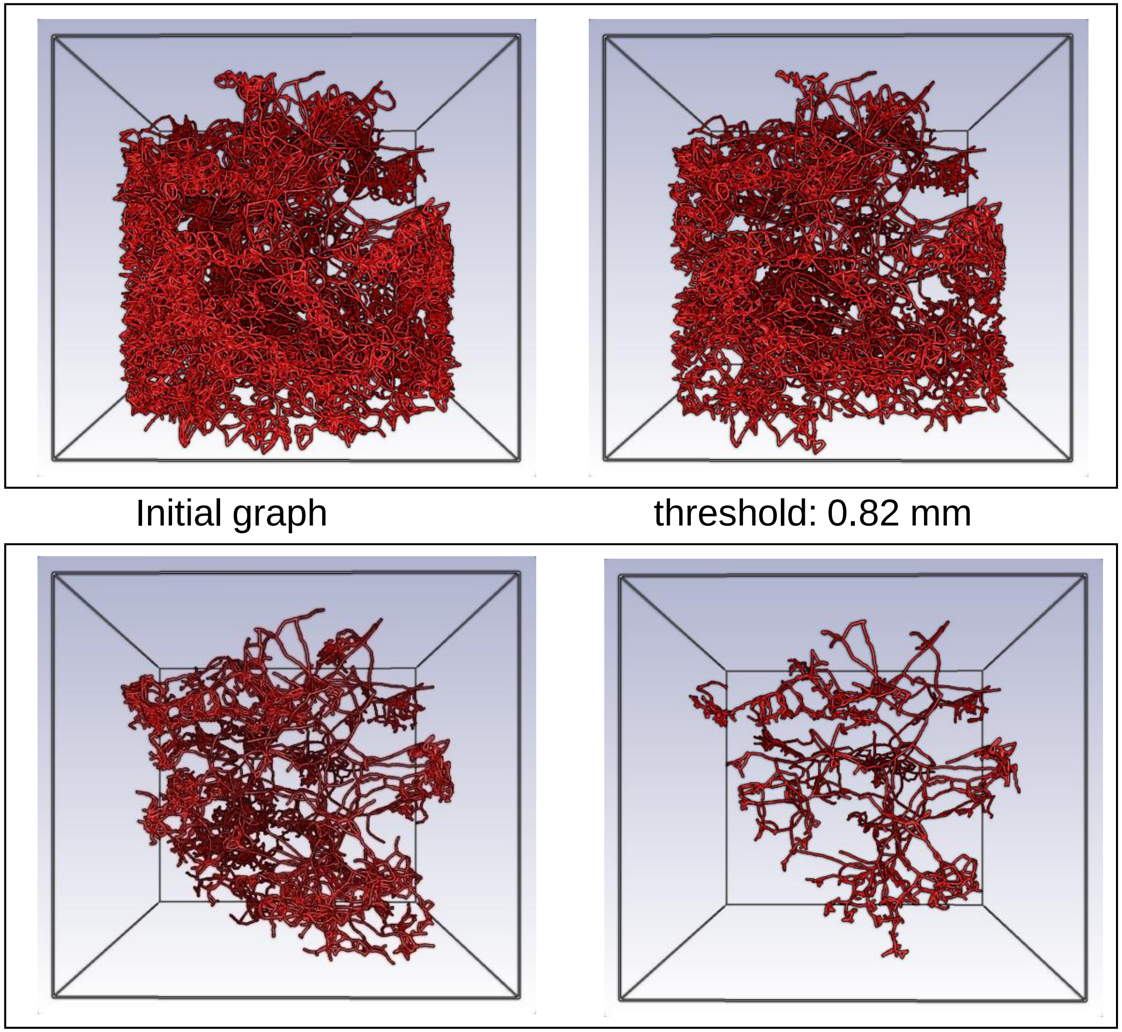


Pore network of an real well graded soil [Homberg et al., 2012]

Session 1.2, paper 181

Micro CT-scan visualization

Visualization of possible pathways for a particle with a certain diameter



Initial graph — threshold: 0.82 mm

threshold: 1.4 mm — threshold: 1.95 mm

[Homberg et al., 2012]

Advantages and limits
Experimental methods

- Replica technique + CT Scans
  - Duration for the preparation of sample and scan – Homogeneity ?
  - Large data to handle, Uncertainty due to merging procedures
  - Almost undisturbed samples of natural soils
  - For any type of material
  - Very precise results

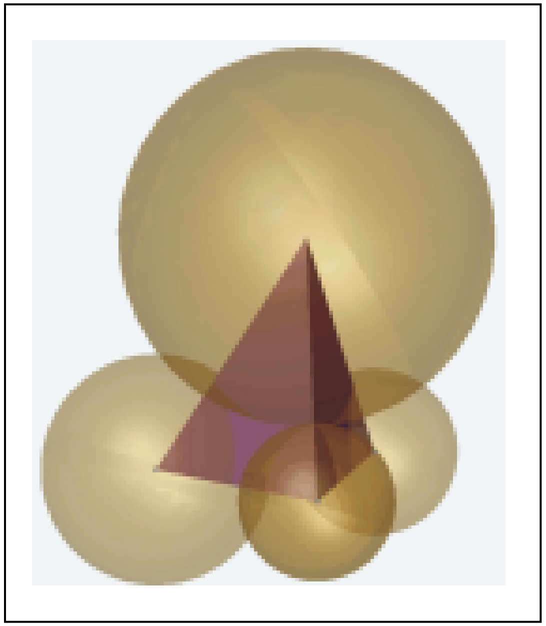
- Base suspension method
  - Test is mainly unidirectional
  - sample size, scale effect, representative volume
  - Takes several days (4 tests)
  - For any type of material; relatively easy to handle
  - Quantitative result of the true performance

Delaunay approach

- Principle
  - Build up a solid structure with DEM
  - Partition of the space into tetrahedra

    Tetrahedral tessellation until a cluster of non-overlapping, space-filling tetrahedra is formed

- Postulate
  - Each tetrahedron has a pore chamber and four constrictions



vertices of each tetrahedron are the centers of four neighboring spheres

- Definition for a constriction
  - Largest empty disk on a face and included in the void space
  - Powell Search Algorithm for a Minimum

    [Reboul et al., 2008; To, 2012]

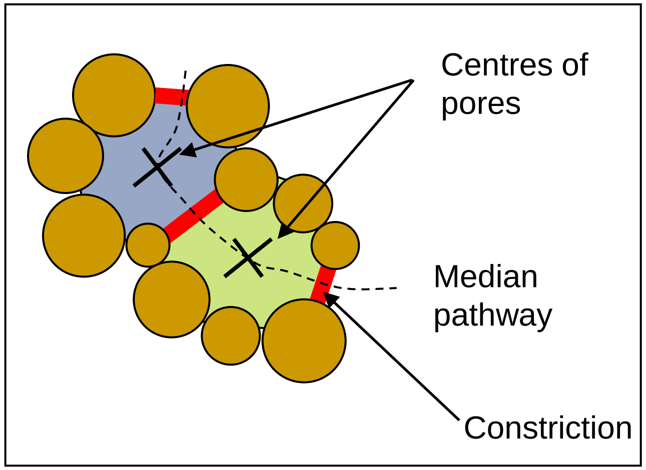
- Statistics of constriction sizes over the sample

General Voronoi graph

- Property associated to each point of the void space

  Distance to the surrounding solid particles (distance mapping)

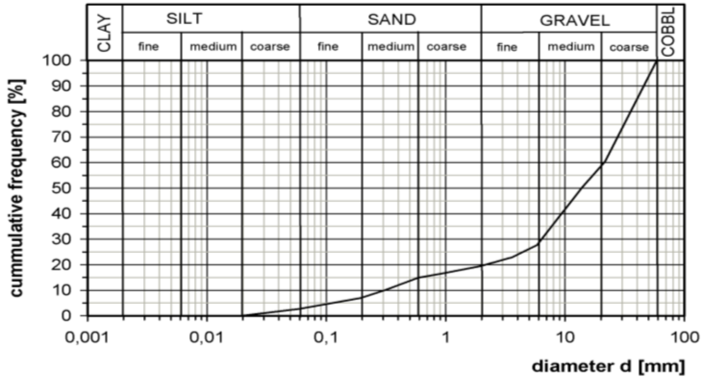
- Deduction of a median pathway and branches
- Greatest average distance → centre of a pore
- Smallest average distance → a constriction
- Merging criteria to remove a constriction between two adjacent pores



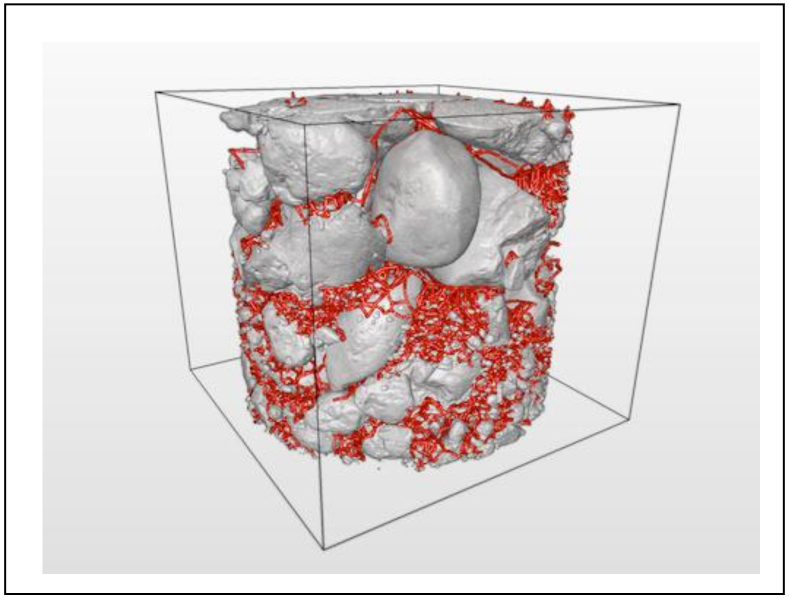
Two pores with strong interaction

→ merging?

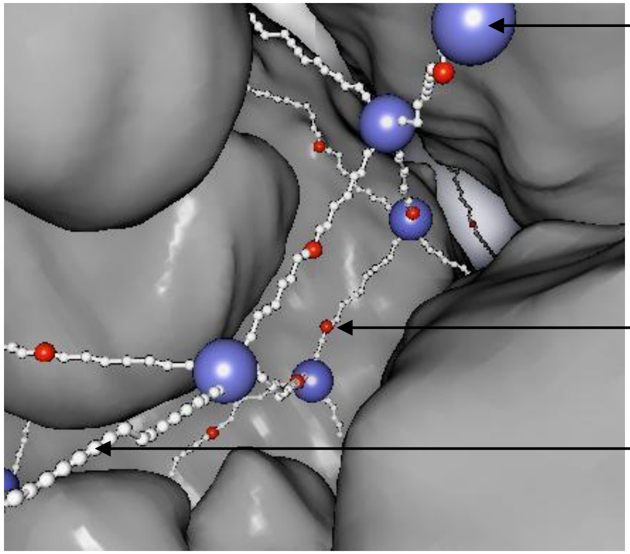
General Voronoi graph



Example of a gap graded material



Overall sample



Main properties of the pore space

[Homberg et al., 2012]; Session 1.2, paper 181

Advantages and limits

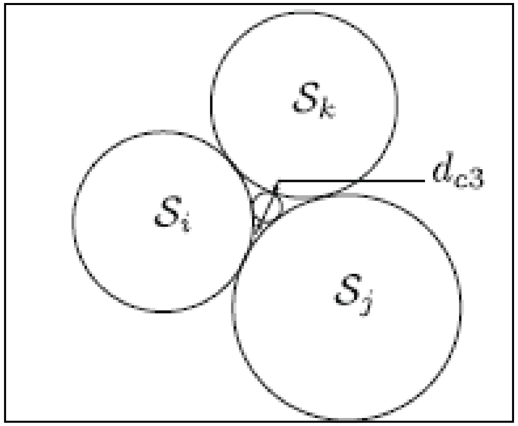
Numerical methods

- Delaunay approach
  - Only for the approximation of spherical material
  - Definition for a local pore is artificial → biased CSD
  - Quick computation
  - Careful analysis of different phenomena: anisotropy, paths, heterogeneity of samples….

- General Voronoi graph
  - preparation of specimen for CT-scan; Large data to handle
  - Validation of merge criteria
  - For natural materials and undisturbed natural soil samples
  - Precise analysis, all relevant data available, visualization

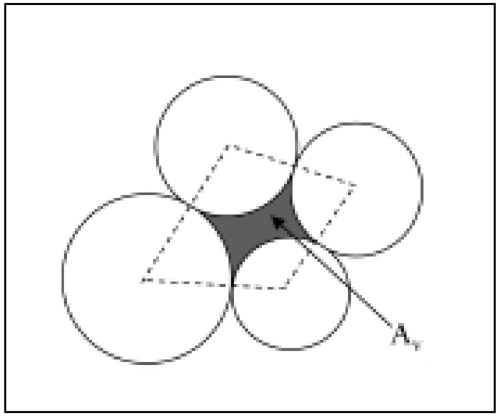
Reconstruction of the CSD

Particals are approximated as spheres with two geometrical configurations

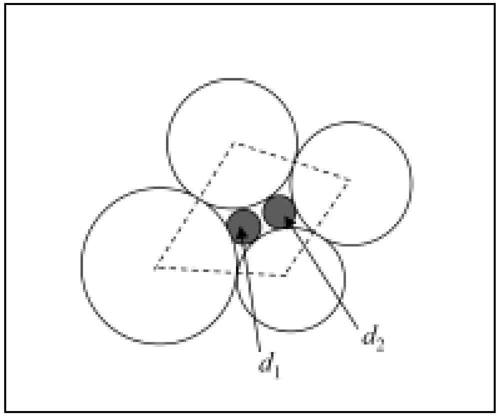


[Silveira, 1965]

Geometrical dense state



[Silveira, 1975]



[Schuler, 1996]

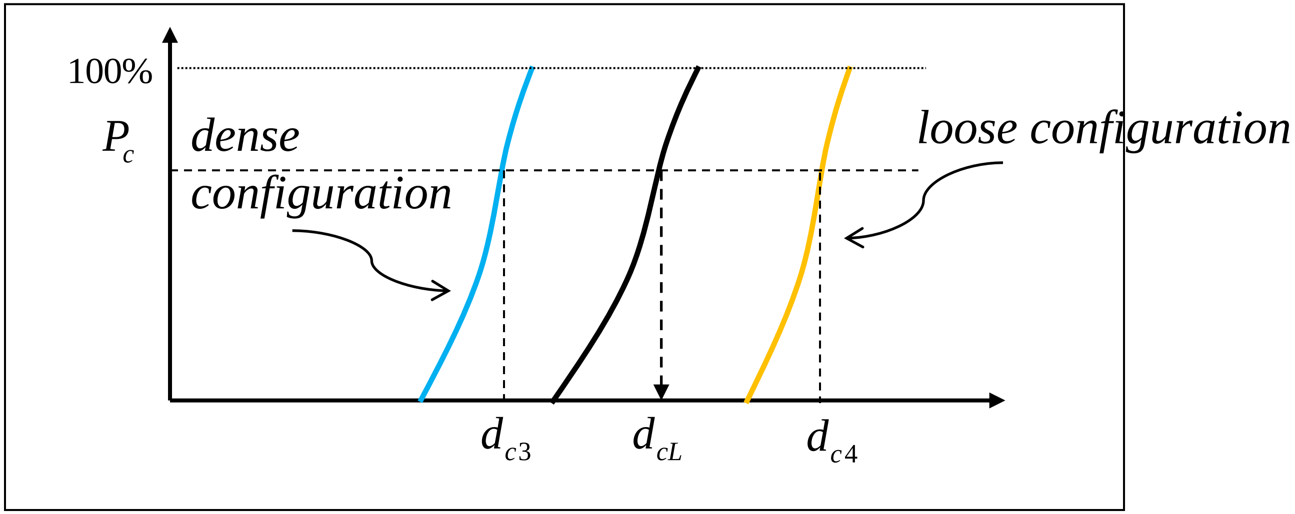
Geometrical loose state

- Step 1: compute the CSD for each configuration given the occurrence of particles sizes by statistics of random permutations
- Step 2: design a weighted contribution of these two configurations (loosest – densest state)
- Step 3: CSD for any density state

Reconstruction of the CSD

Example: continuous grading

Loosest state *[Locke et al., 2003; Reboul et al., 2008]*



$$d_{cL}(P_c) = 1.11\left(d_{c3}(P_c) + P_c.\left[d_{c4}(P_c) - d_{c3}(P_c)\right]\right)$$

- Any density state (void ratio e) *[Reboul et al., 2008, 2010]*

$$d_c(P_c, e) = d_{cL}(P_c) + \frac{e - e_{\max}}{e_{\max}}.\left[d_{cL}(P_c) - d_{c\min}\right]$$

$$d_{c\min} = \frac{D_0}{6.5}$$

Advantages and limits
Analytical methods

- Approximation of spherical grains throughout the method
- Influence of particle shape not included in the models
- Not enough validation for well and gap graded materials

- Very easy and quick to handle
- Only two information are required: PSD and porosity (density) of the soil
- Very precise for continuous grading

Conclusion

- The size of the constrictions between the single pores is the most evident parameter passage or retention along pore paths in a dynamic process of spatial filtering
- governing
- All the methods are based on assumptions and requirements. Limitations come up from grain size distribution, accuracy, computer time consumption, data handling...

- Appropriate experiments – base suspension tests – will show the true performance

- Analytical and numerical models seem to be promising to calculate CSD but:
  How to modify the models to take into account the particle angularity and shape?
  Need for further validations of the model for well and gap graded materials

- CT scan is a powerful experimental-numerical tool to characterize and quantify the overall pore space: pores, pathways, constrictions, visualization.
  Need for a clear definition for merging criteria between adjacent pores

- Up to now the methods assume a homogeneous random packing of the soils structure. Most of the internal erosion problems are caused by heterogeneity and segregation. This may be the most challenging part of future research

Bauhaus-Universität Weimar

Laboratoire de Tribologie et Dynamique des Systèmes

ÉCOLE CENTRALE LYON

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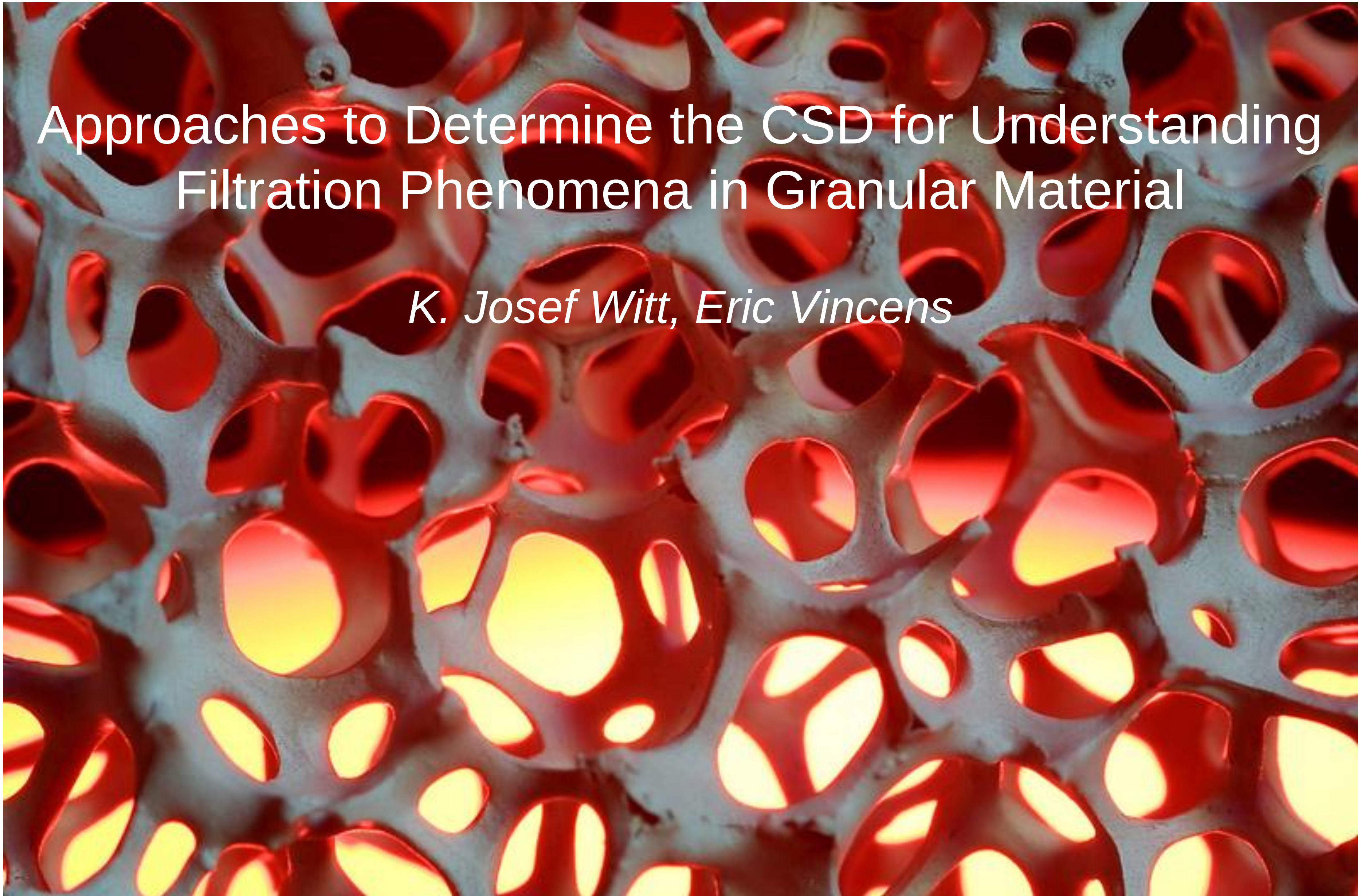

ISCE-6   29 August 2012, Paris