Micro and Macro Modeling of Internal Erosion and Scouring with Fine Particle Dynamics

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Large Model Test for a reservoir dike with heavy rain: occurrence of piping

Conducted by
National
Agriculture and
Food **R**esearch
Organization, **NARO**
(Japan)

Heavy rain **130-150 mm/*h*** with water storage of high water level

Surface flow and then seepage into slope , small piping

Piping, ***erosion*** ***(loss of fine particle)*** and Jamming-sealing

Sliding and cracking

clean water -> **loss of fine particle** -> **muddy water** -> outflow of large particle with loud rumbling sound

.....depression and sink hole

in tidal river , collapse of bank and shore protector

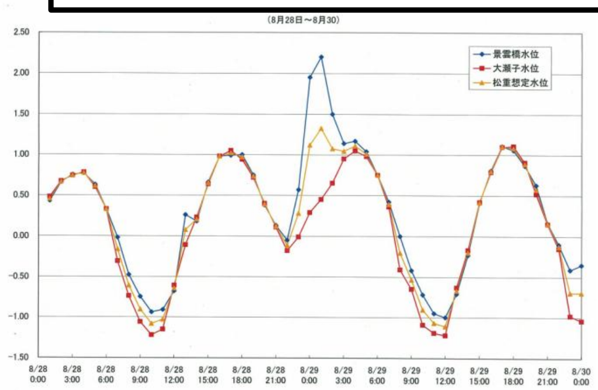
2010.1

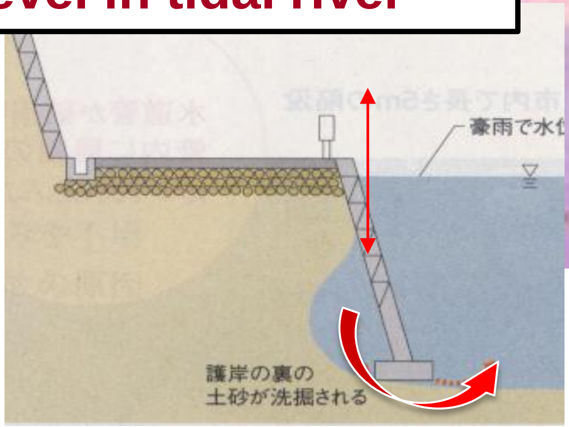
2008.8

On water service tube that becomes superannuated

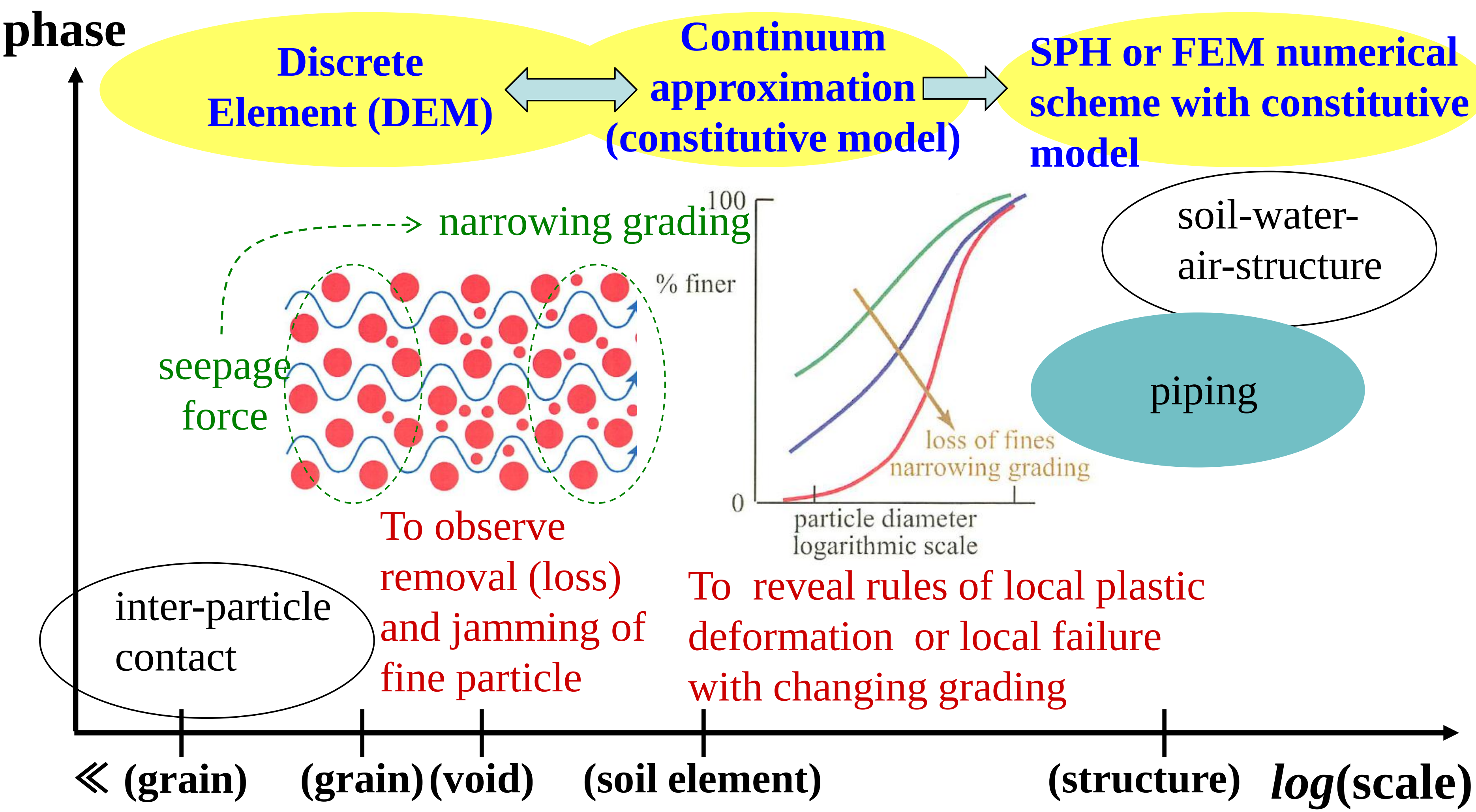
shore protection adjust to sea

Fine particle movement Due to undulation of water level in tidal river



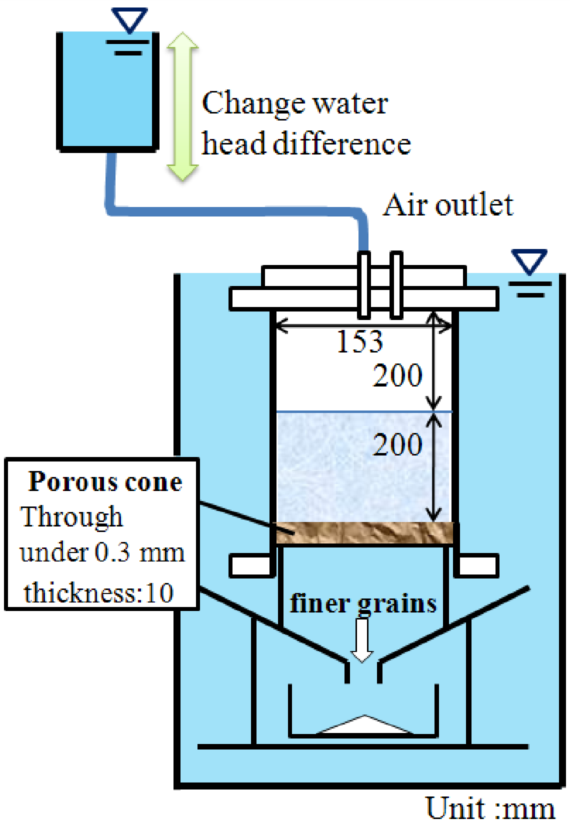


A purpose of this study to solve internal erosion in multi-scale and multi-phase



1D Seepage test (downward flow)

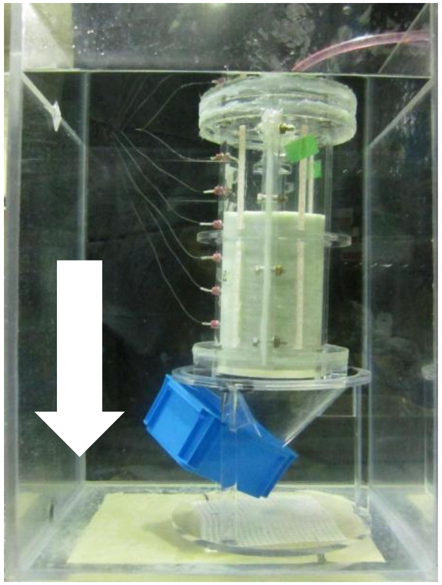
To measure amount of leached particle (removal and jamming of particle)



the bottom filter hole size = 0.3mm

Sample: Glass beads

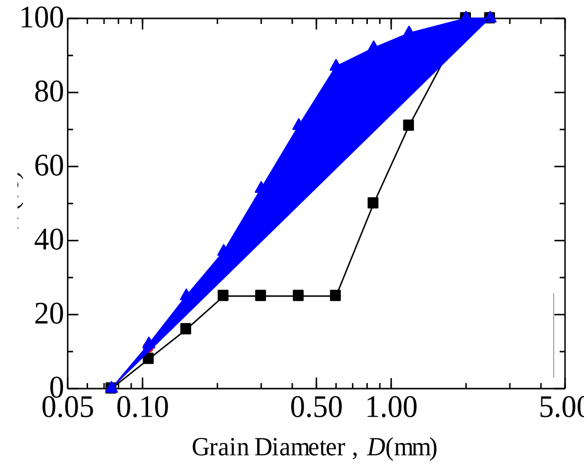
Relative density Dr=80%



Downward Hyd. Grad.
From small to very large 10

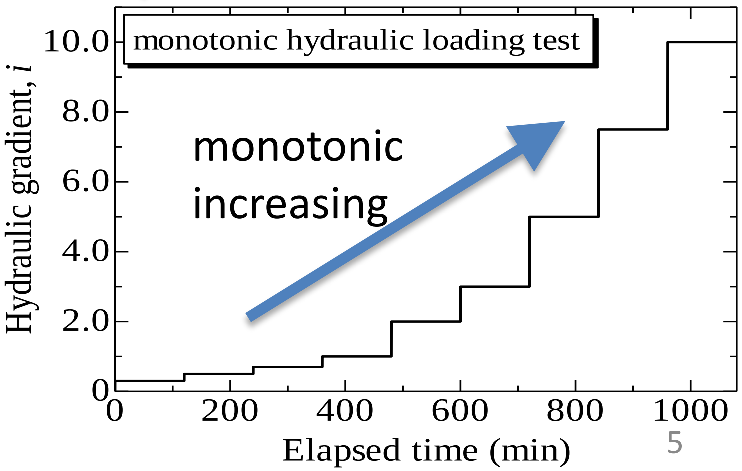
- Existence of movable void size

➡ **Different grading shapes**



- External force(Seepage force)

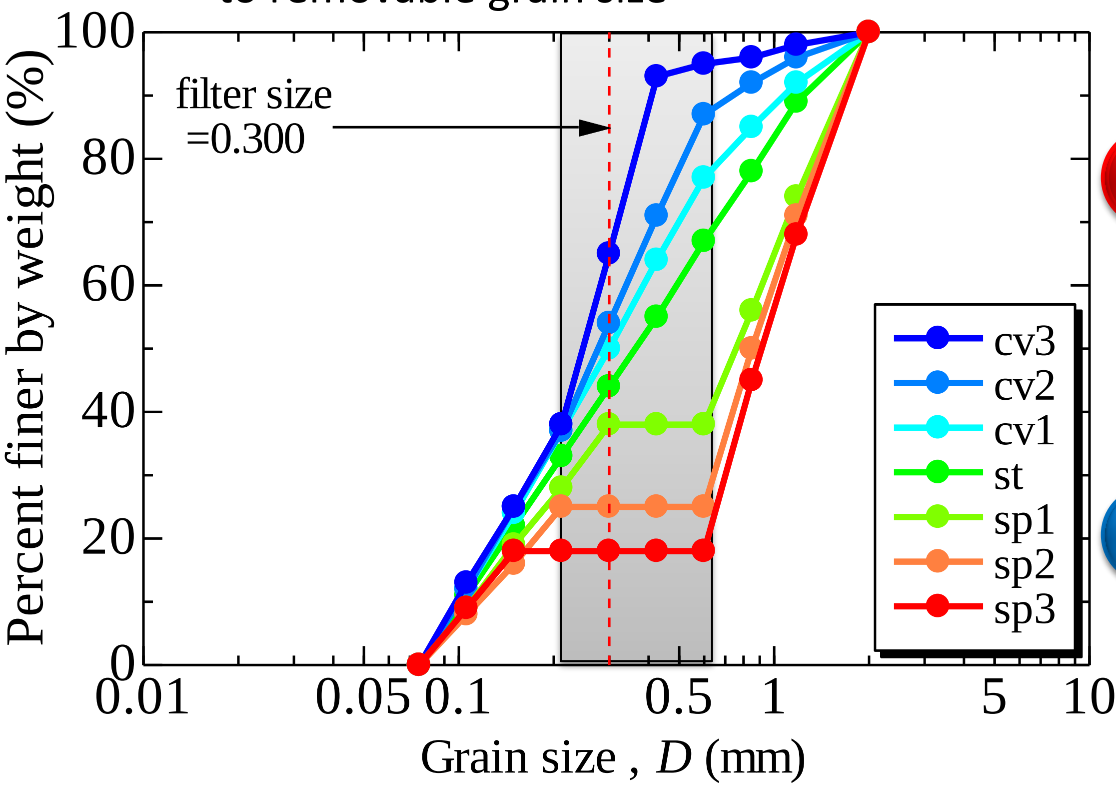
➡ Change in hydraulic grad.



Grain size distribution of samples

Effect of Grading Shape

Pay attention to range of 4D against to removable grain size



This series can be divided to 3 group

Straight（st）

Satisfy H=F in all finer grain

Step grading（sp）

Not contain enough filter particle(4D) for clogging (**convex downward grading**)

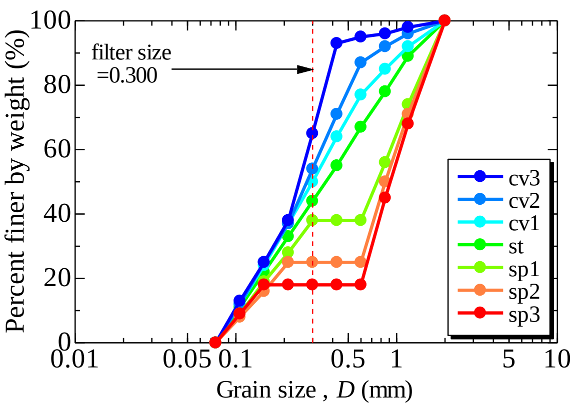
Coarse grading(cv）

Satisfy H>F for all finer grain

(**convex upward grading**)

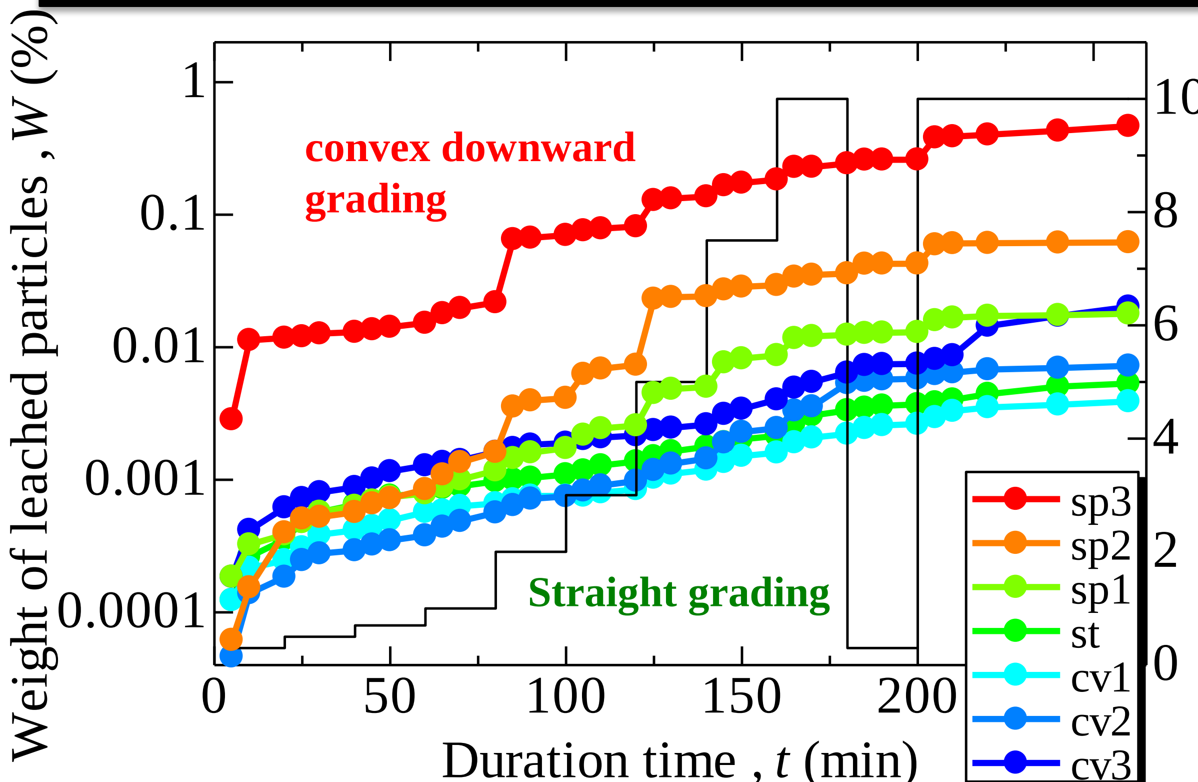
Leaching process with different grading shapes

Grading



Due to fine particle removal, the soil with convex downward grading becomes to have more convex downward grading; internal erosion induces removal particle.

Time history of Leaching (erosion)

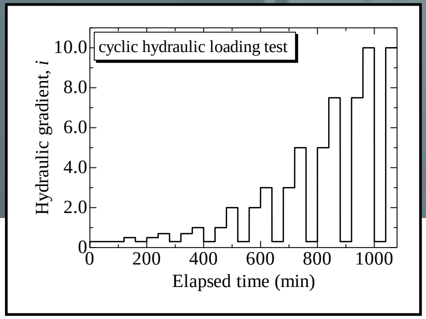


Amount of Leached particle (internal erosion)：

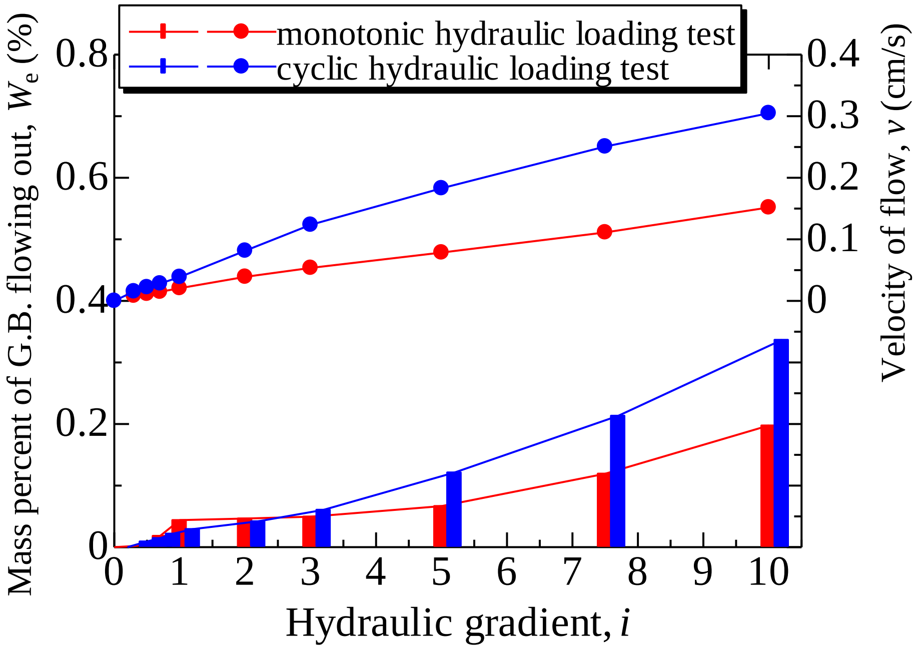
convex downward ≫ convex upward ≧Straight

Increase along with the distance from straight grading

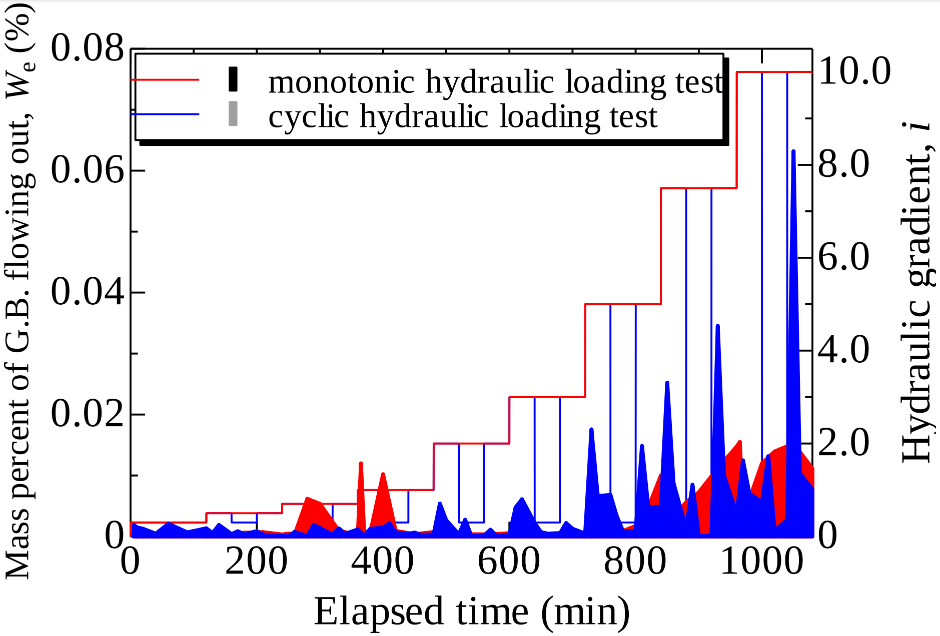
Effect of hydraulic undulation



We - hydraulic grad.



Time history



- Amount of internal erosion in **cyclic loading** is **1.5 times as that in monotonic loading**
- An undulation of seepage force

DEM simulation: particle and void size

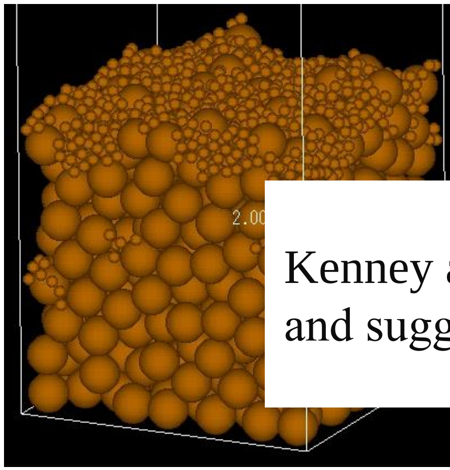
Particle mobility: DEM + CFD biaxial mixture: D_{max} and D_{min}

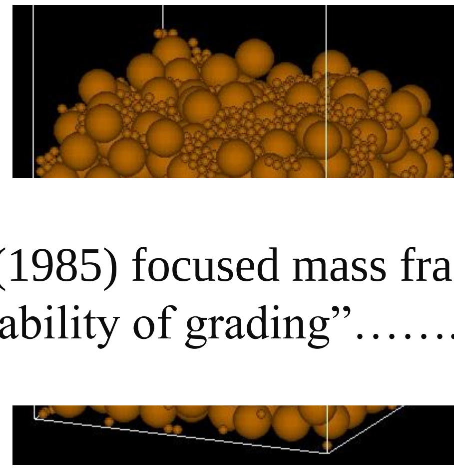
Drag force depending on *R*e number is applied to particles

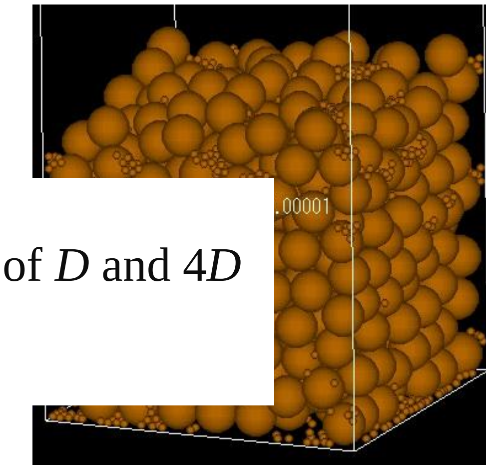
$R_D=D_{max}/D_{min}=3$

$R_D=D_{max}/D_{min}=4$

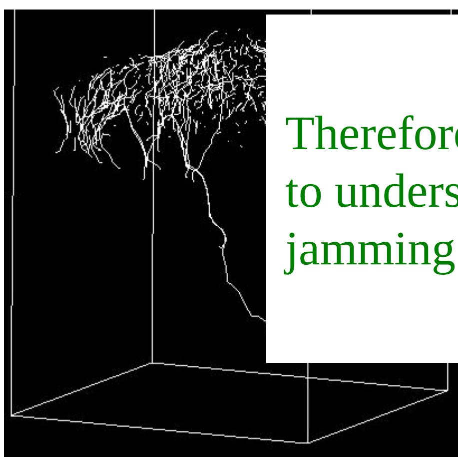
$R_D=D_{max}/D_{min}=5$

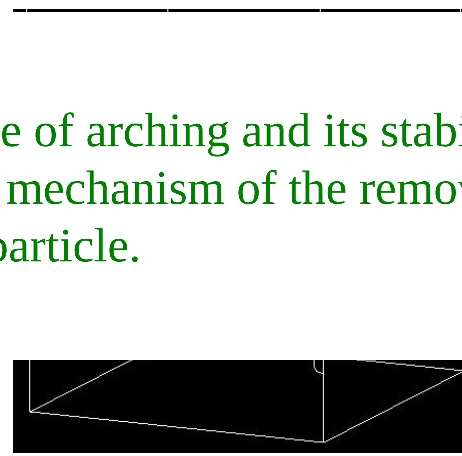


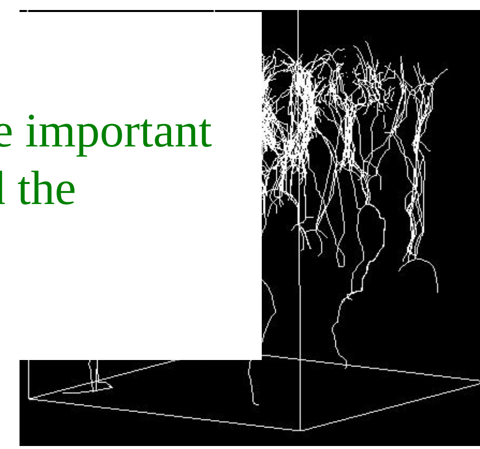




Kenney and Lau (1985) focused mass fractions of *D* and 4*D* and suggested "stability of grading"…….

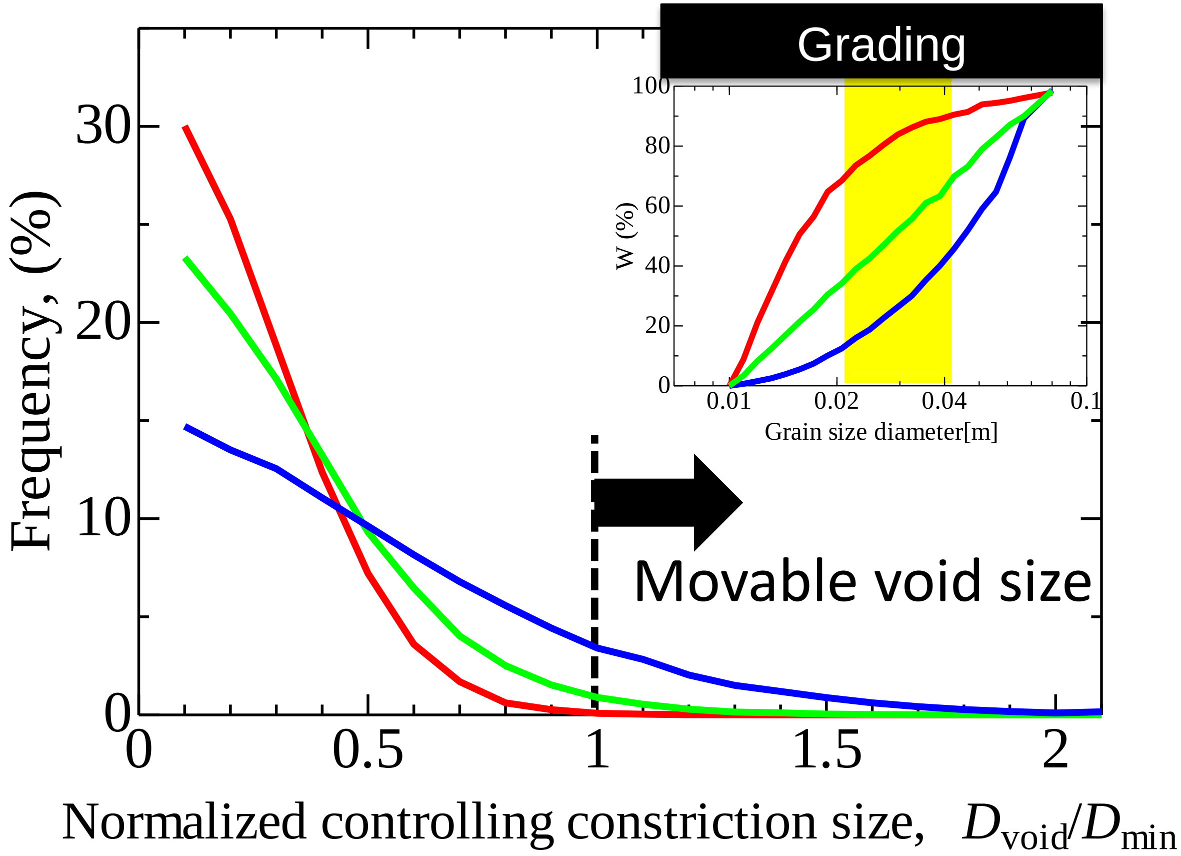


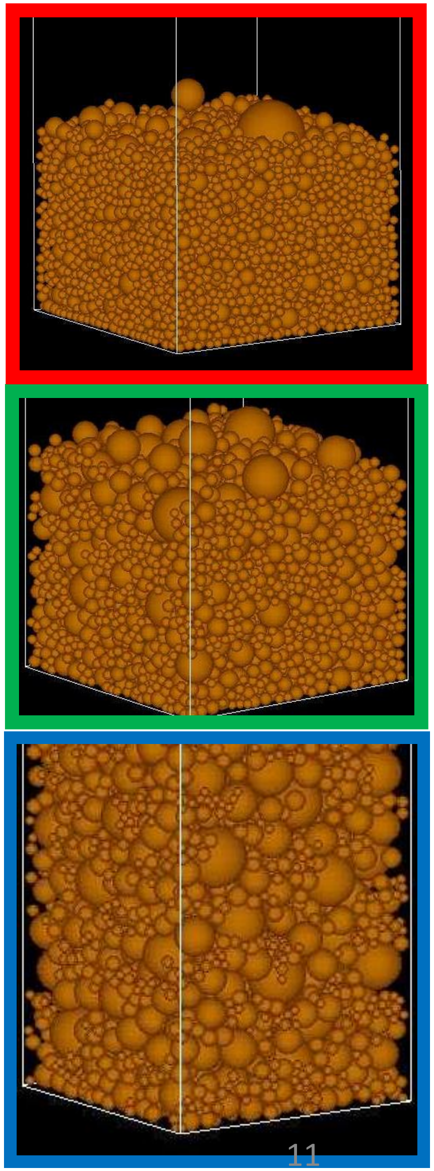




Therefore, the size of arching and its stability are important to understand the mechanism of the removal and the jamming of fine particle.

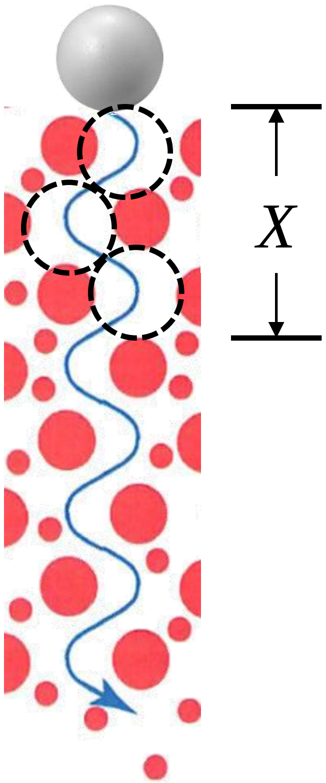
To observe **void size and its frequency** with different grading shapes

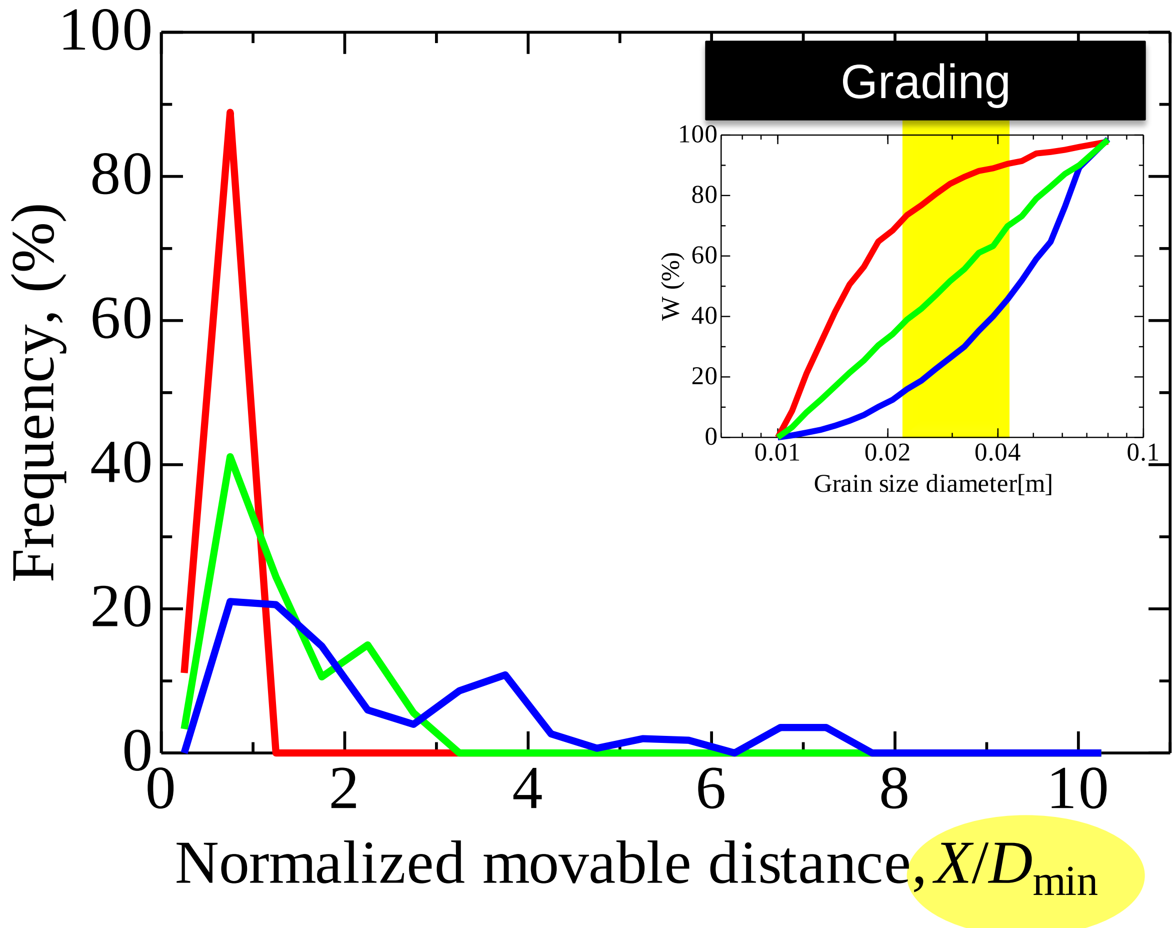




The number of void whose diameter is larger than D_{min}, is largest in the case of convex downward and is less than 5% of total number voids.

To observe **continuity of void** with different grading shapes





Continuity length of voids is about 1-4 times as small particle. Smaller particle just go around larger particle.

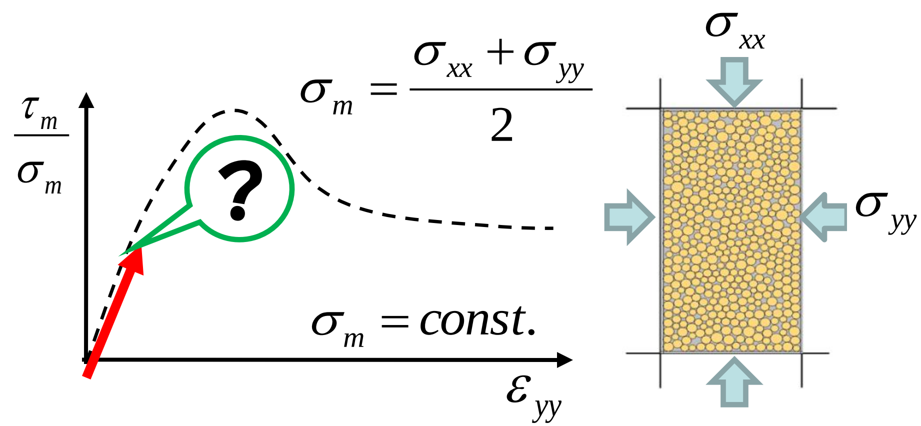
From DEM simulation to develop Continuum modelling : soil element size

stress-strain-dilatancy: 2D DEM

1) monotonic loading test

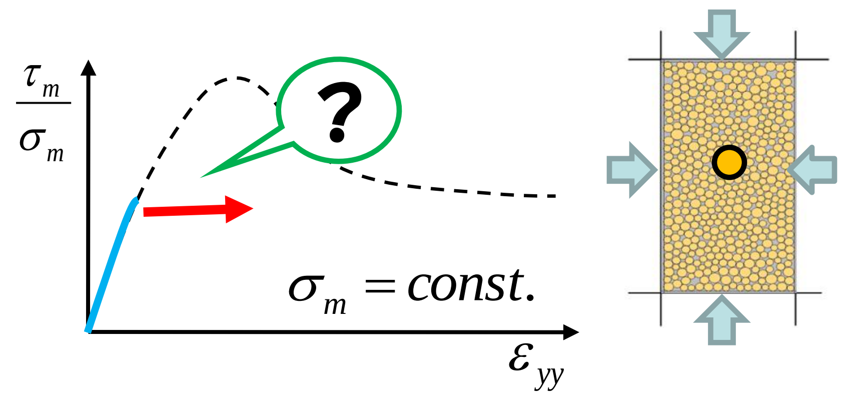
biaxial compression test:

shearing with constant σ_m



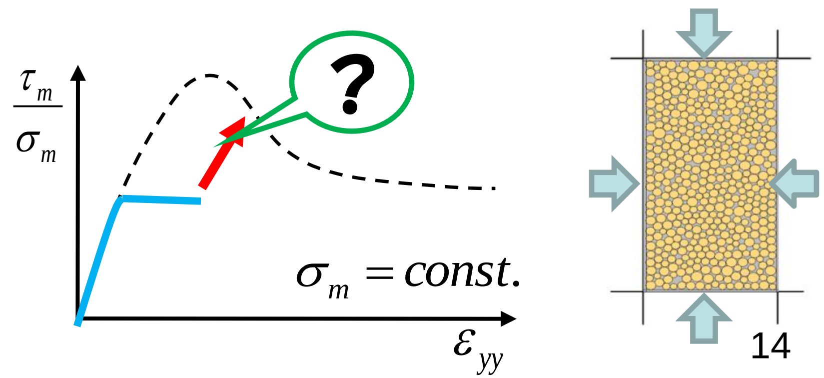
2) removal (erosion) test

the finest particle is forced to be removed: and observation of deformation behaviors under constant stress

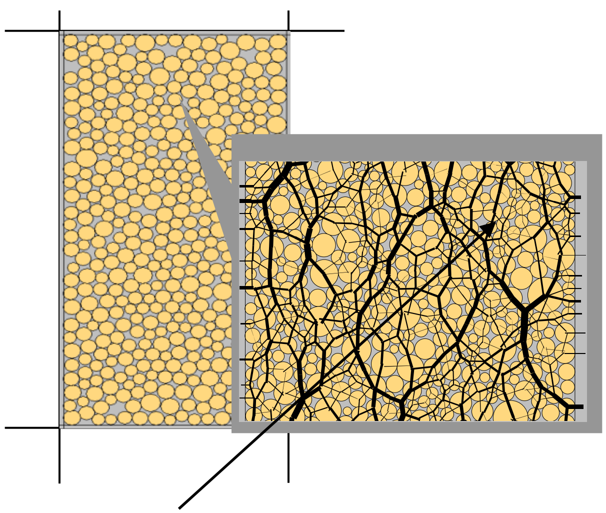


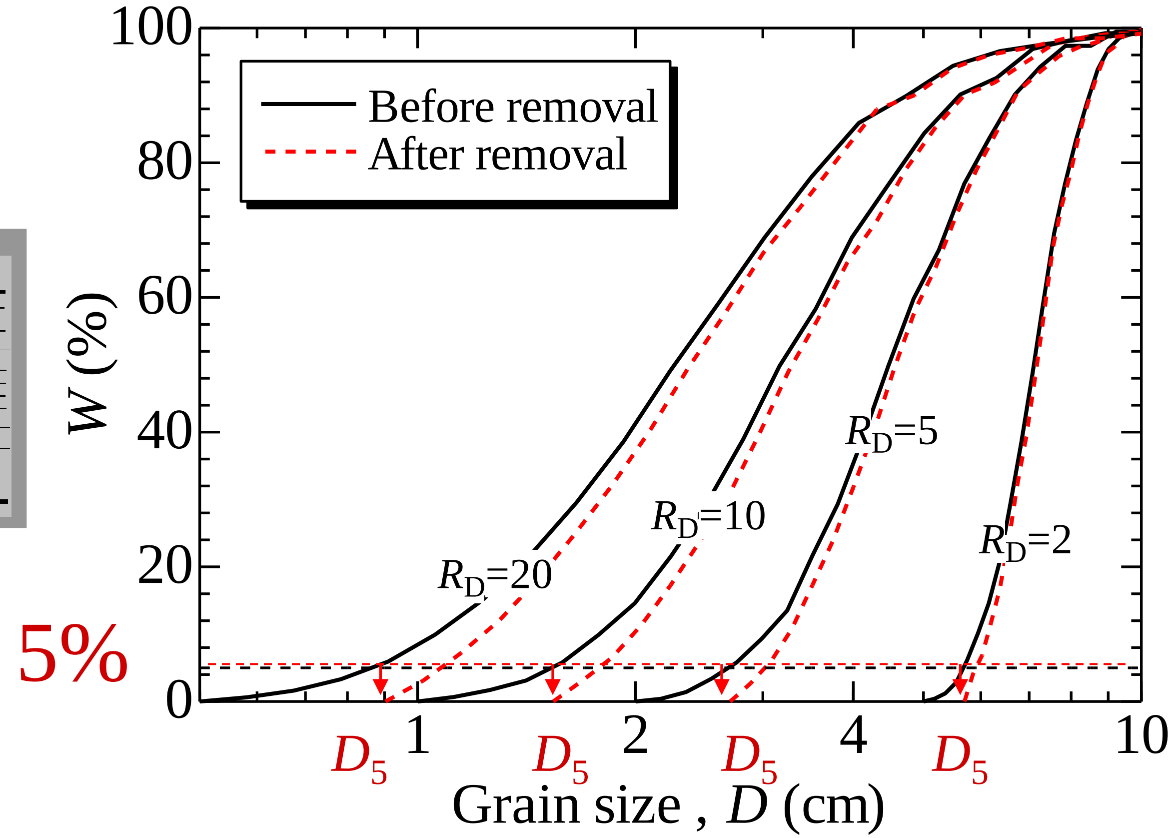
3) reloading test (shearing after erosion)

shearing sample subjected to erosion



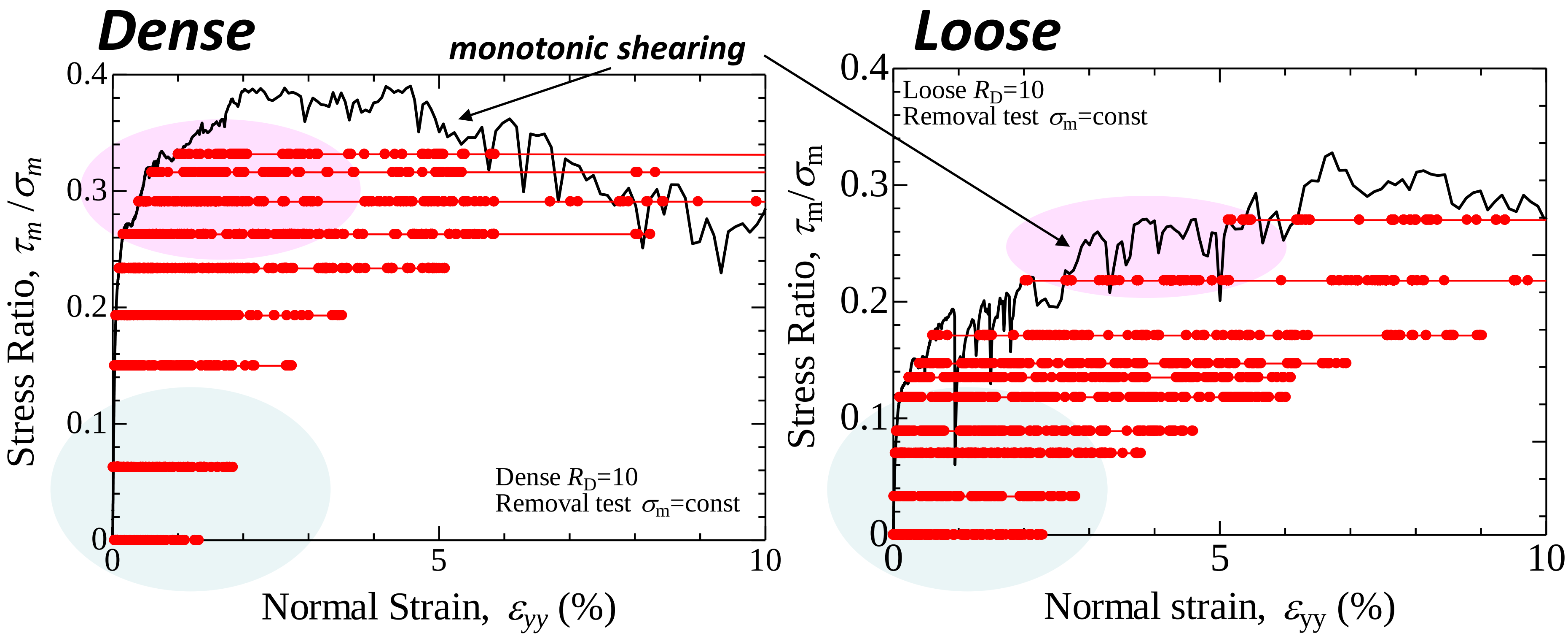
Deformation-failure of soil element removal test of fine particle in 2D DEM





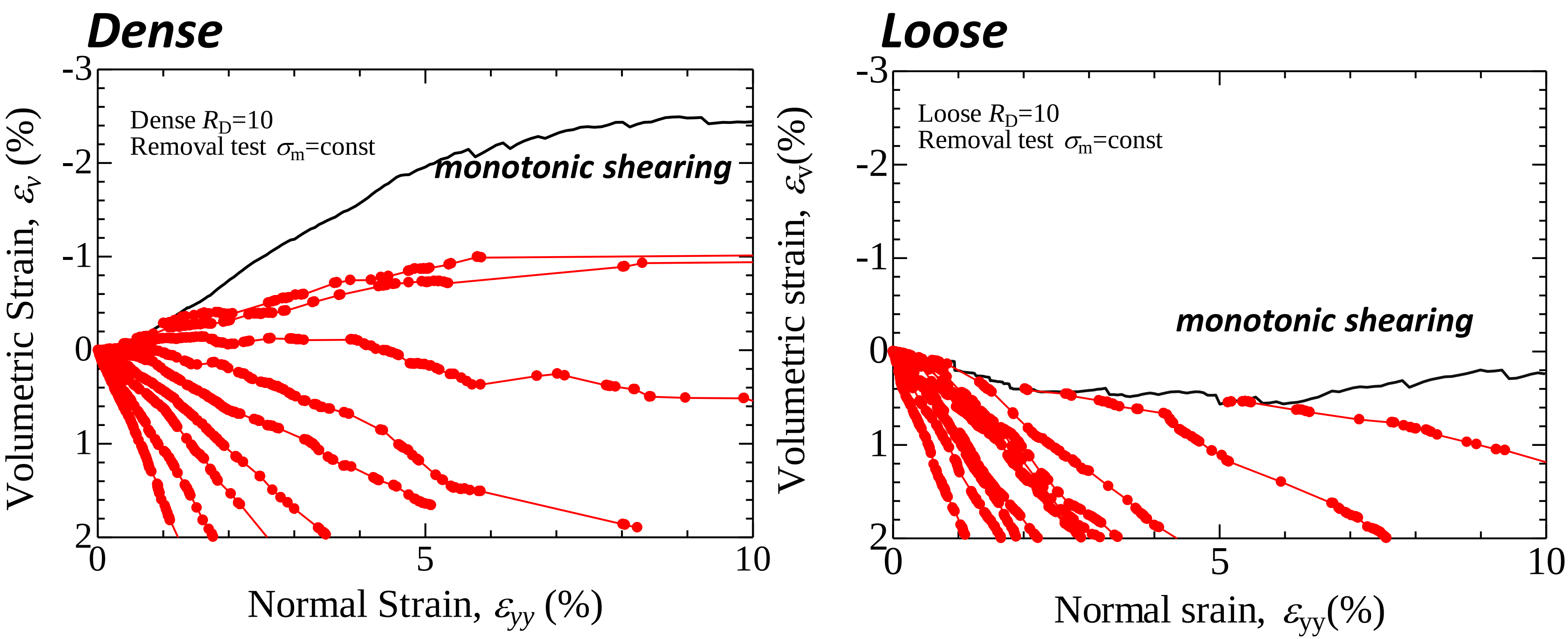
The finest particle was forced to be removed repeat to simulate internal erosion: Two criteria for terminating this repeated process of particle removal: the normal strain exceeds 25%; the removed particle size is equal to the 5% grain size (D_5) of the original sample.

stress-strain due to fine particle removal



The 5% grain size (D_5) of the original sample can be removed under isotropic compression and lower shear stress ratio but large strain generated strain under high shear stress level even if about 1.5% grain size of the original samples.

Volumetric change (dilatancy) due to fine particle removal

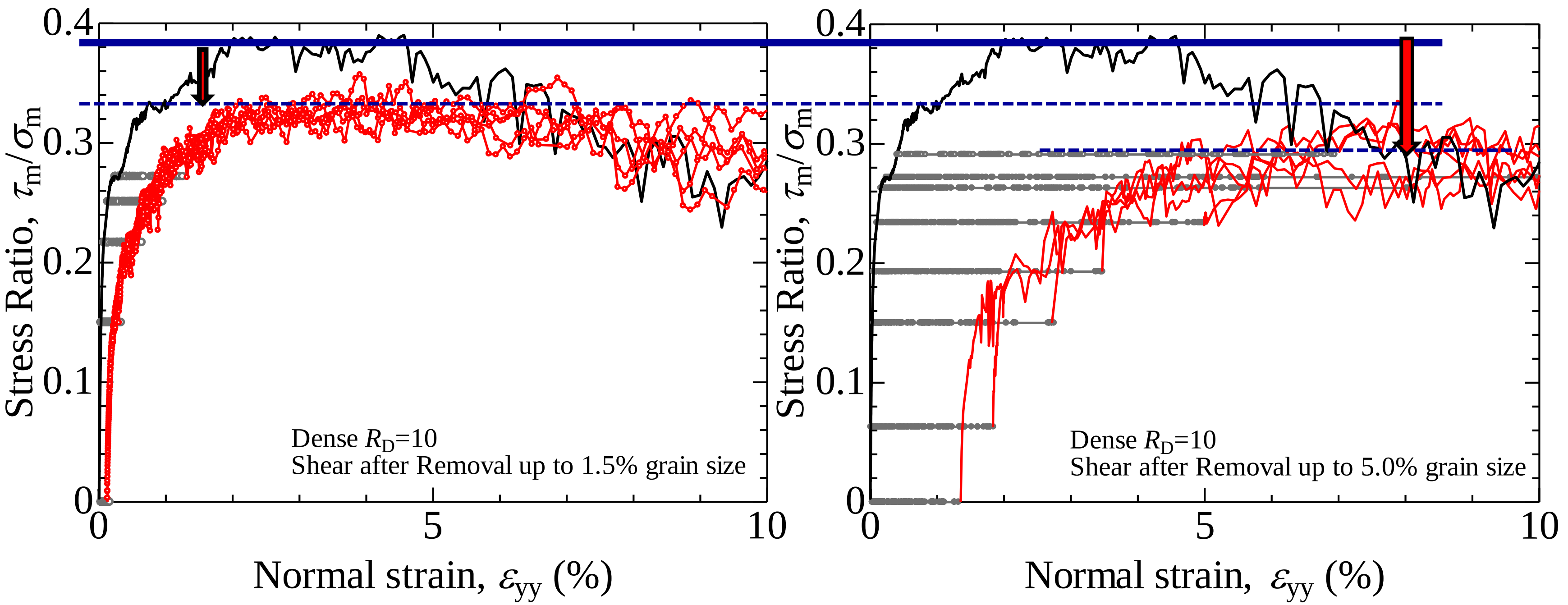


Volumetric change due to particle removal shows contractive; negative dilatancy. Particle removal induce compression in soil element, but increase void ratio in dense sample.

reloading test (shearing after eroion due to fine particle removal)

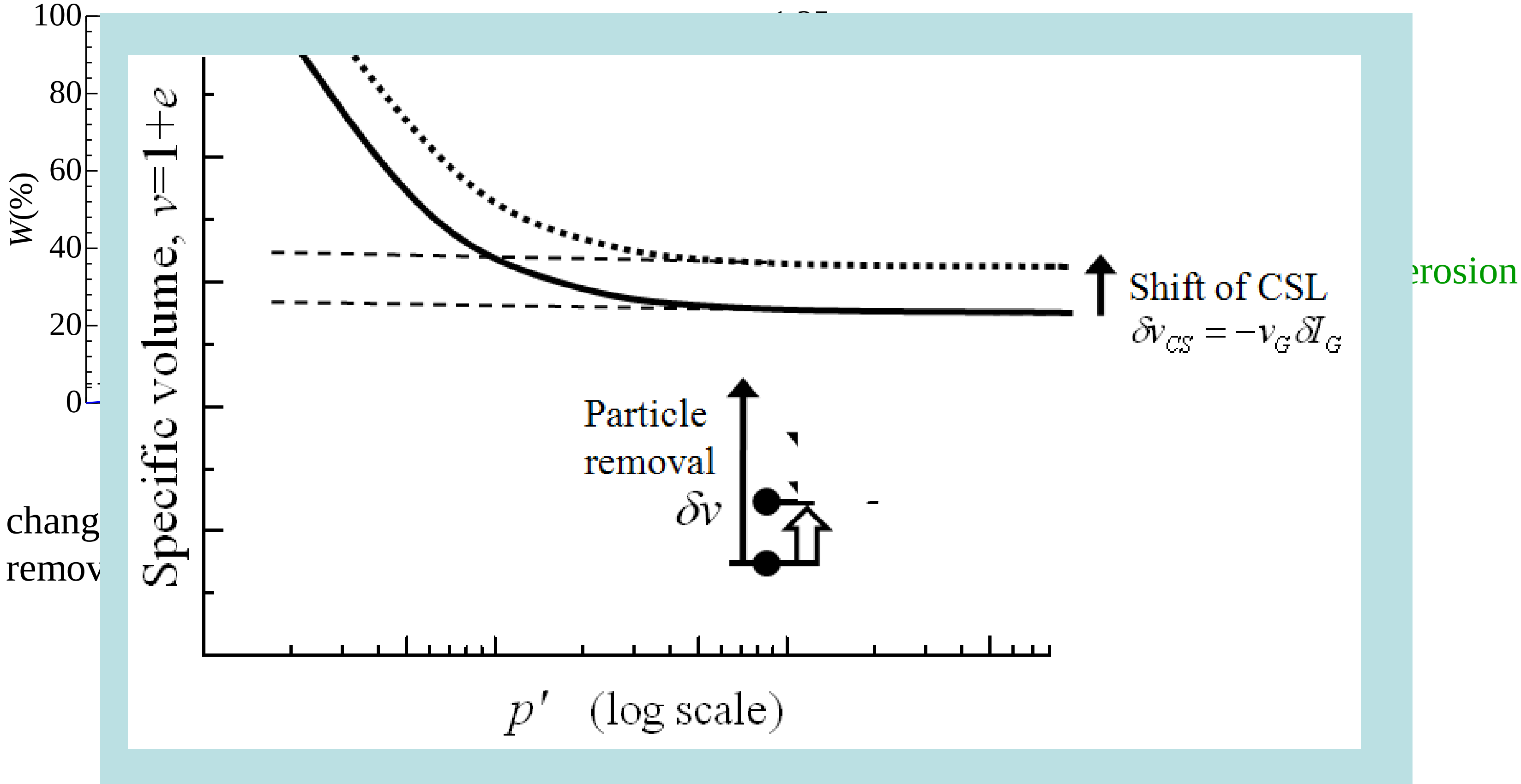
the removed particle size is equal to the 1.5% grain size of the original grain size.

the removed particle size is equal to the 5.0% grain size of the original grain size.



the reduction of peak strength of soil element due to erosion (fine particle removal)

For express plasticity in internal erosion critical state soil mechanics with changing grading by shifting “critical state line”

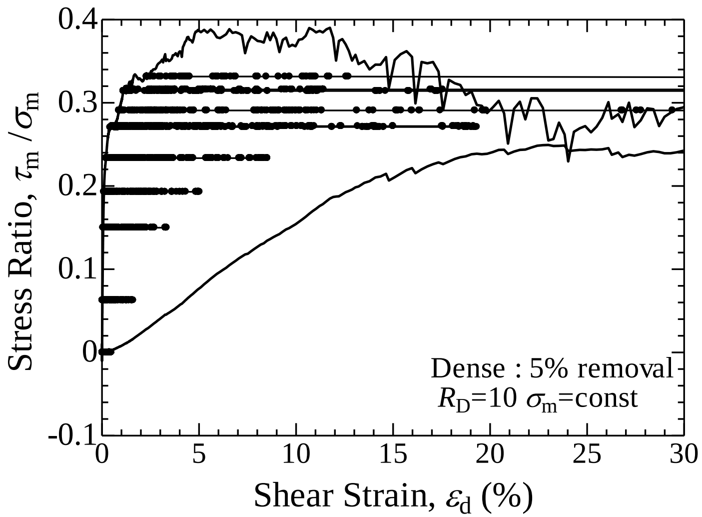


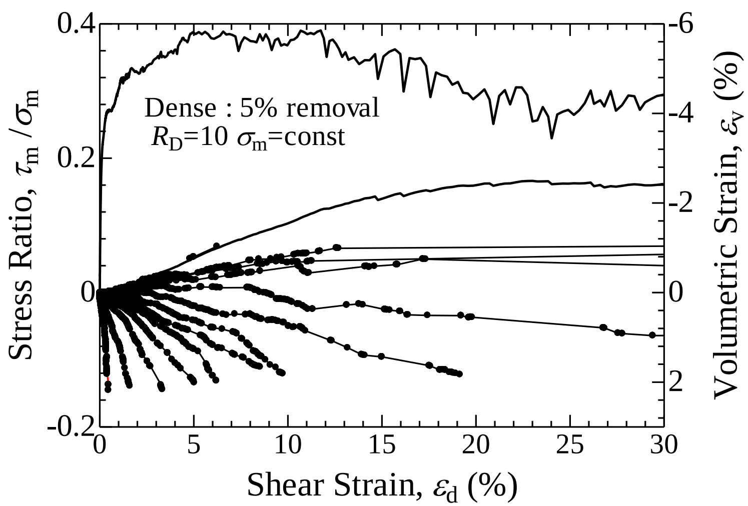
D. M. Wood & K. Maeda: *Acta Geotechnica* (2007);
D. M. Wood, K. Maeda & E. Nukudani : *Geotechnique*, 60 (6) (2010)

From previous 3 results, we made the continuum model.

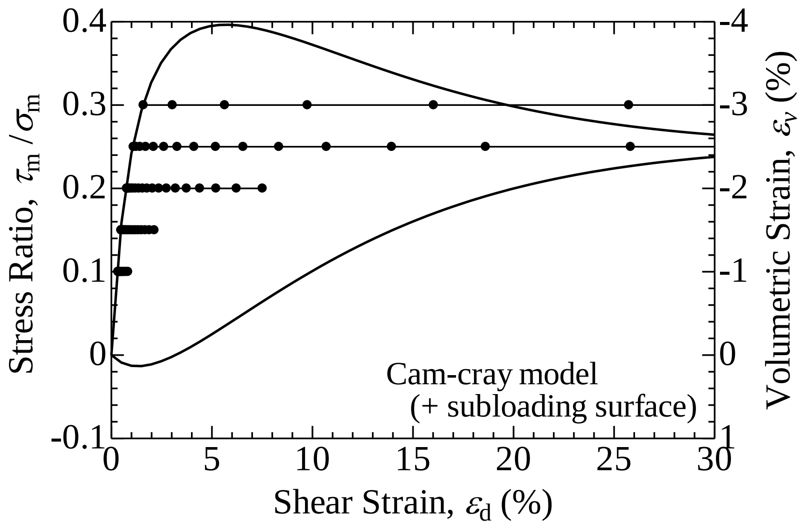
Performance of proposed model

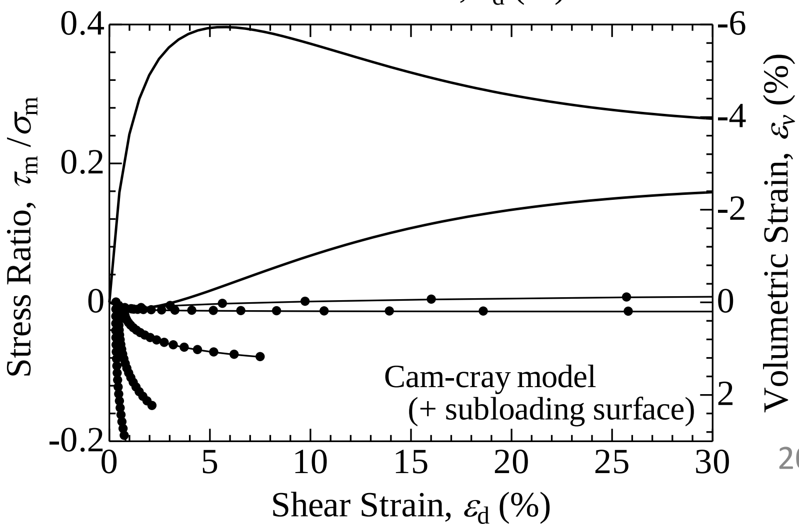
DEM simulation results





Proposed continuum model Including erosion effect

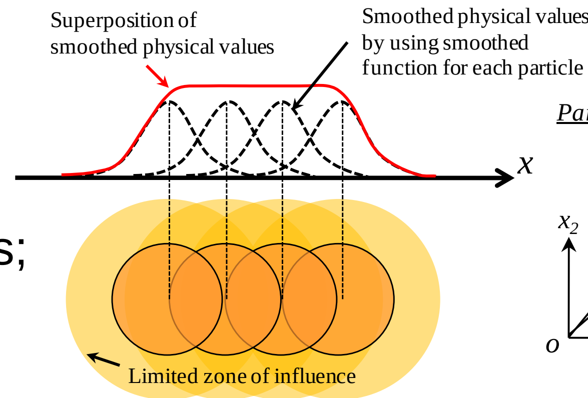


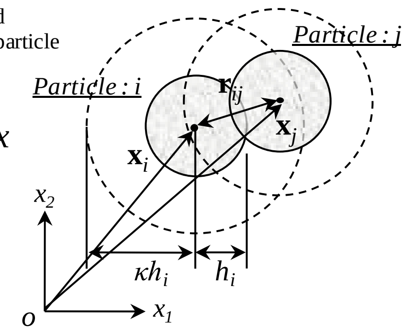


IVBC problem involving continuum modelling with erosion structural size

Smoothed Particle Hydrodynamics (SPH)

$$< f(\mathbf{x}) >= \int W(\mathbf{x}-\mathbf{x}', h) f(\mathbf{x}') d\mathbf{x}'$$





The feature of the SPH method is as follows;

- Mesh free
- Lagrangian method
- Initial modeling is easy.

Soil-fluid coupling

Tentatively Darcy's law is kept.

$$\mathbf{f}^{sf} = n^2 \frac{\rho_f g}{k} (\mathbf{v}^s - \mathbf{v}^f)$$

n : Porosity

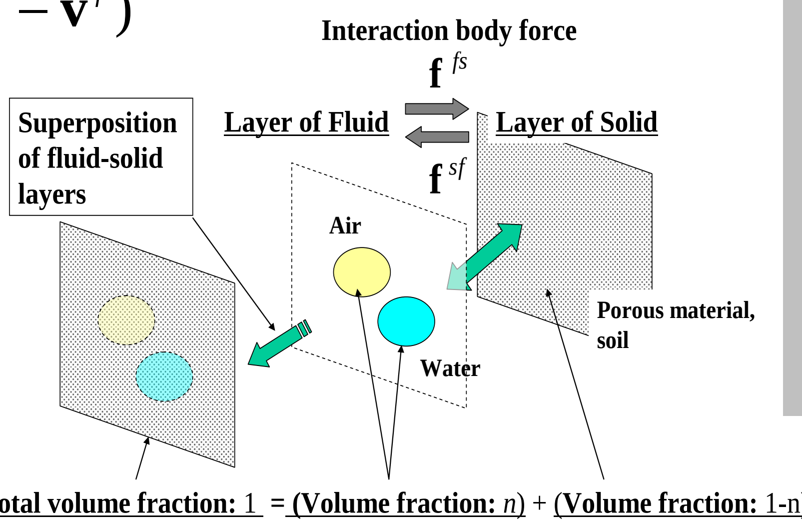
k : Permeability

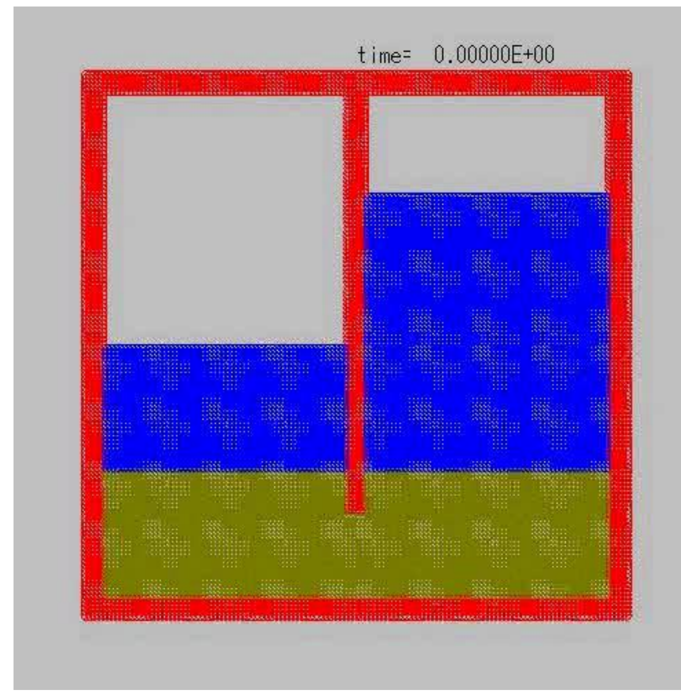
ρ_f : Density of fluid

g : Acceleration of gracity

v^s : Velocity of solid

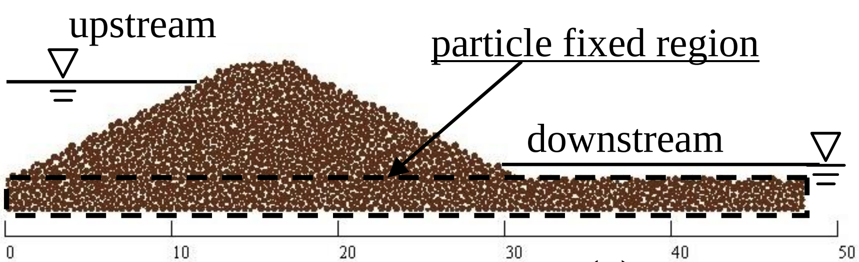
v^f : Velocity of fluid



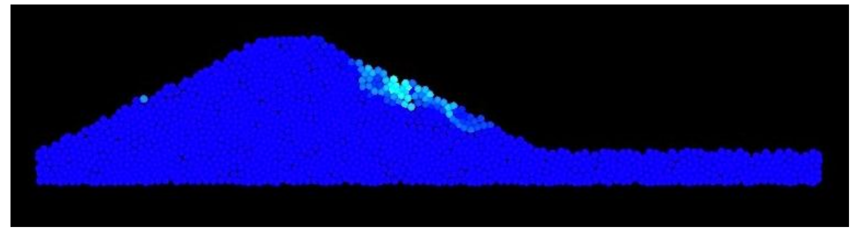


Seepage around sheet pile
(K. Maeda, M. Sakai (2004))

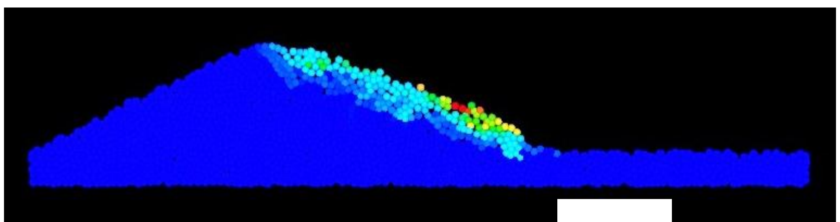
ex.) dike failure and washed-out under constant water level



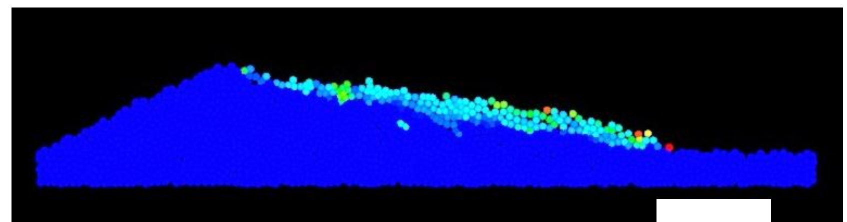
(a)



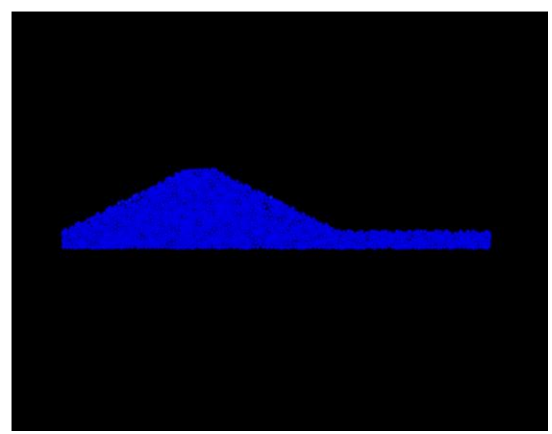
(b)



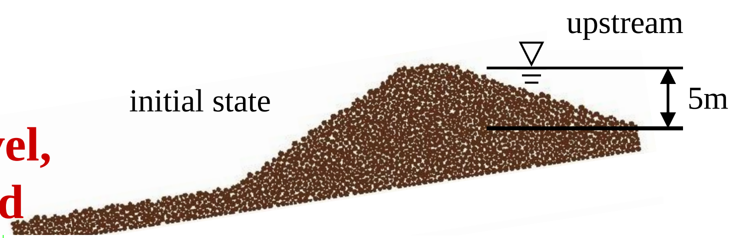
(c)



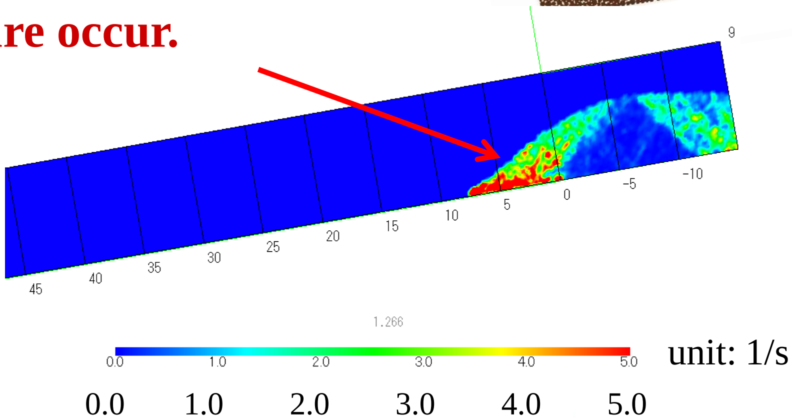
(d)

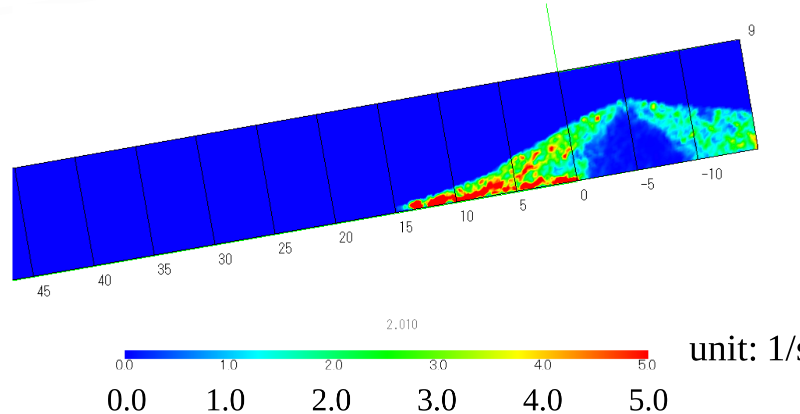


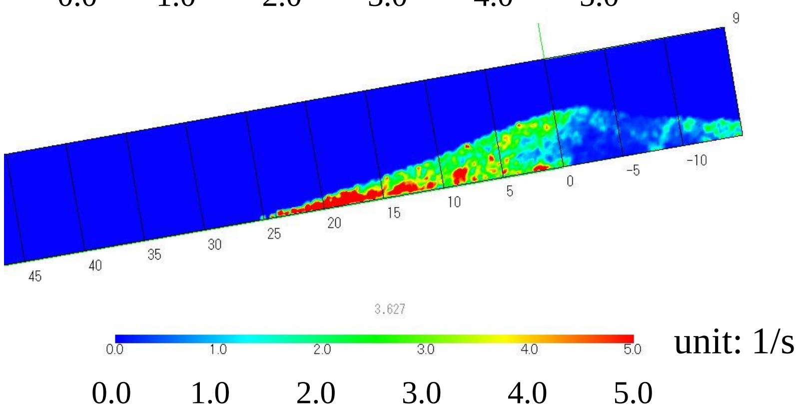
ex.) natural dam (landslide dam) failure under constant water level

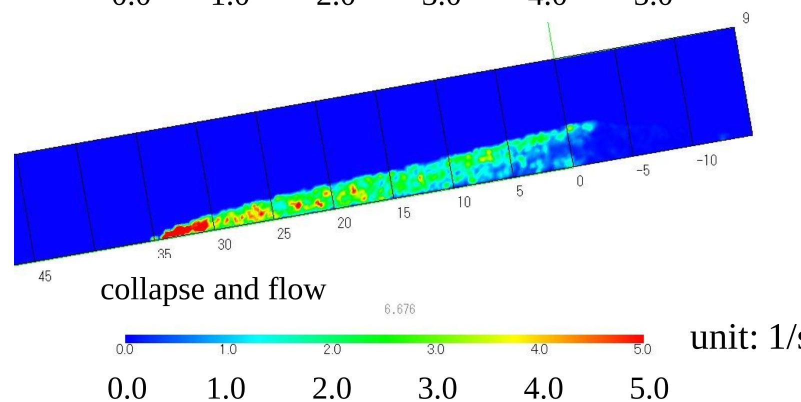


Even under constant water level, localization of deformation and failure occur.

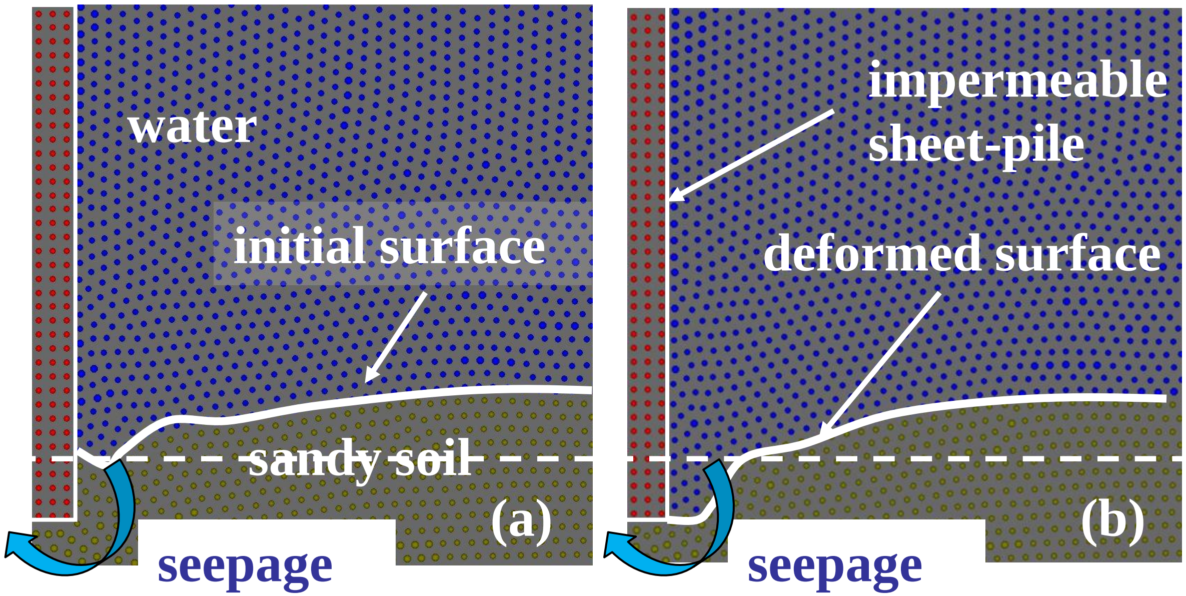








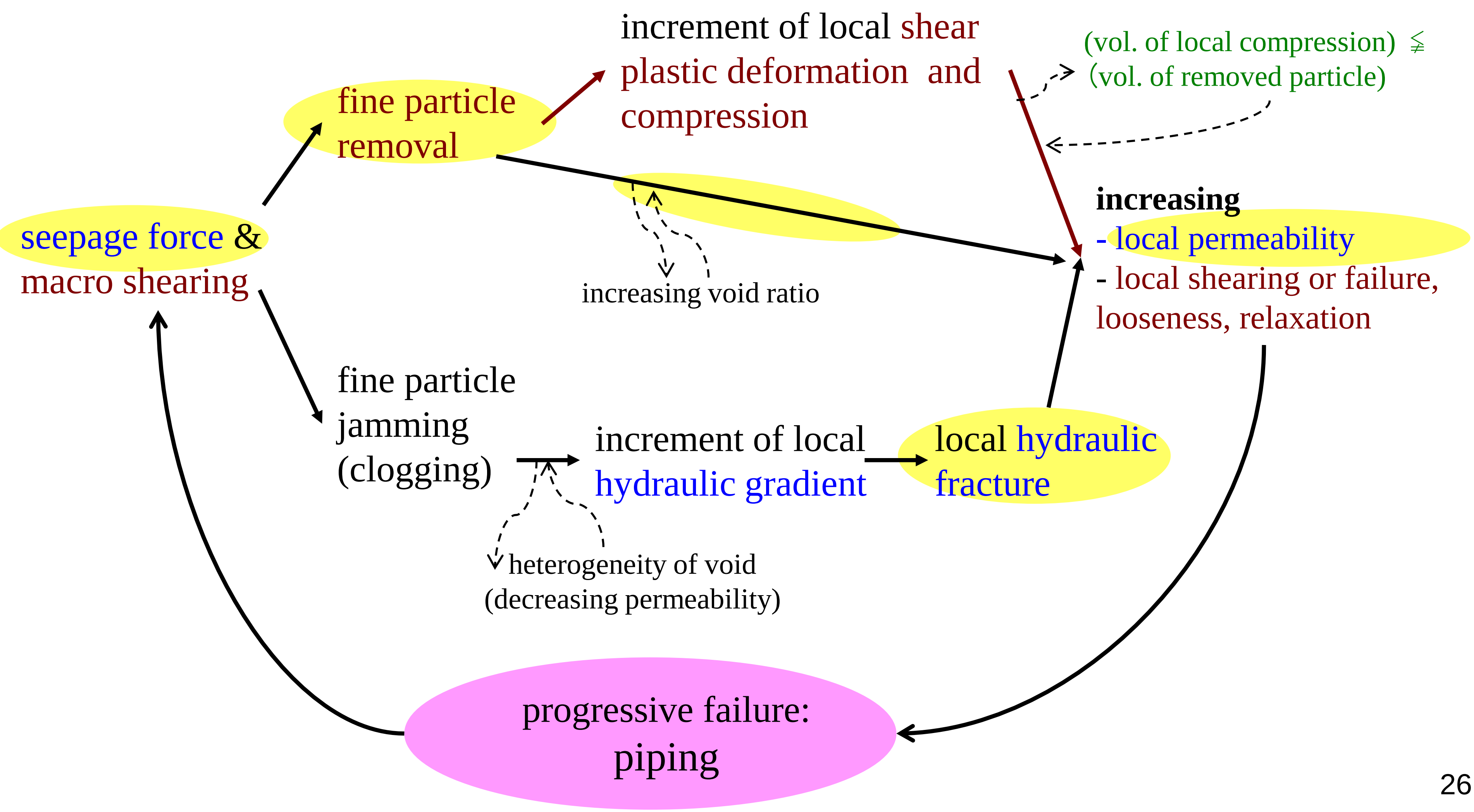
ex.) seepage and erosion around sheet-pile under constant difference in water height



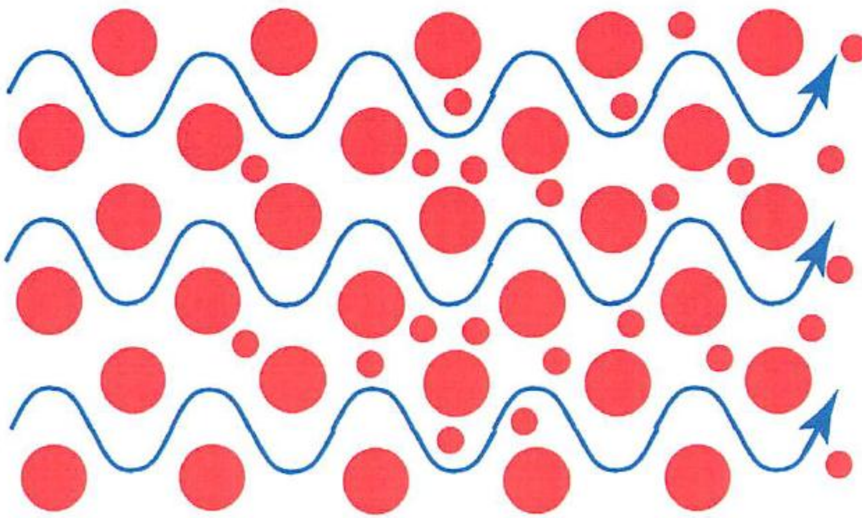
(a) without internal erosion; (b) with internal erosion (fine particle removal). Water level was kept constant where water flowed from right to left and the erosion was controlled by (changing rate in narrowing grading) the value of δI_G.

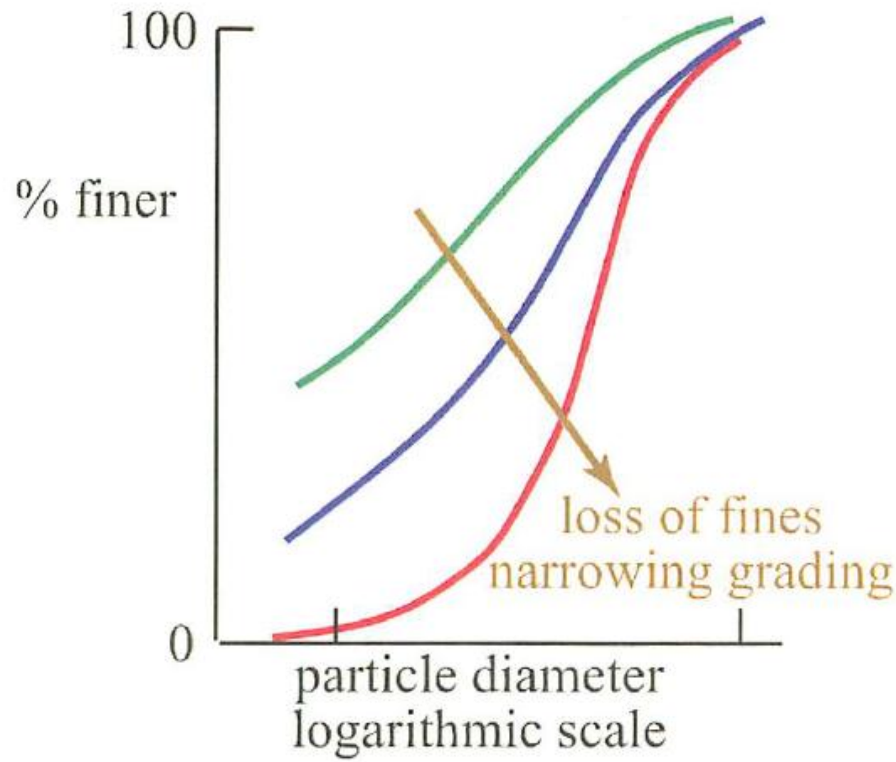
The settlement in Fig. (b) with erosion is larger than that without erosion in Fig.(a), and the deformation in Fig. (b) is localized.

role of local plastic deformation due to fine particle dynamics on internal erosion



internal erosion





According to the site investigations

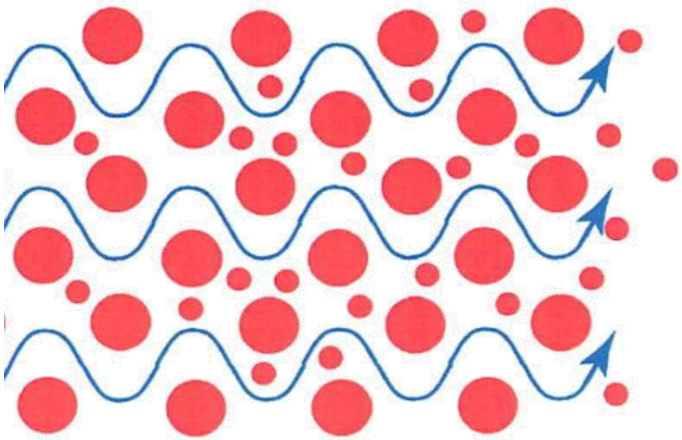
Loss of finer particle & narrowing grading

was observed, and it called *internal erosion*.

How can we deal with this phenomenon?

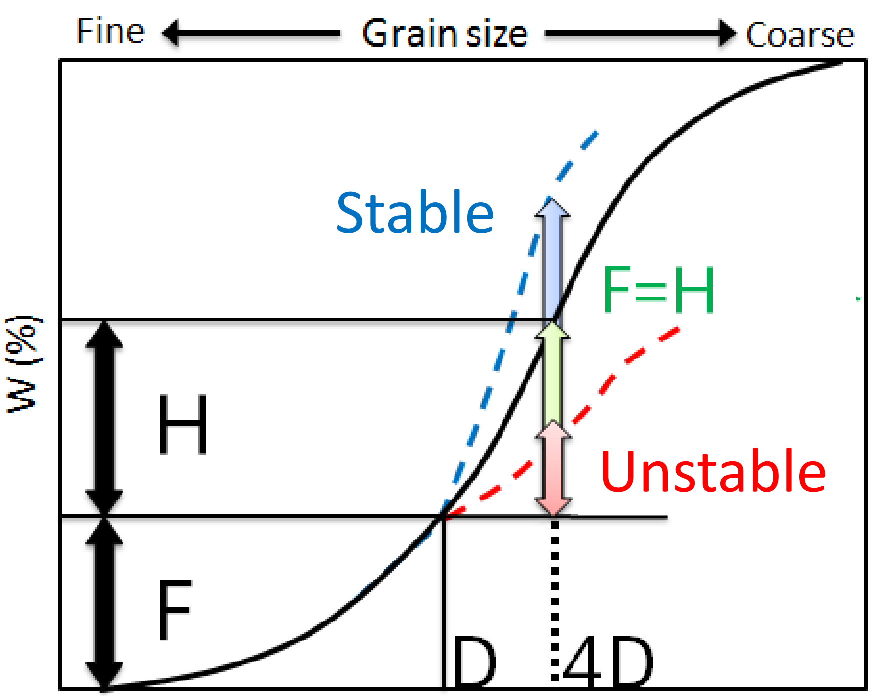
"The internal erosion changes soil property itself progressively. "

Focus on particle moving (previous research)



It's necessary following three condition

- Existence of movable void size
- External force (Seepage force)
- Not constitute microstructure



To consider the certain particle stability…

Stable condition for internal erosion (Kenny et.al, 1985)

1, $D < \frac{1}{4} D_{Filter}$

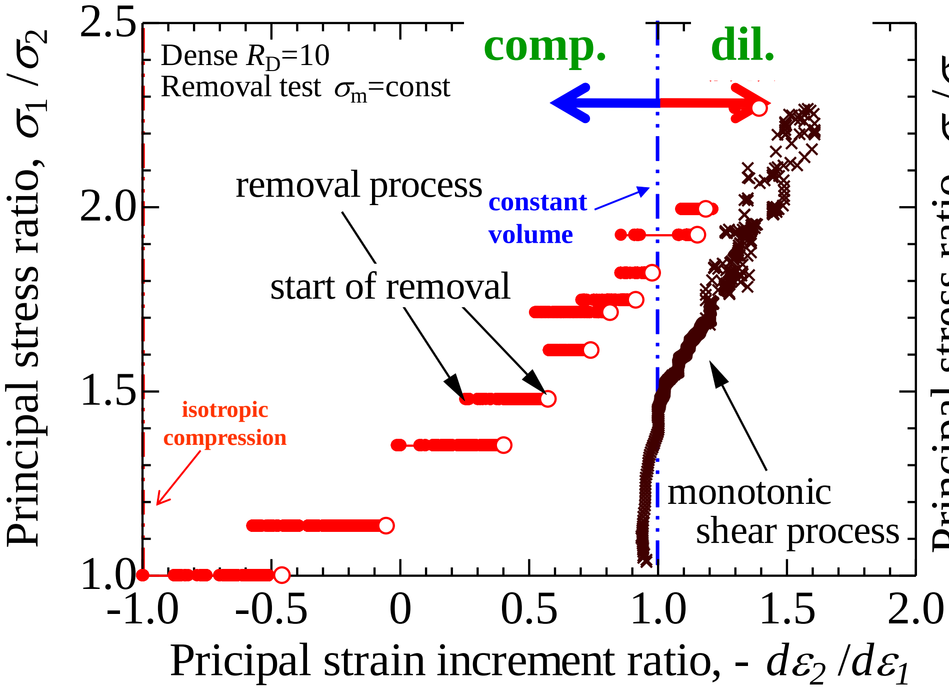
Removable size: D is 1/4 of filter min. size

2, $H > F$

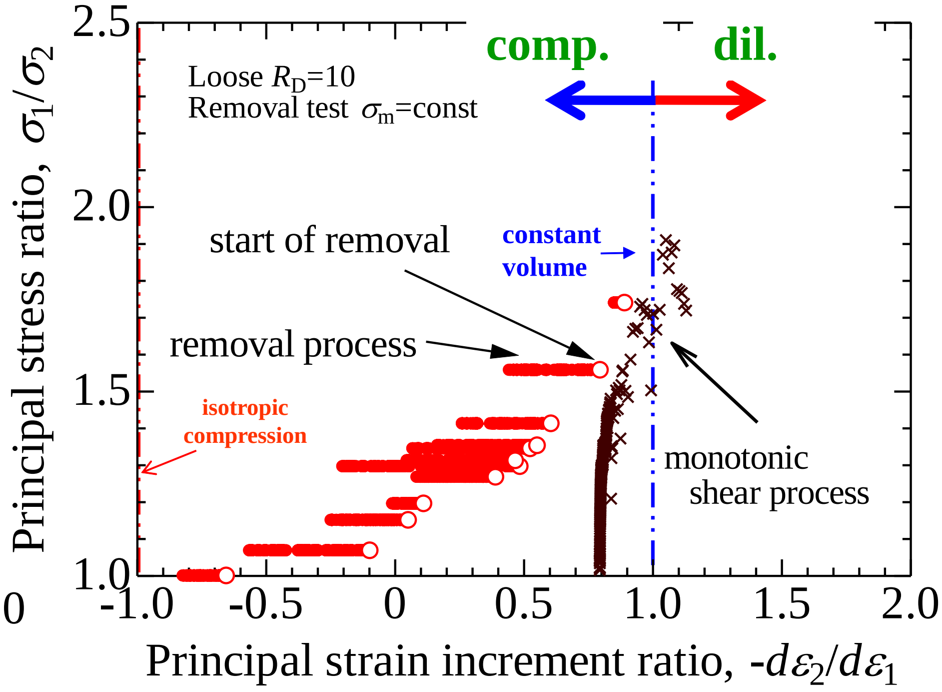
Filter particle need to contain more than finer

stress-dilatancy due to fine particle removal

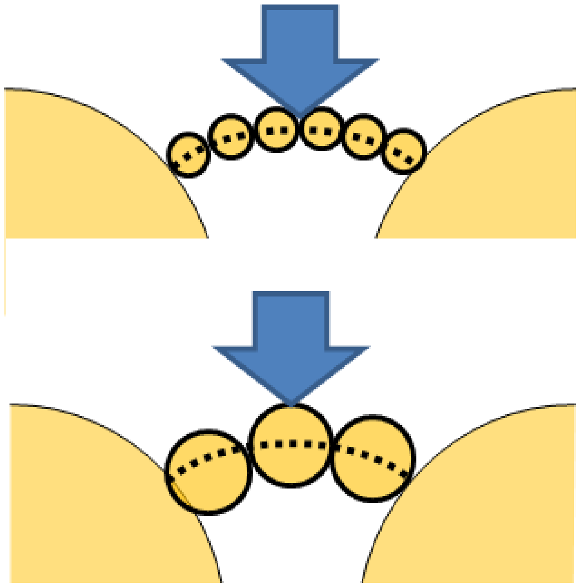
Dense



Loose



Arch microstructure As Clogging model



Basically,

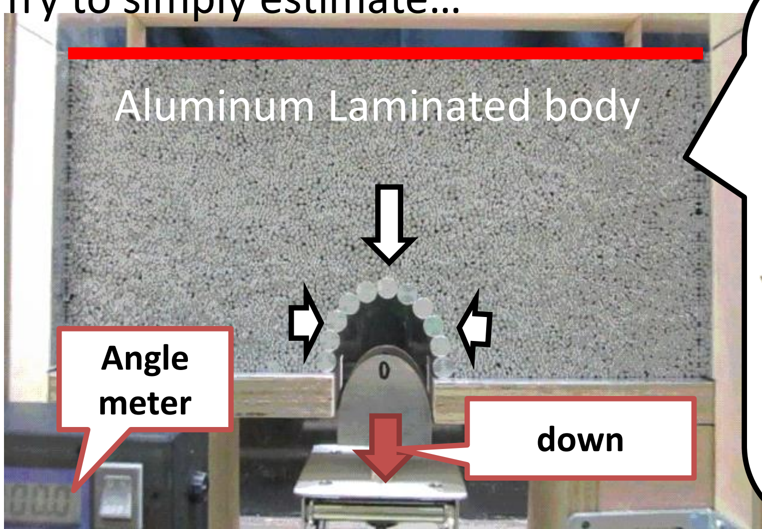
arch structure doesn't break by seepage force …

Not influenced from arch shape and number of composing particles ?

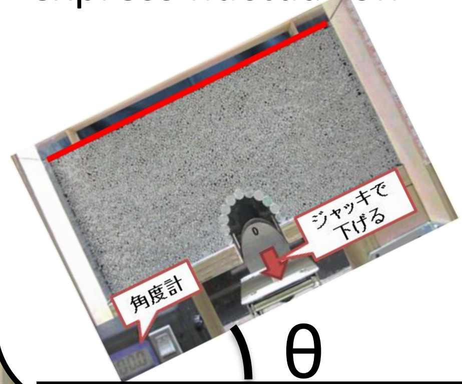
But, cyclic loading causes particle removal.

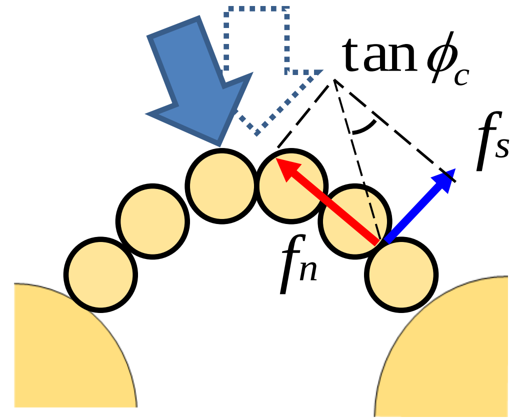
It's necessary to estimate stability against forcing fluctuation

Try to simply estimate…



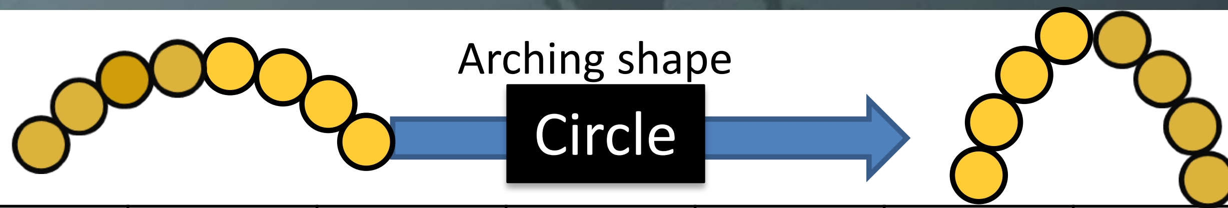
Rotate principal stress direction by sloping to express fluctuation



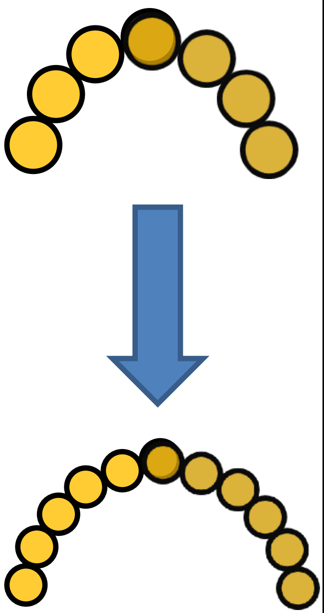


$$\tan\phi_c = f_s / f_n$$

Arch microstructure As Clogging model



Composing num.

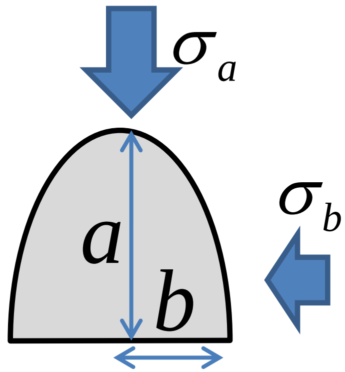


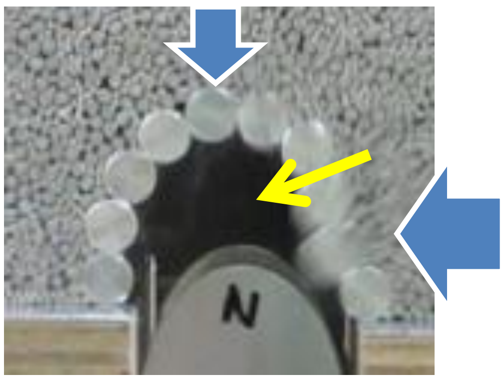
a/b Num.	0.5	0.75	1	1.25	1.5	1.75
7	29.3°	f	A	F	K	P
8	23.4°	34.7°	B	G	34.4°	26.2°
9	11.7°	h	C	33.0°	34.0°	29.4°
10	18.0°	i	D	33.4°	28.2°	32.6°
11	9.2°	j	E	32.3°	31.1°	24.0°

Angle in chart: breakage slope angle. if it blank, not break by sloping

Stable condition: Arch shape close to *circle*
composed number of particle is *few*

Stability of Clogging microstructure



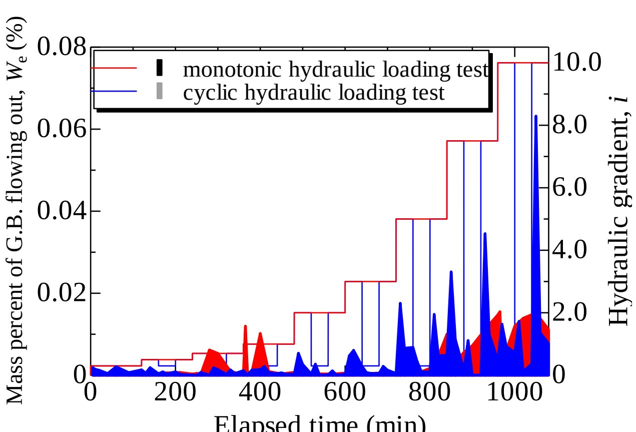


Most stable shape is determined by current stress condition.

$$\frac{a}{b} = \frac{\sigma_a}{\sigma_b}$$

Resistible fluctuation range exists.

+ if number of particle have a lot, it goes unstable by a lot of num. of breakable point.



As a reason…

Removal amount increase by cyclic loading

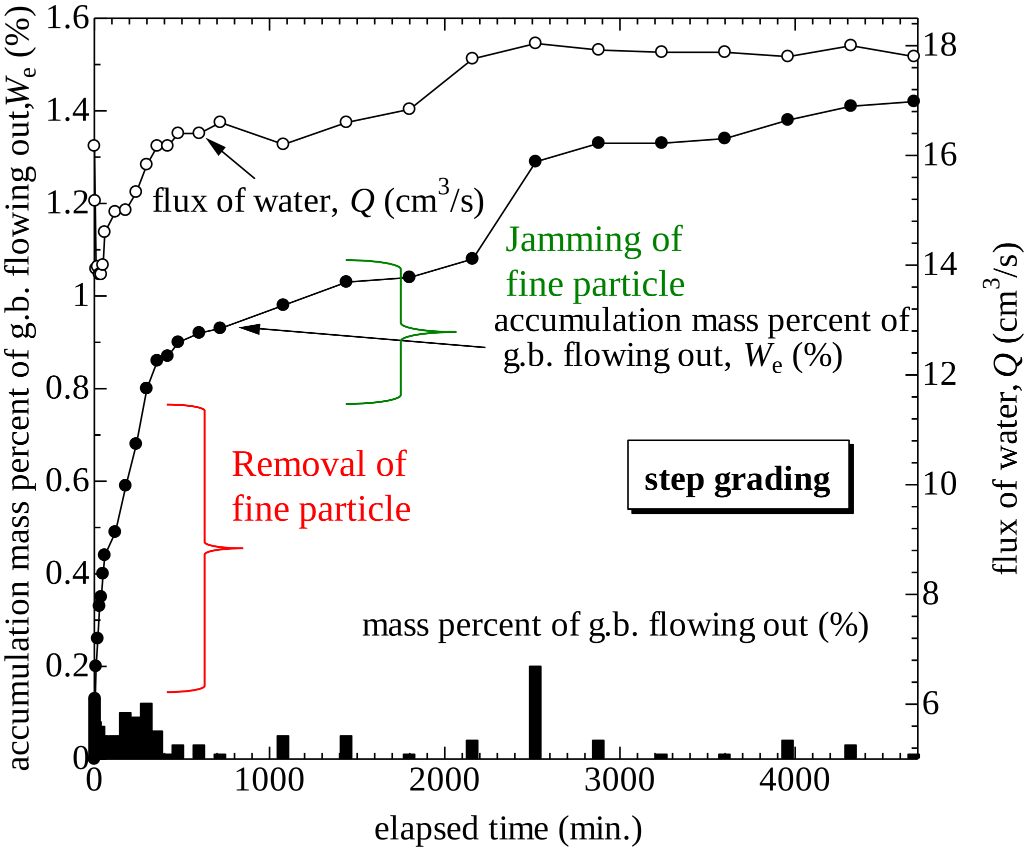
Erosion concentrate just after i changed

It along with the amplitude of fluctuation even hydraulic grad. Just only decrease

to solve internal erosion in geotechnical problems

- ✓ To simulate removal and jamming of fine particle -> model test & DEM
- ✓ To fined a rule of plastic deformation and failure due to fine particle removal -> DEM
- ✓ To suggest continuum modelling of internal erosion: changing grading :
- ✓ To calculate of IVBC problem by Smoothed Particle Hydrodynamics (SPH)

under constant hydraulic gradient

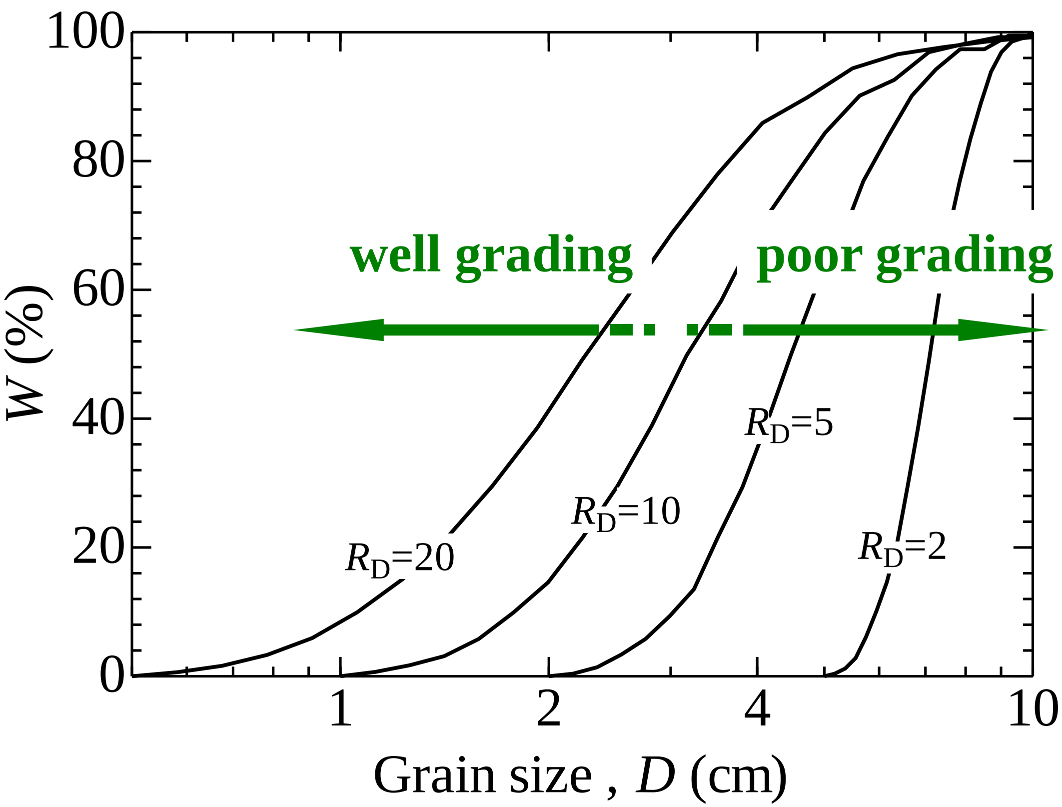


Even under constant hydraulic gradient, some fine particles were removed from the sample. And the removal and the jamming of fine particle occurred alternatively.

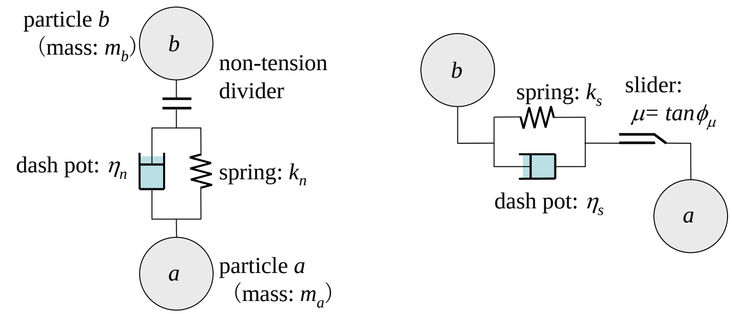
Finally internal erosion stopped.

changing grading: grading became coarser

sample use and DEM parameter



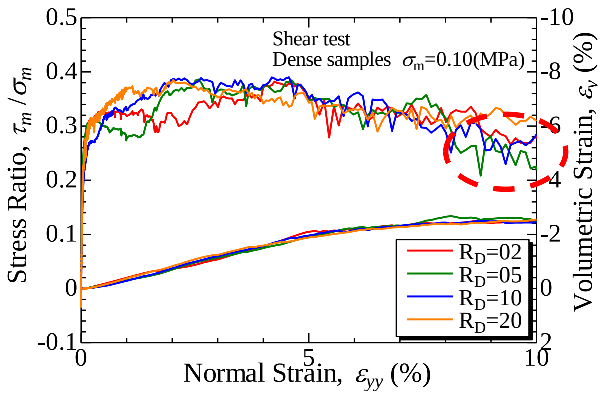
$$R_D = D_{max}/D_{min} = 2,\ 5,\ 10,\ 20$$



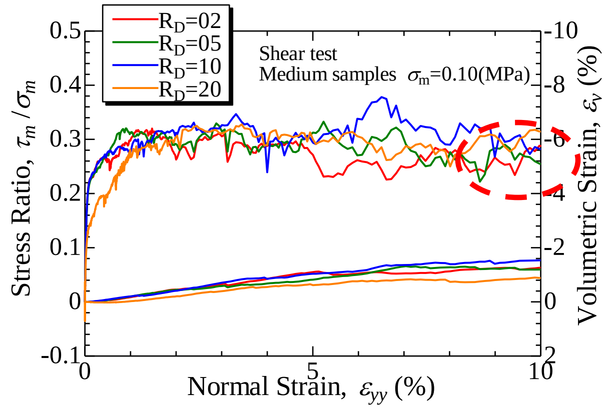
parameter	sym.(unit)	value
[particle; contact model]		
Diameter	D_{min} – D_{max} (m)(R_D)	0.5 - 0.10 (2) 0.02 – 0.10 (5) 0.01 – 0.10 (10) 0.005 – 0.10 (20)
particle density	ρ_s (kg/m^3)	2700
spring coeff. in normal direc.	k_n (N/m)	1.0×10^8
spring coeff. in shear direc.	k_s (N/m)	2.5×10^7
viscous damping (normal)	h_n	1 (critical)
viscous damping (shear)	h_s	1 (critical)
interparticle friction coeff.	$tan\phi_\mu$	0.25
calculation time	Δt (s)	1.0×10^{-6}
[assembly: referred value]		
density	ρ (kg/m^3)	1800
P-wave velocity	V_p (m/s)	266
S-wave velocity	V_s (m/s)	133

monotonic shearing

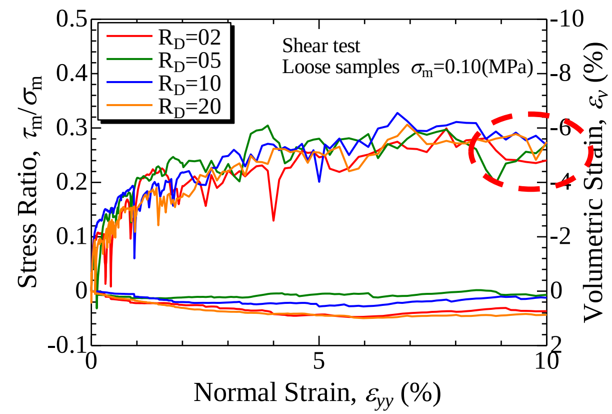
Dense

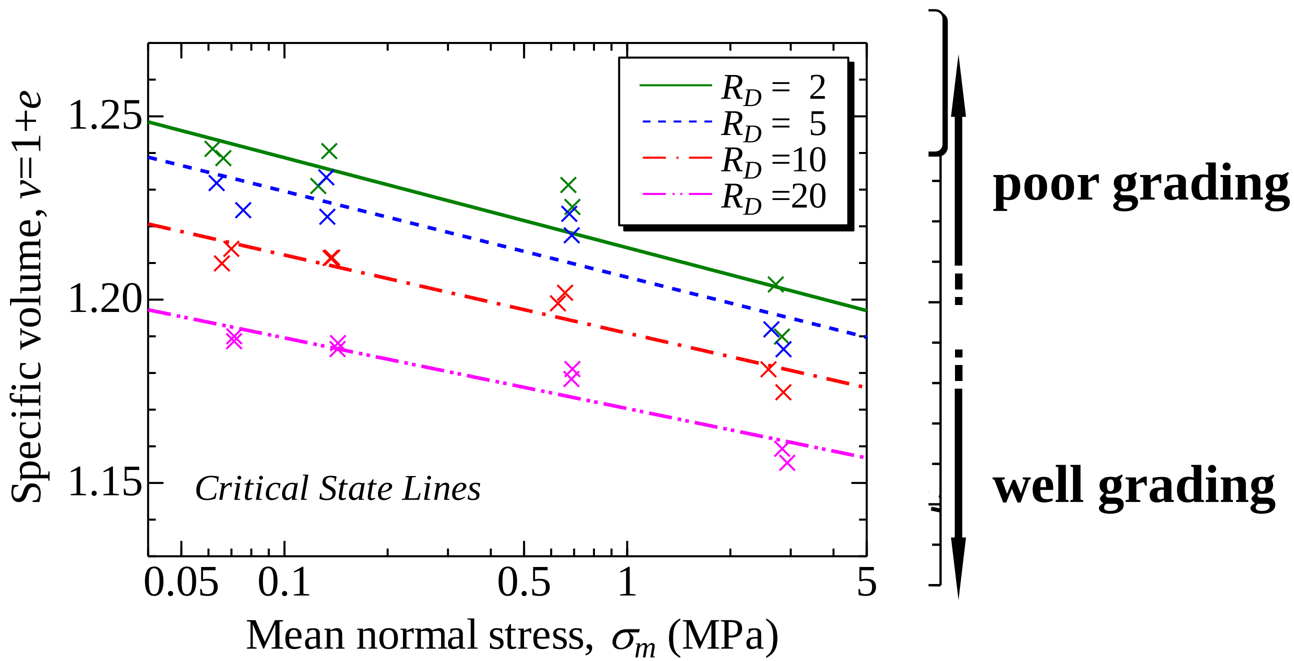


Medium



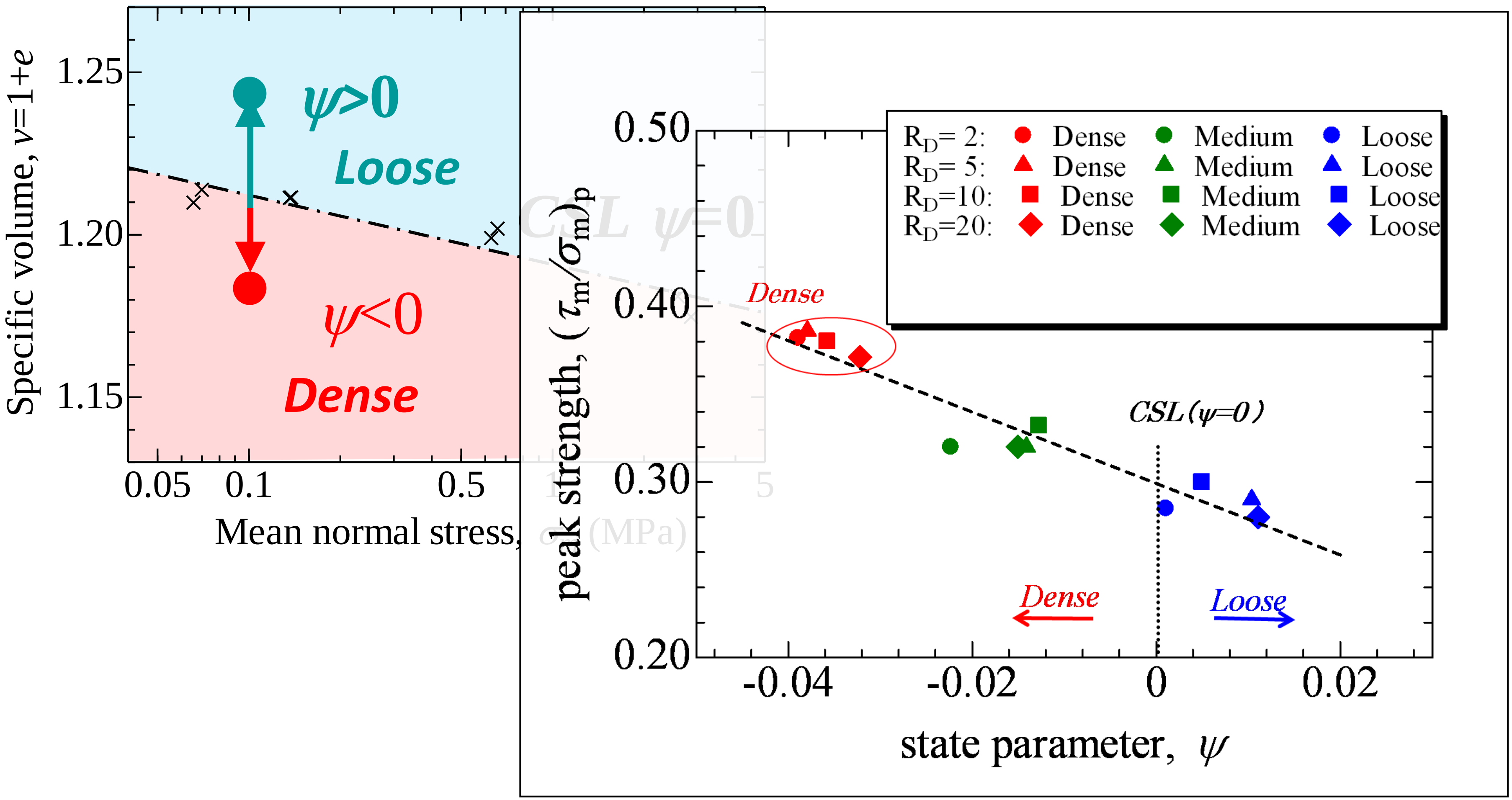
Loose



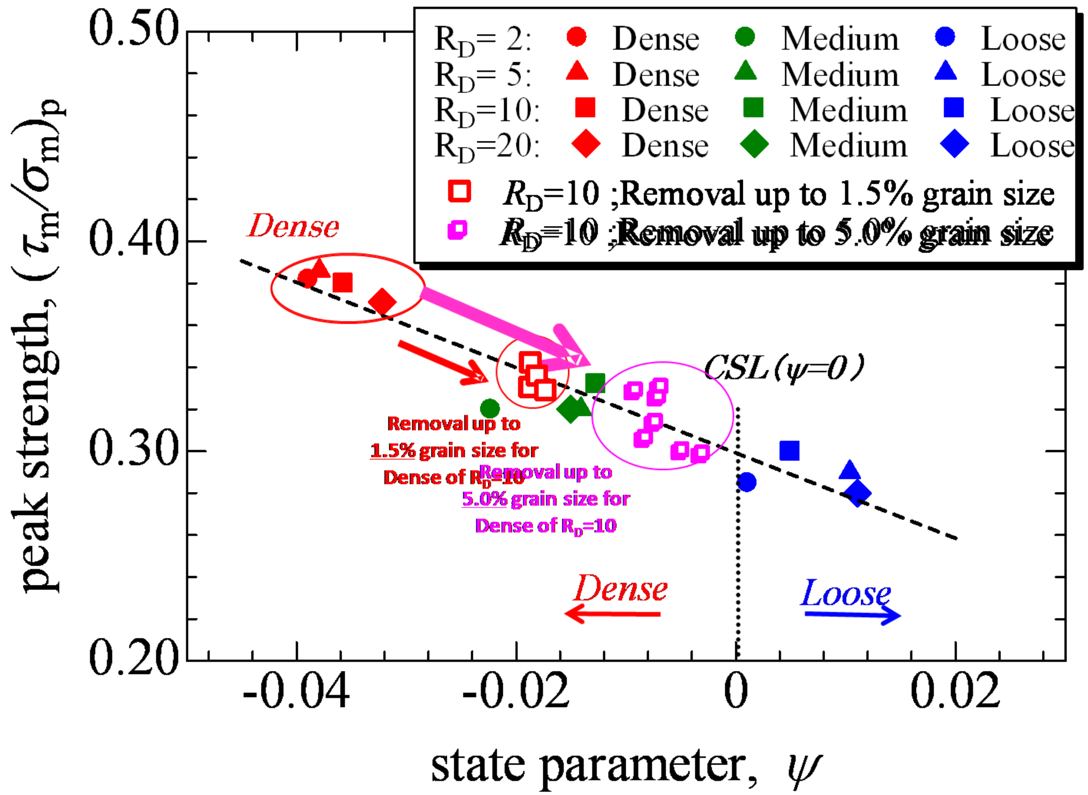


State parameter : ψ

$$\psi = v - v_{cs} = (1+e) - (1+e_{cs})$$

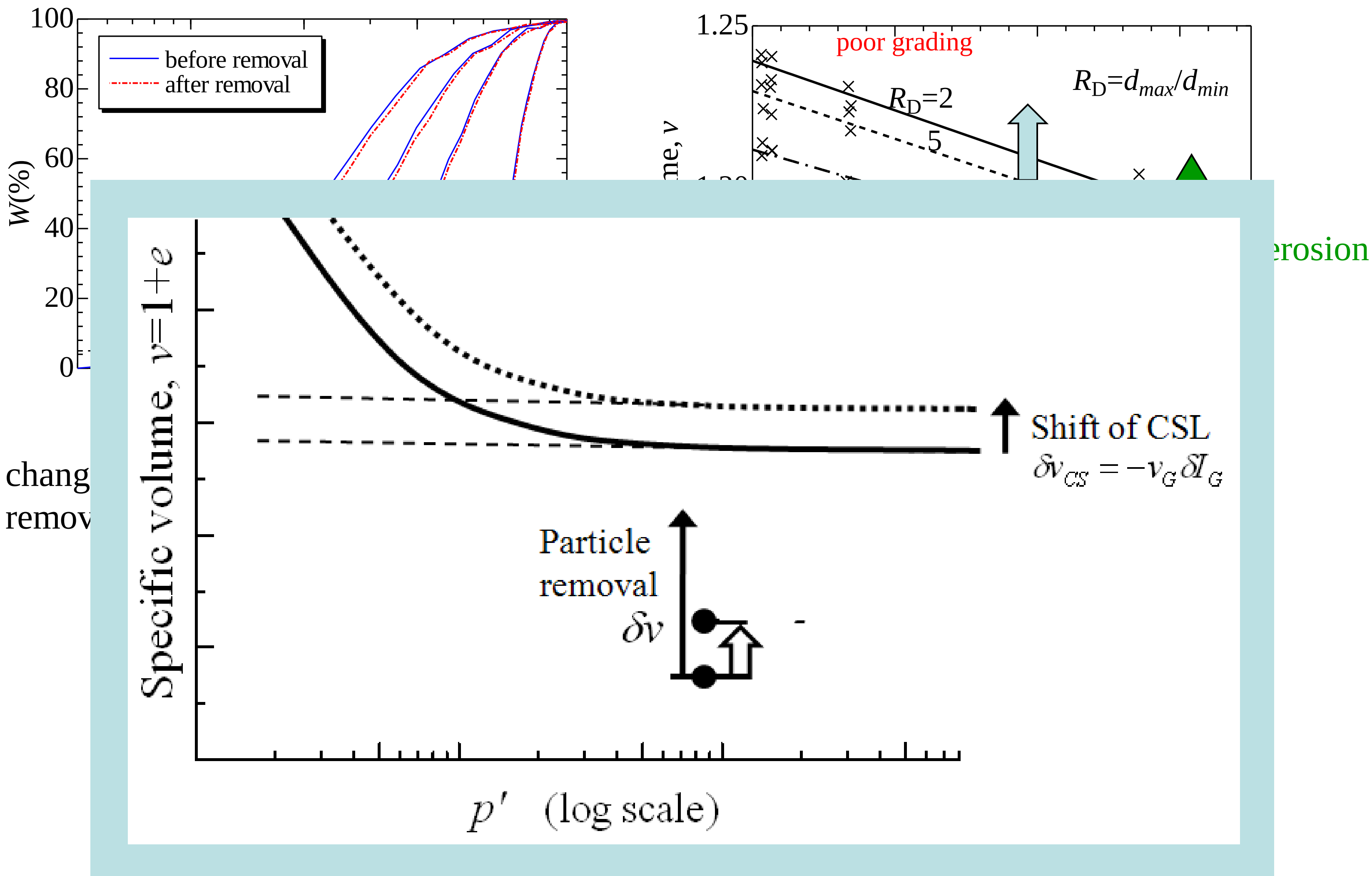


State parameter : ψ



The granular material subjected to erosion changed to be a different material with different grading. The state parameter is useful to the available strength not only for the material before erosion but also after erosion, independently of degree of erosion.

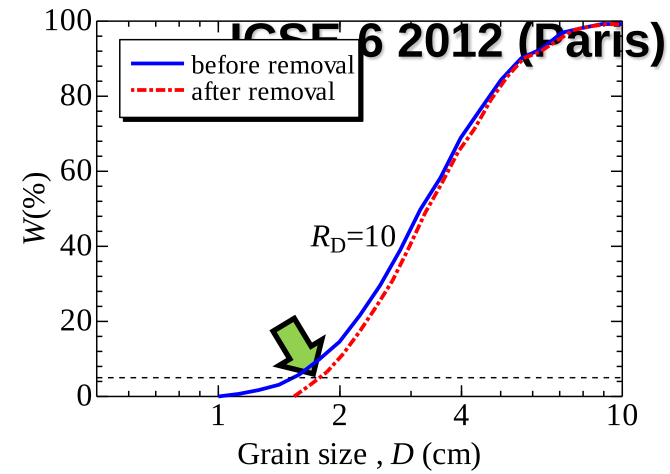
Modelling mechanical erosion
soil mechanics with changing grading

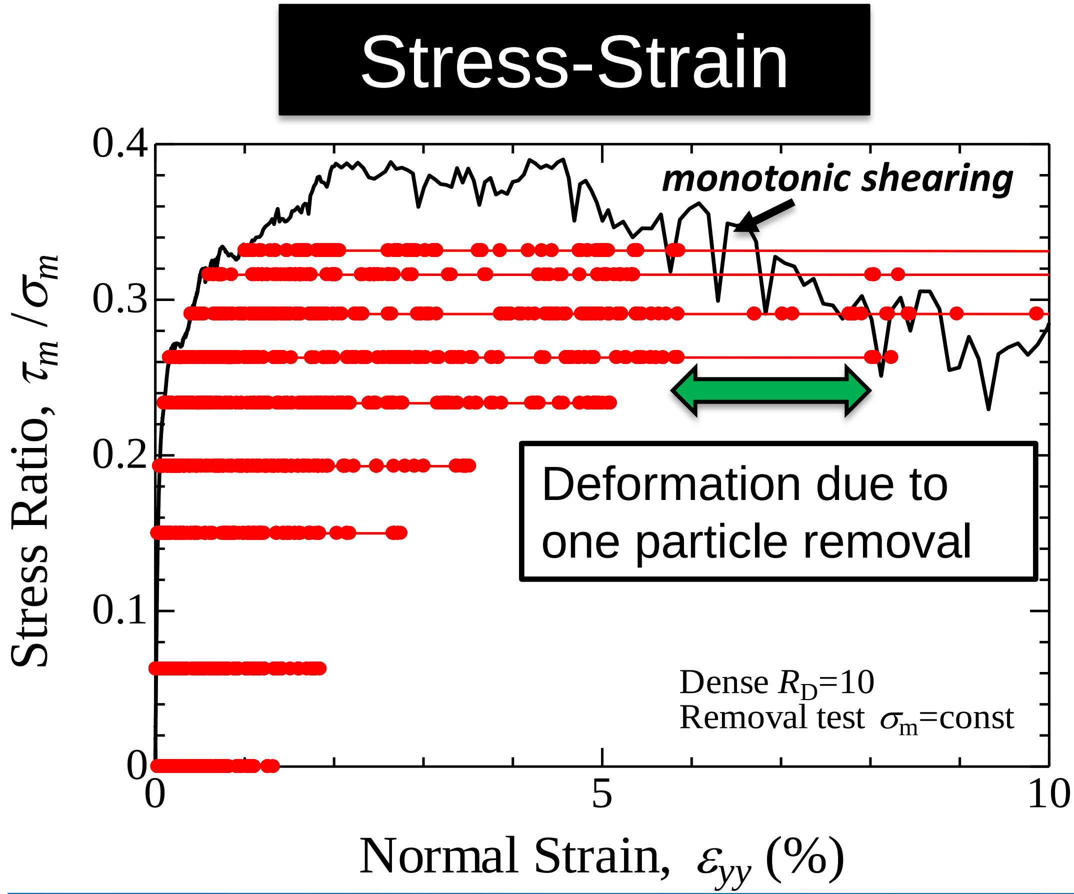


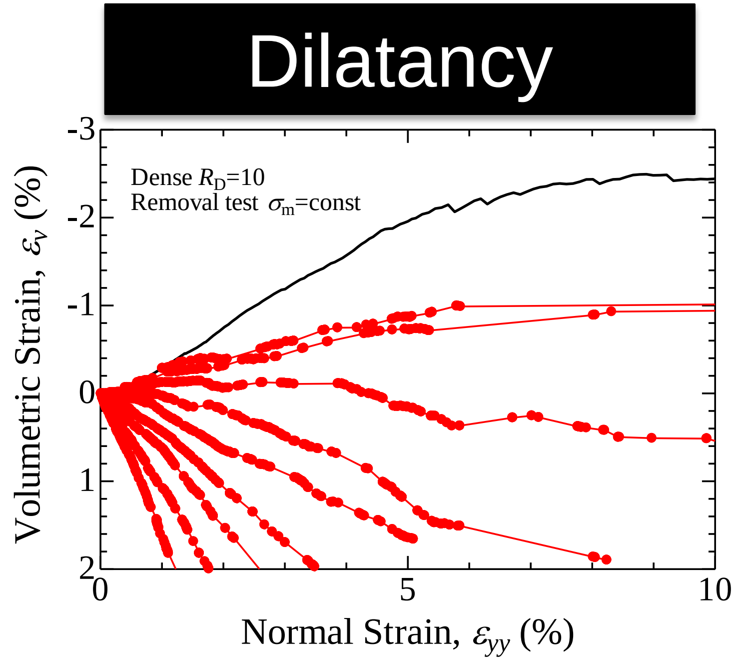
D. M. Wood & K. Maeda: *Acta Geotechnica* (2007);
D. M. Wood, K. Maeda & E. Nukudani : *Geotechnique*, 60 (6) (2010)

Removal Test

Catch up the deformation by progressively removing finer under constant stress





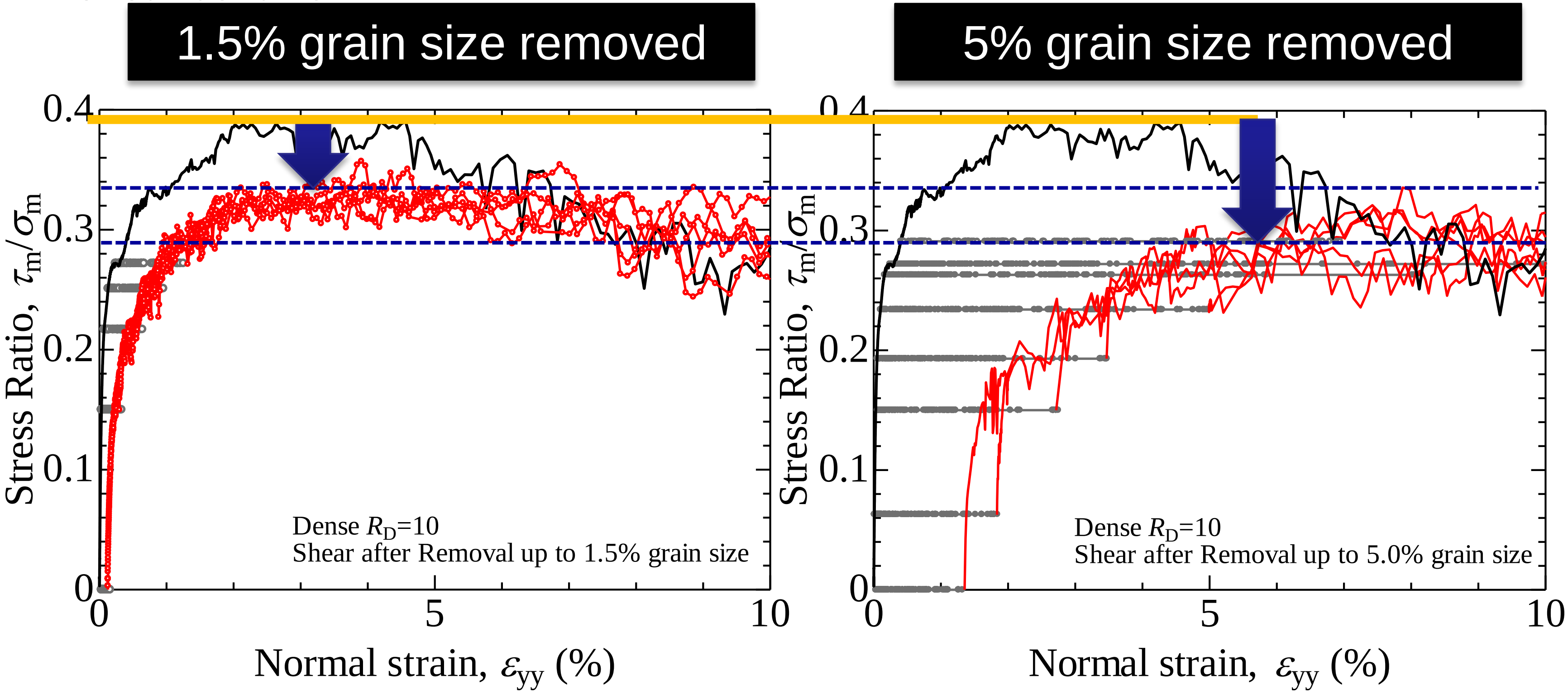


Even under the constant stress condition, sample have compression and reach to critical state by <u>5% finer removal & high stress ratio</u>.

Reloading test
(shearing after erosion)

Aims to evaluate the effects for potential of sample strength, it's verified by the shearing after erosion test.

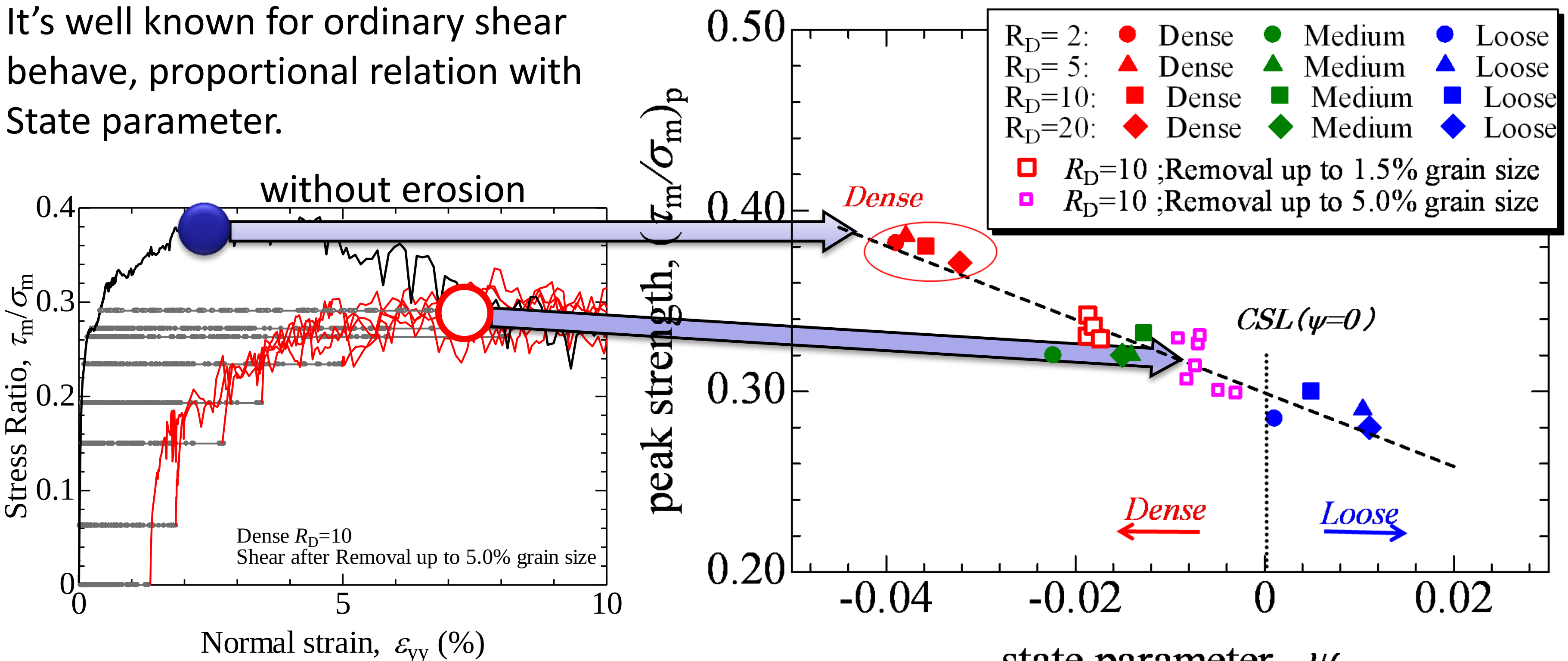
Shear behavior



Reduction of peak value due to removal can be observed

Proportional relation between *Potential of peak strength* and *State parameter*

It's well known for ordinary shear behave, proportional relation with State parameter.



It can put on same line by thought Removal behave as loose sample.

Relative density index for critical state

Potential of peak strength can be expected same as without one by state parameter(ψ=ν - ν_{cv}): *relative density index for critical state*

Two large sink holes in a fill dam