Evaluation of oil contamination in porous media by X-ray CT image analysis and LBM simulation

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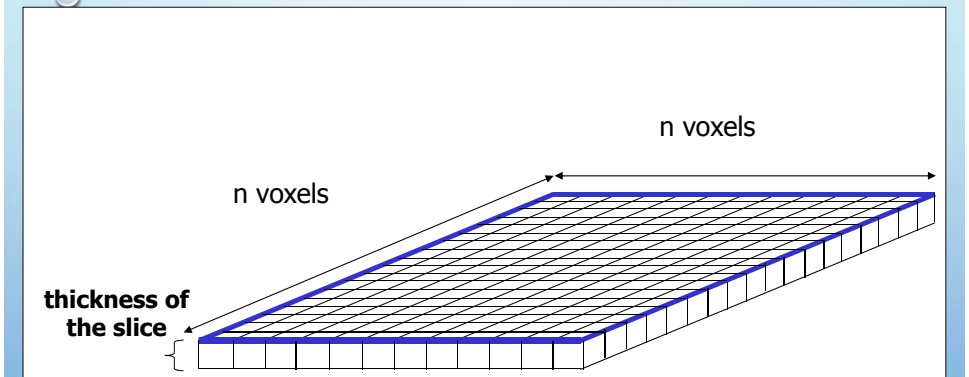
X-Earth Center
X-ray CT for Eco, Aqua and Resource Technology

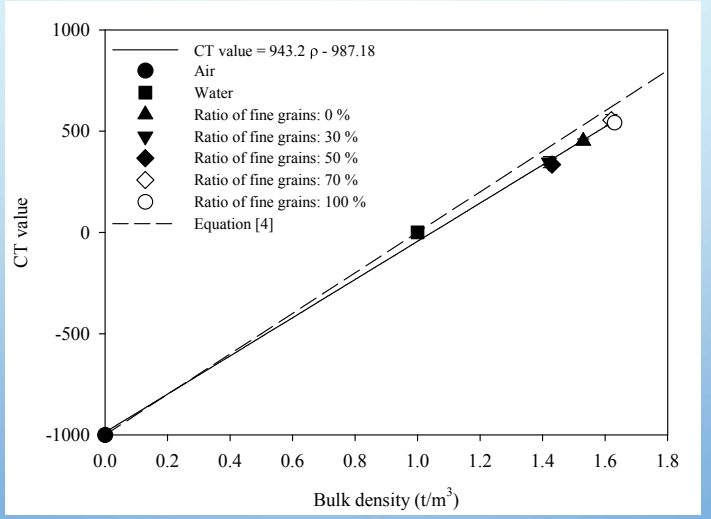
BASICS OF X-RAY CT METHOD

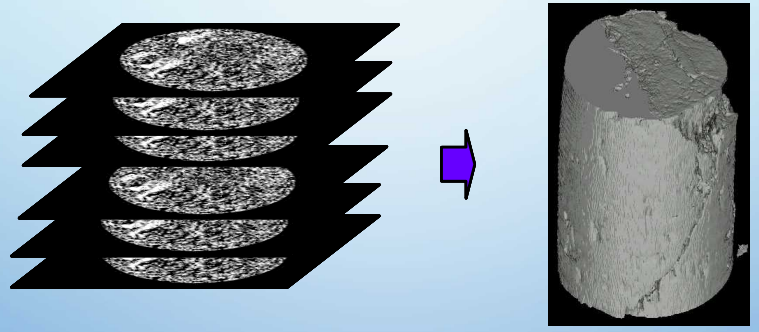
GENERAL PRINCIPLE, VOXEL AND CT VALUE



CT image is a digital image.

$$CT - value = 1000\rho_d - 1000$$



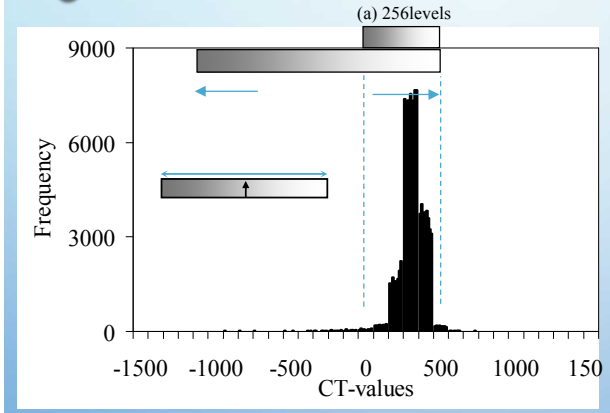


Reconstruction of 3-D CT image

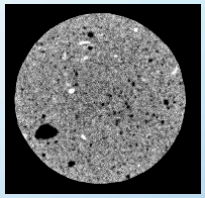
IMPORTANT FEATURES IN IMAGE ANALYSIS

- THRESHOLD VALUE
- BEAM HARDENING EFFECT
- PARTIAL VOLUME EFFECT

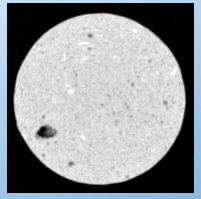
THRESHOLDING VALUE



(I) Histogram of CT value



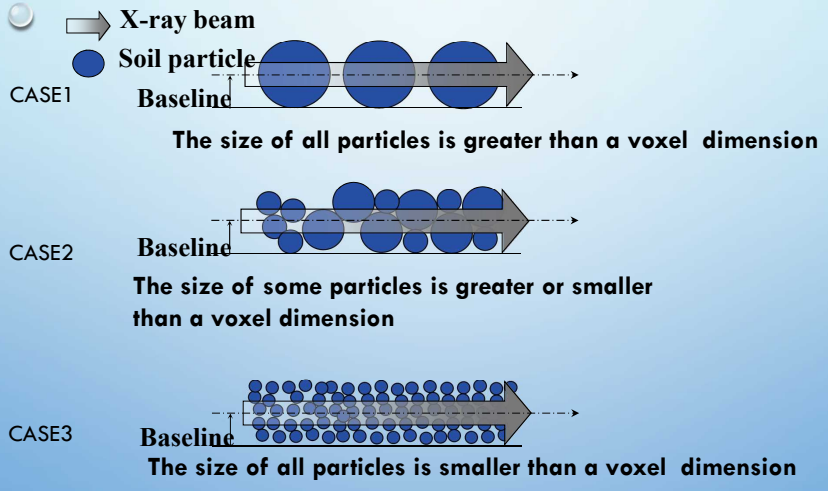
(a) 0<CT-value<500



(b) –1000<CT-value<500
(II) CT image

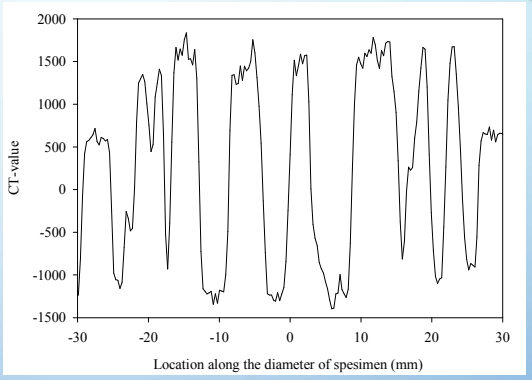
Figure 3

PARTIAL VOLUME EFFECT



CASE1

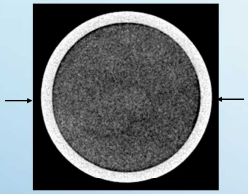
(a)



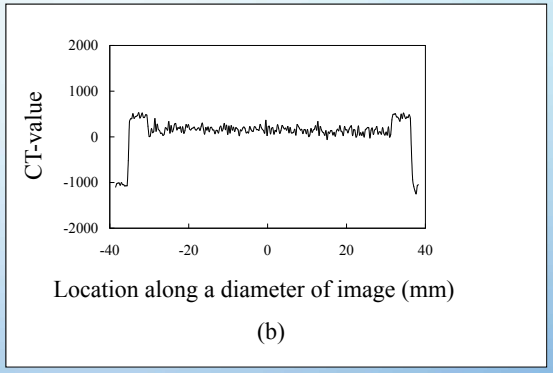
(b)

Figure 14

CASE3



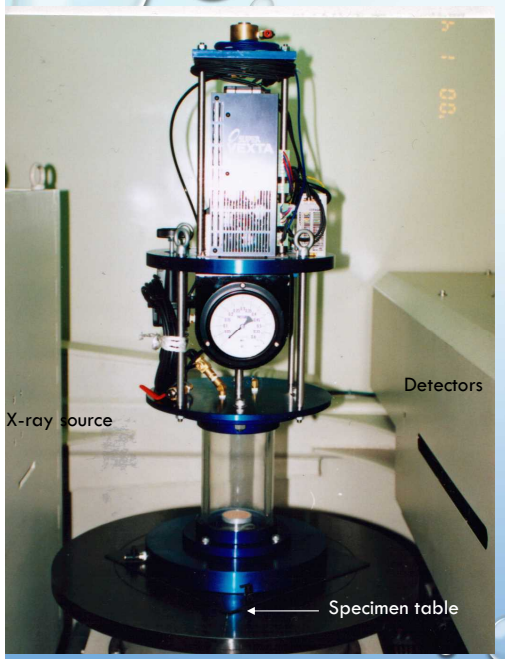
(a)



(b)

Figure 15

IMAGE PROCESSING ANALYSIS TO X-RAY CT IMAGE



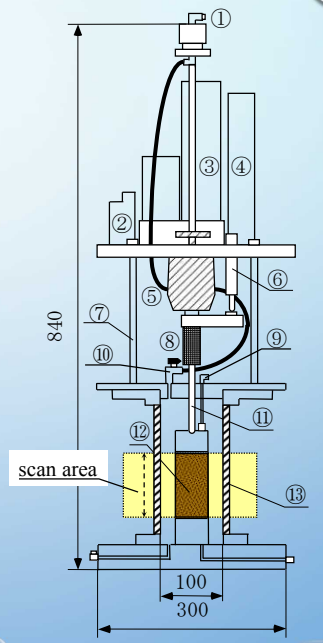
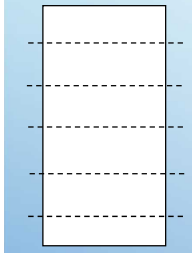
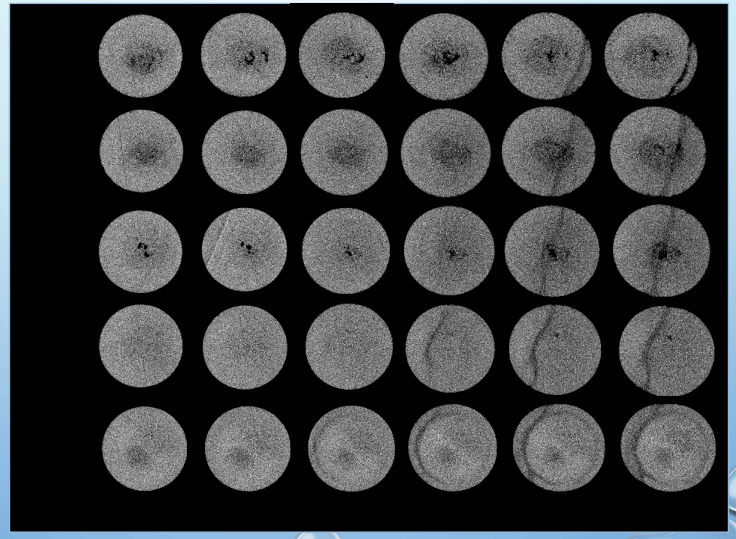


Fig. 4

Basic analysis of X-ray CT image(2)





SMOOTHING TECHNIQUE

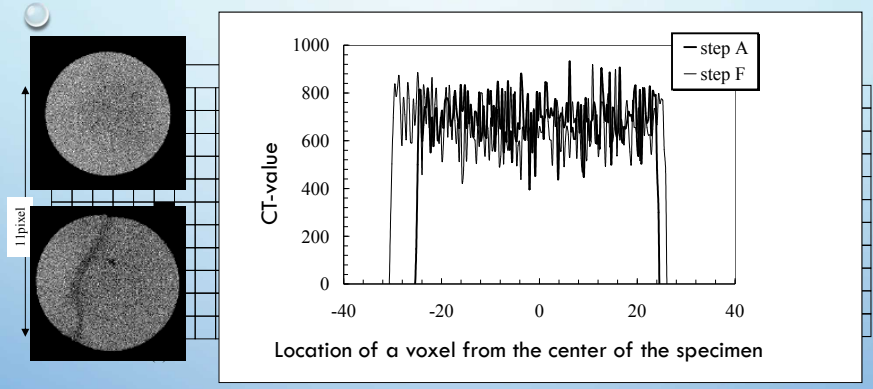
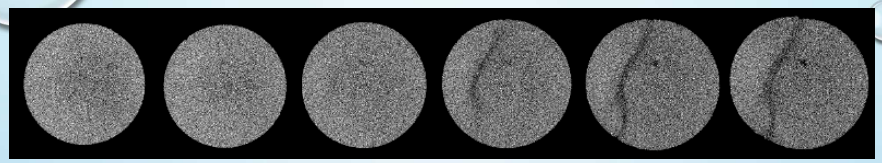
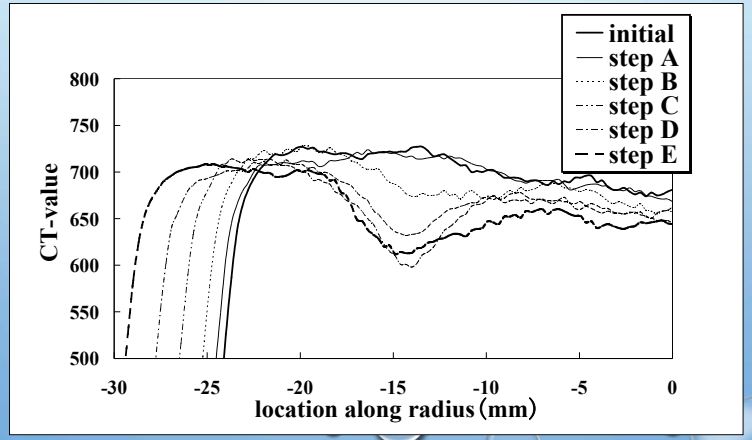


Fig. 15

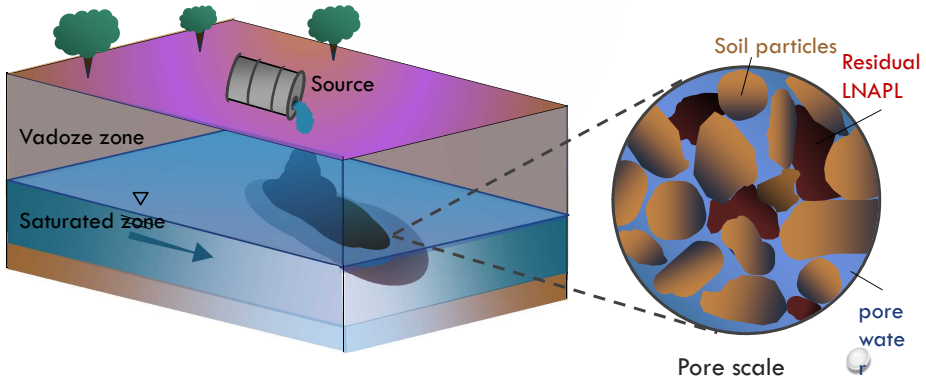




MAIN TOPIC

Introduction

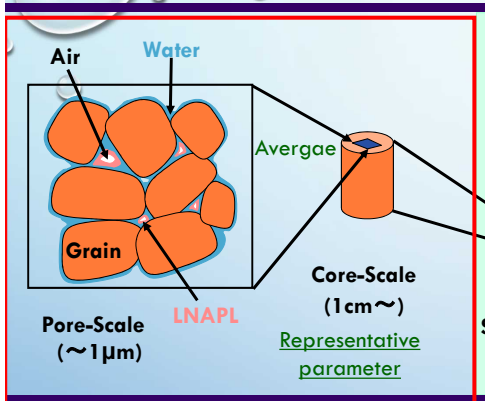
LNAPL: Light− non aqueous phase liquids (gasoline, diesel, etc) → Ground contamination



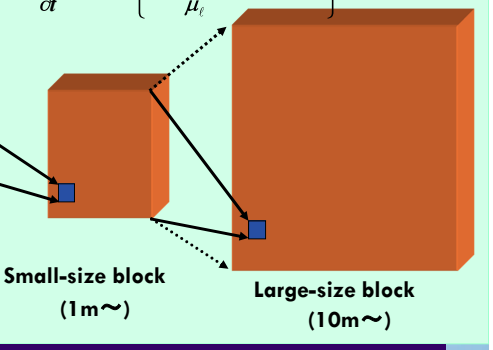
Residual LNAPL causes long-term pollution

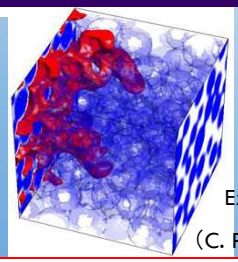
It is important to know the mechanism of LNAPL migration

Motivation



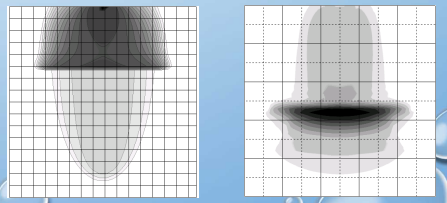
$$\frac{\partial \phi S_\ell \rho_\ell}{\partial t} - \nabla \bullet \left\{ \rho_\ell \frac{k_{r\ell} K}{\mu_\ell} (\nabla p_\ell + \rho_\ell g) \right\} = 0$$





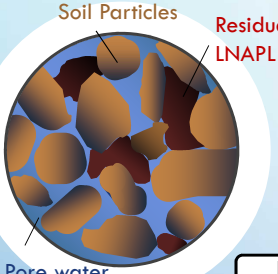
Numerical Analysis for Micro scale

Ex.Pore-Scale (C. Pan et al,2004)



Numerical Analysis for Macro scale

Introduction



- Transfer mechanism of oil flow
  - Image analysis
  - CFD analysis
  - Pore structure
    - Pore size
    - Pore shape
    - Connectivity
  - Fluid distribution
  - Velocity and Pressure distribution

Objective

To clarify the transfer mechanism of oil and water in pore structure of sandy soil using Image analysis and CFD analysis

MXCT image

Image analysis

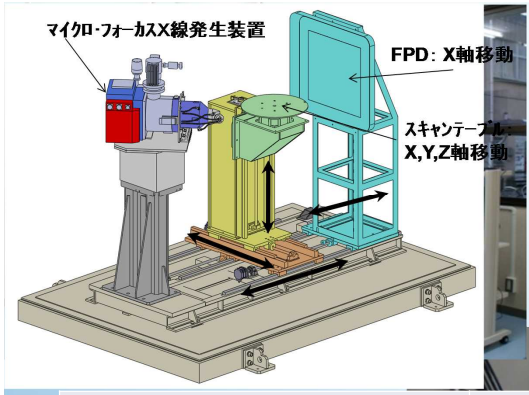
Generation mechanism of blobs in sandy soils

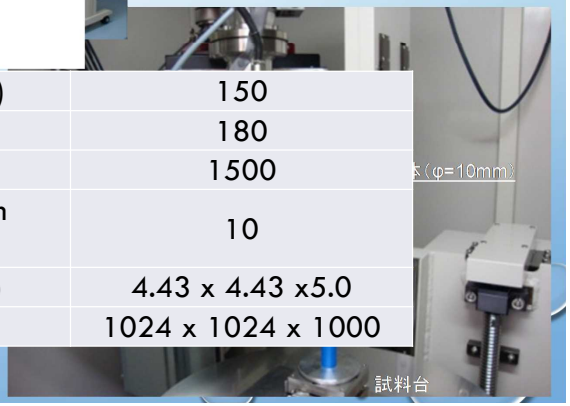
L B M analysis

LBM simulation can be performed using MXCT image

APPLICATION OF M-FOCUSED X-RAY CT SCANNER FOR THIS STUDY

M-FOCUSED X-RAY CT SCANNER GIVES THE SPATIAL DISTRIBUTION OF MATERIAL DENSITY. A CT IMAGE IS NOT A MICROSCOPE PHOTOGRAPH BUT A DIGITAL IMAGE.





Power of voltage (kV)	150
Current (mA)	180
Numver of views	1500
Number of integration treatment	10
Voxel dimension (mm)	4.43 x 4.43 x5.0
Number of voxel	1024 x 1024 x 1000

23

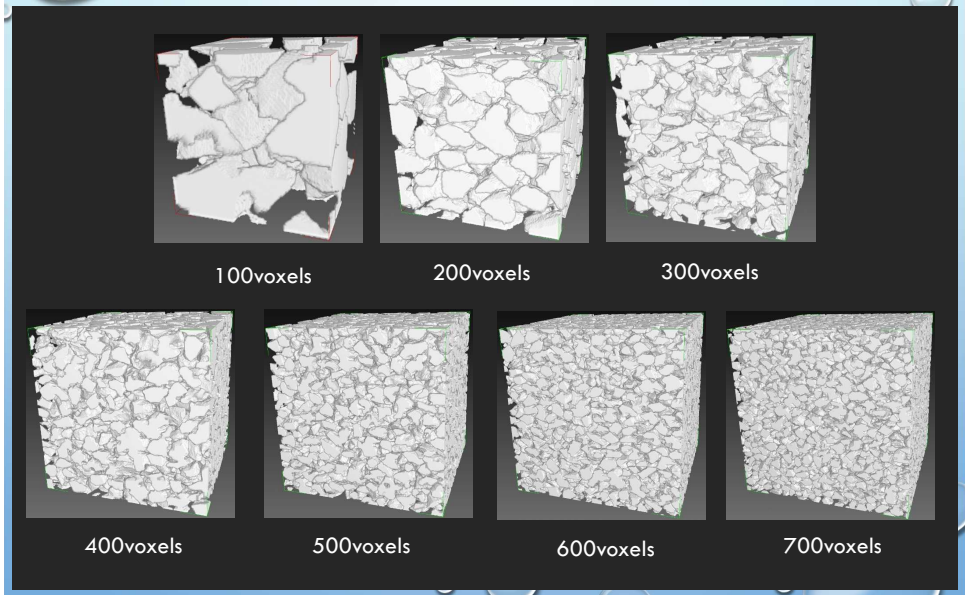
Imgae processing

NOWADAYS, SO MANY USEFUL APPLICATIONS ARE DISTRIBUTED IN THE IMAGE ENGINEERING

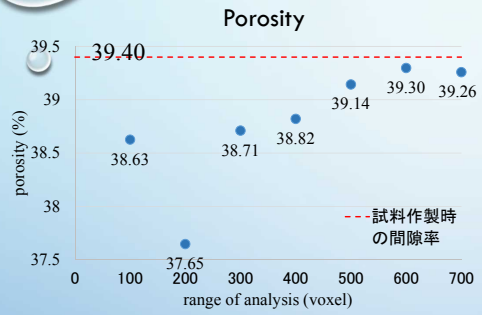
- IMAGE J (ONE OF POPULAR APPLICATION FOR CT USERS)
- ITK (IMAGE TOOL KIT: LANGUAGE IS C++
- MOST OF CASE, WE DON'T NEED TO DEVELOP VERY NEW ALGORISM WHICH WE WANT TO DO IMAGE ANALYSIS.

24

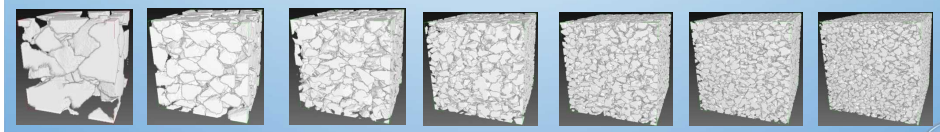
Decision of analyzing area

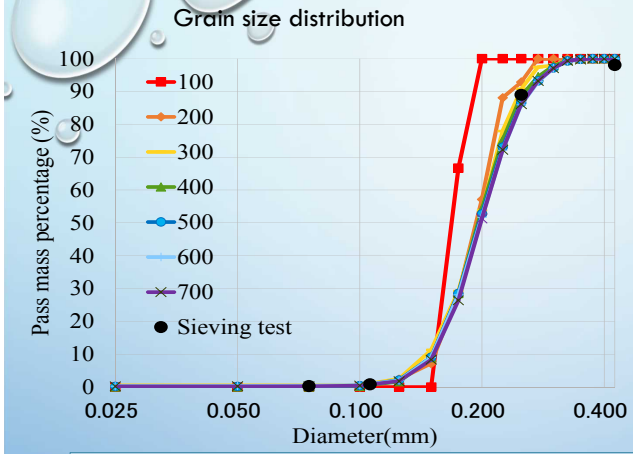


Decision of analyzing area



The are for evaluation of porosity is changed and then, 500 voxels should be enough dimensions because errors are within 1 %.





一辺のサイズ (voxel)	平均粒径 (μm)
100	190
200	195～200
300	200～205
400	200～205
500	200～205
600	200～205
700	200～205
試料作製時の平均粒径	200

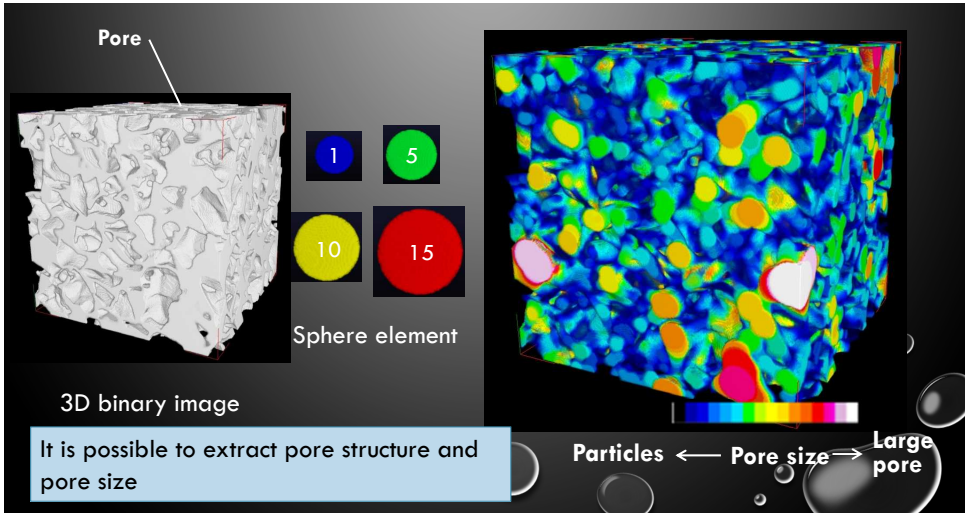
When 1voxel =5μm
We concluded that we should use 500 cubic voxels for image analysis and numerical analysis.

As for grain size distribution, dimension of 300 cubic voxel is enough for evaluation of grain size distribution.

3D distribution of pore size

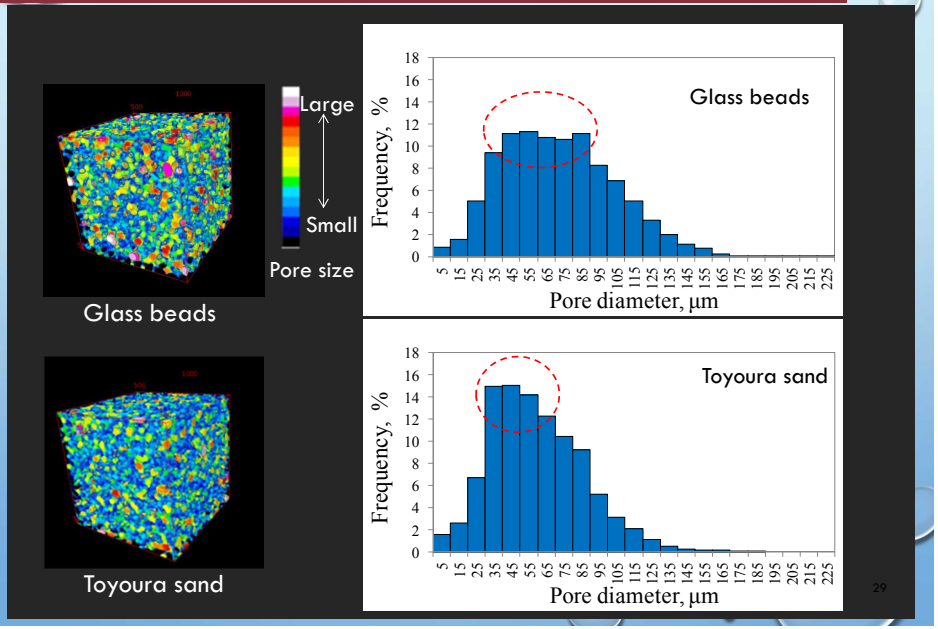
Mathematical Morphology: Opening and Closing

$$\gamma_B(X) = \bigcup_X \{B_X \mid B_X \subseteq X\}$$



It is possible to extract pore structure and pore size

3D distribution of pore size



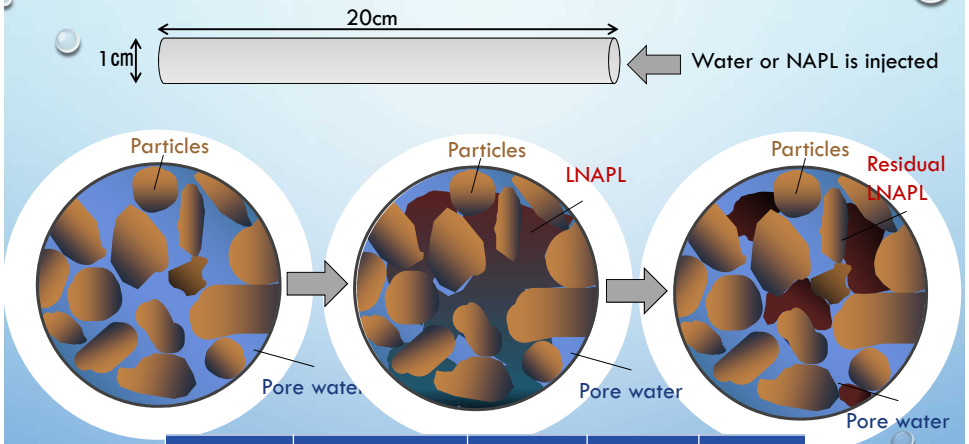
29

NAPL INJECTION TEST

30

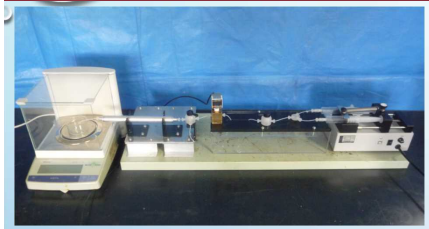
1D INJECTION TEST

31

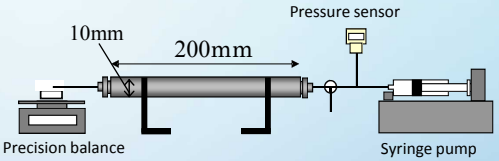


	Sample	Mean diameter (μm)	Particle density (t/m³)	Porosity (%)
Case 1	Glass beads	300	2.45	36.0
Case 2	Toyoura sands	200	2.65	39.4

Test Method



Injection test apparatus



Illustration

Flow

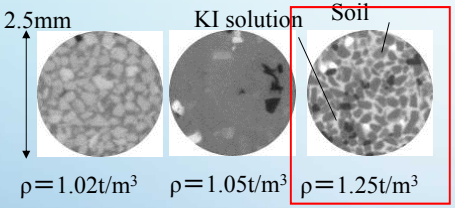
Sample should be fully saturated → LNAPL was injected → KI solution was injected → CT scan

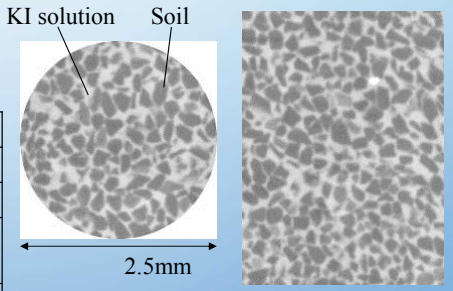
	試料	粒径（μm）	土粒子密度 (t/m³)	乾燥密度 (t/m³)	相対密度
CASE1	ガラスビーズ	250-350	2.45	1.57	0.89
CASE2	ガラスビーズ2種	250-350と1000の混合	2.45	1.75	0.89
CASE3	ガラスパウダー	250-450	2.45	1.49	0.89
CASE4	豊浦砂	200	2.64	1.6	0.87

4. Test materials

KI solution was used.

For saturation, we injected CO2 gas using 120 kPa pressure.

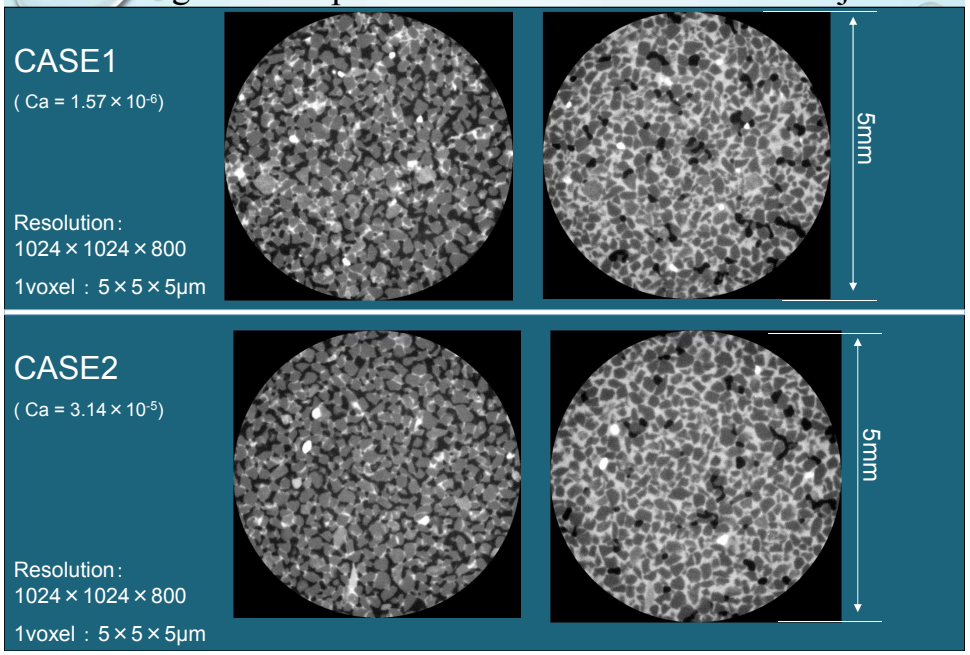




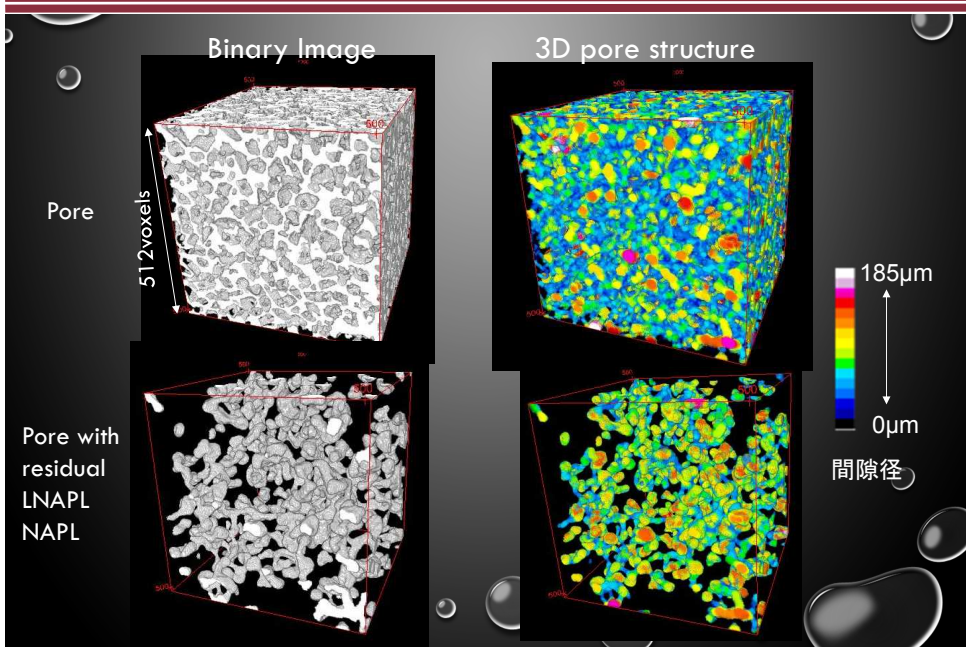
KI ρ=1.25t/m³ Main properties (18℃)

	KI solution	Water
Density (t/m³)	1.25	1.00
Surface tension (mN/m)	72.45	72.94
Interfacial tension with LNAPL (mN/m)	54.5	52.9
Contact angle (°)	61.5	53.7
Viscosity (mPa·sec)	0.966	1.002

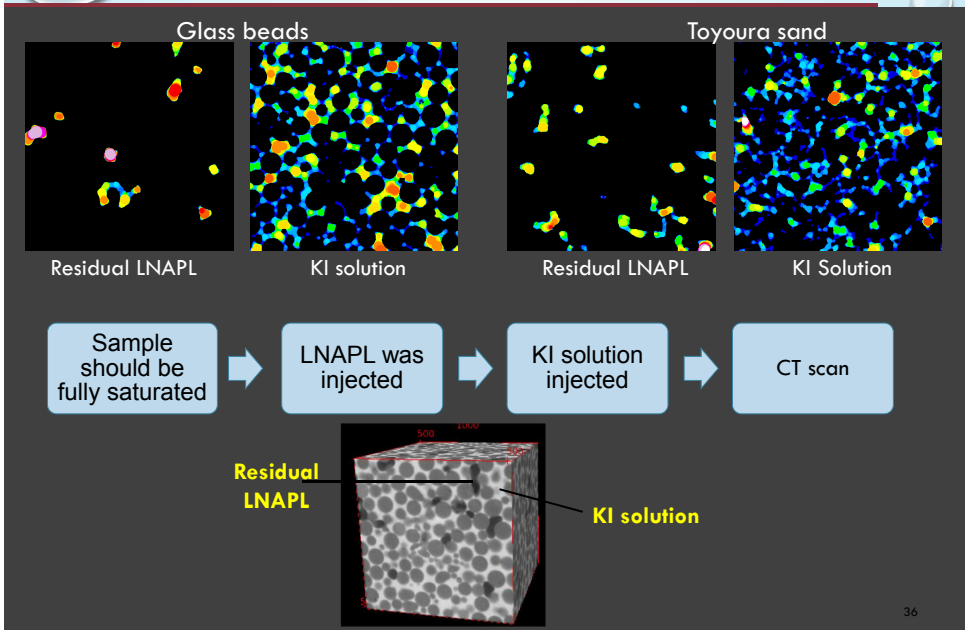
❖ CT images of sample before and after KI solution injection



3D pore distribution



Evaluation of residual LNAPL and KI solution



Conclusions

- Micro X-ray CT scanner is a powerful tool to evaluate pore structure of sandy soil and its techniques can be applied to the evaluation of pore structure with LNAPL .

Ongoing work

- To perform LBM simulation using X-ray CT image obtained from these test.

Lattice Boltzmann Method (LBM)

LBM - INTRODUCTION

LBM models the fluid consisting of **fictive particles,** and such particles perform consecutive **propagation and collision** processes over a **discrete lattice mesh.**

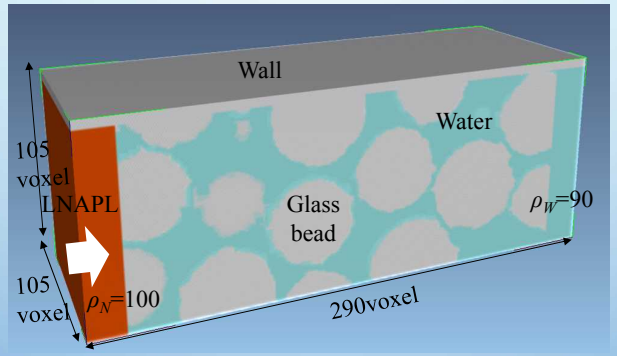
Advantages of LBM over traditional methods:

- Allows modelling of **multi-phase** behaviour at **local scale**
- Allows dealing with **complex boundaries**
- Allows incorporation of **microscopic interactions**
- Allows **parallelization** of algorithm (for example using GPU)

Disadvantages of LBM:

- **Limited memory** and mesh size (depends on efficiency of parallelization modelling and hardware)
- **Lack** of use of classic **physical parameters**

LBM simulation for two-phase flow in porous materials

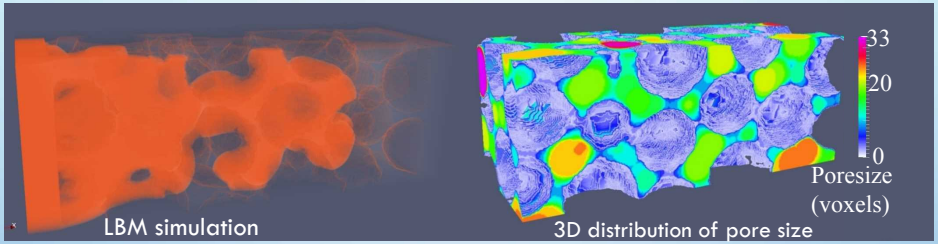


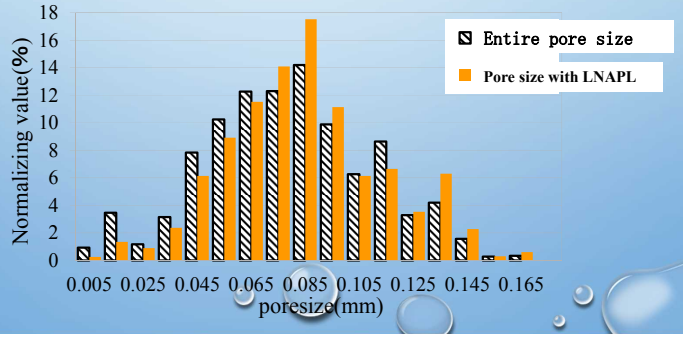
$$P^k = \frac{3}{7+\lambda^k}\rho^k$$

λ^k:流体の圧縮性に関係するパラメータ

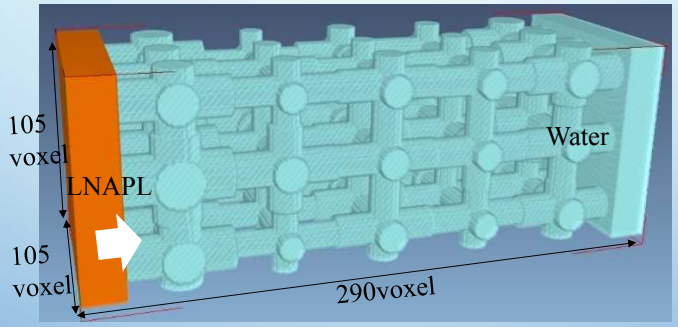
parameters	LNAPL	Water
Density ratio	1	
Relaxation time (τ)	1.167	1
fluid-fluid Interaction (gf)	0.0015	
fluid-solid Interaction (gs)	-0.020	0.020

LBM simulation for two-phase flow in porous materials





Pipe model for LBM simulation



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Density ratio	1	
Relaxation time (τ)	1.167	1
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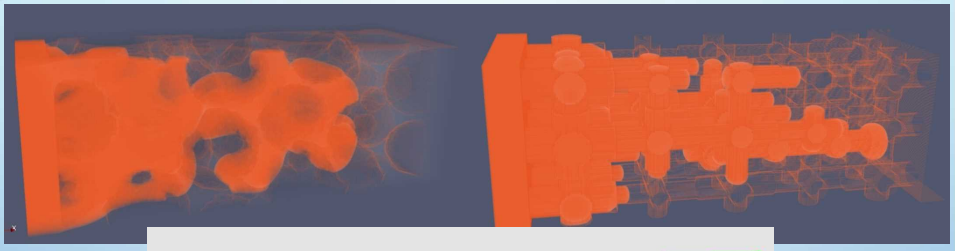
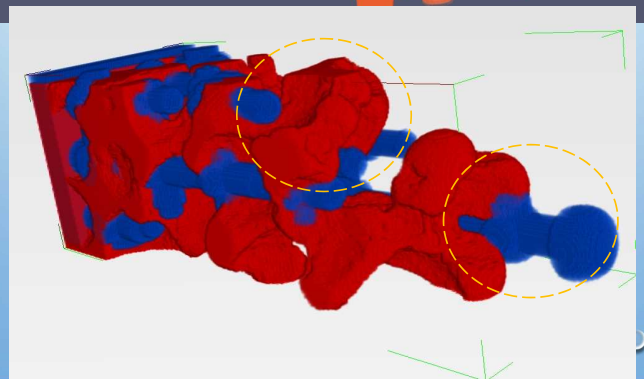
fluid-solid Interaction (gs)	-0.020	0.020

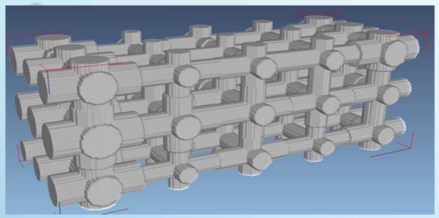
Comparison porous material with pipe model

Glass beads | Pipe model

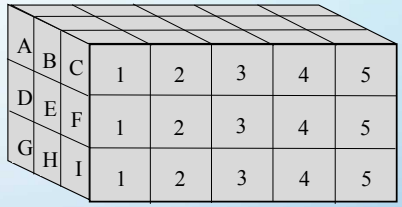




Discussion of results for pipe model



Pipe model



Definition of each area

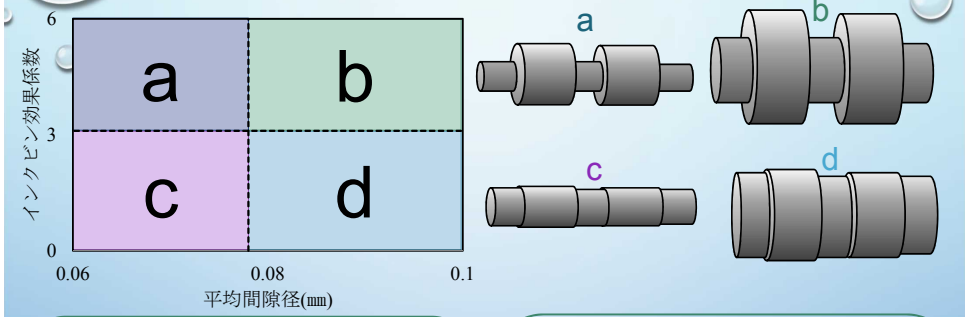
Mean diameter along the flow direction =

$$\frac{\sum_{n=1}^{5} X_n}{5} \quad X: \text{location}(A \sim I)$$

Aspect ratio along the flow direction =

$$\frac{\sum_{n=1}^{4} |X_{n+1} - X_n|}{4} \quad X: 場所(A \sim I)$$

Discussion of results for pipe model



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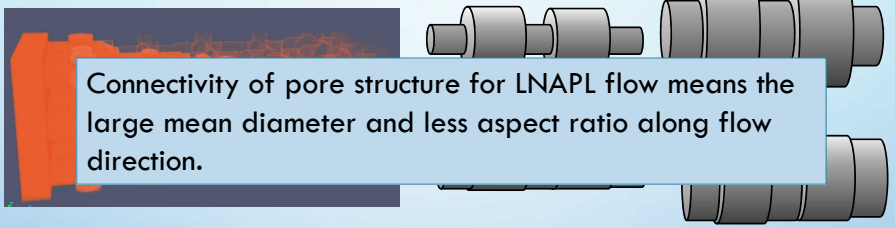
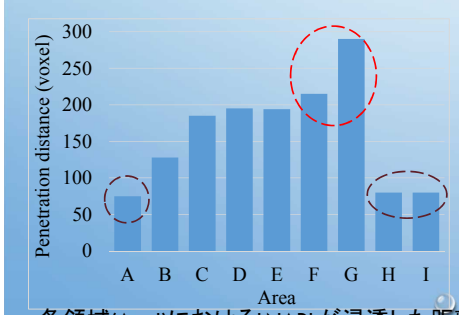
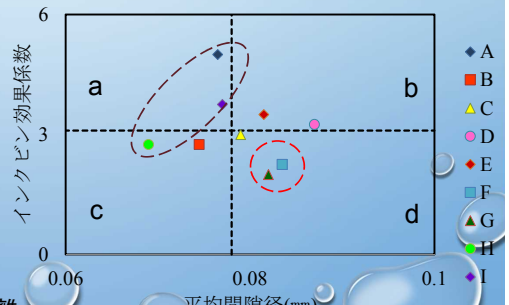
Discussion of results for pipe model



Connectivity of pore structure for LNAPL flow means the large mean diameter and less aspect ratio along flow direction.

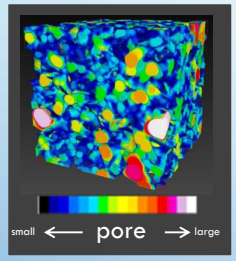


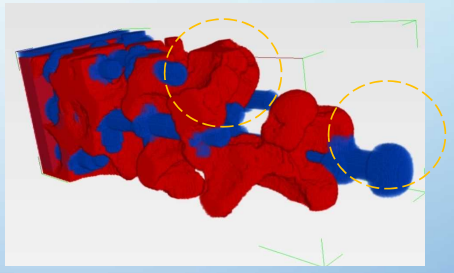
各領域(A～I)におけるLNAPLが浸透した距離



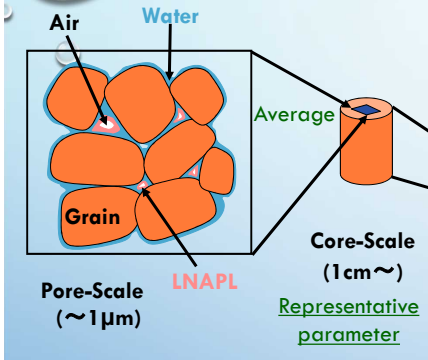
Conclusions

X-ray CT image analysis and LBM simulation can Evaluate LNAPL migration in porous media.





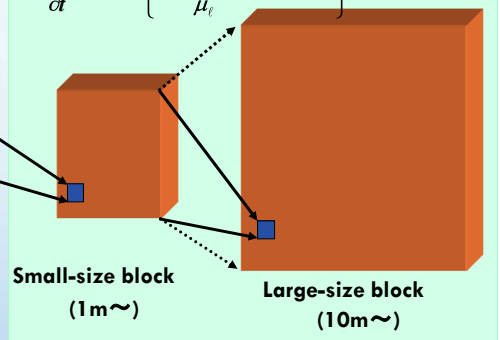
Conclusions



Average

Core-Scale
(1cm～)
Representative parameter

$$\frac{\partial \phi S_\ell \rho_\ell}{\partial t} - \nabla \bullet \left\{ \rho_\ell \frac{k_{r\ell} K}{\mu_\ell} (\nabla p_\ell + \rho_\ell g) \right\} = 0$$



We don't say X-ray CT scanner can solve many geotechnical and geoenvironmental issues. X-ray CT scanner is a powerful tool to observe the inner condition of materials. Of course, the sample size is too small to evaluate real condition. Hence, we need to develop the model to connect micro observation and macro observation.