Symposium on integrated evaluation system
for earthquake-induced slope failure
and resultant damage to infrastructures
2010/03/23 at Southwest Jiatong University, China

Some numerical tools for the simulation of slope failure and debris flow

Takashi Matsushima 松島亘志
University of Tsukuba 筑波大学

1. INTRODUCTION

Recent disasters related slope failures in Japan

2003.7.20	Hougawachi debris flow (Kumamoto pref.)
2004.10.23	Chuetsu earthquake (Niigata)
2006.5.12	East Yokoyama landslide (Gifu)
2007.7.16	Chuetsu offshore earthquake (Niigata)
2008.6.14	Iwate-Miyagi Nairiku earthquake
2009.7.21	Hofu mudslide (Yamaguchi)

http://www.mlit.go.jp/river/sabo/jirei.html

Hougawachi debris flow (Kumamoto pref.) 2003


朝日新聞（夕刊） 2003年

土石流 800㍍一気に

九州豪雨

治山ダム過信、危険

専門家「予測は難しい」

多数の犠牲者が出た熊本県水俣市宝川内の土砂災害は、大雨で保水力の限界に達した急傾斜地から土砂が崩れ落ち、被害を拡大させたとみられる。土石流は裏山の尾根近くから、量を増やしながら沢を流れた。土砂災害の予知の難しさと、早い段階での避難の重要性を改めて示した。

集地区の　落跡は高さ　約300㍍の尾根　くから始まり、　行しながら、直　約800㍍下の集　む。傾斜地がざっく　ぐられ、山腹の地肌　き出しになっている　途中にある3基の　ダムは、いずれも堰　分がもぎ取られ、破　の大きさを物語っ

山肌が大きく削り取られた　川の上流域＝21日午後、熊　県水俣市で、本社ヘリから

An expert says “it’s difficult to predict.”

The debris flow ran 800m and destroyed three sabo dams which results in 19 dead

solid ⇒ liquid ⇒ solid
multi-phase materials
large deformation (flow)
river-bed erosion

Chuetsu earthquake (Niigata) 2004

M=6.9, depth=15.8km

1600 slope failures

45 landslide dams

total damage=30 billion dollars

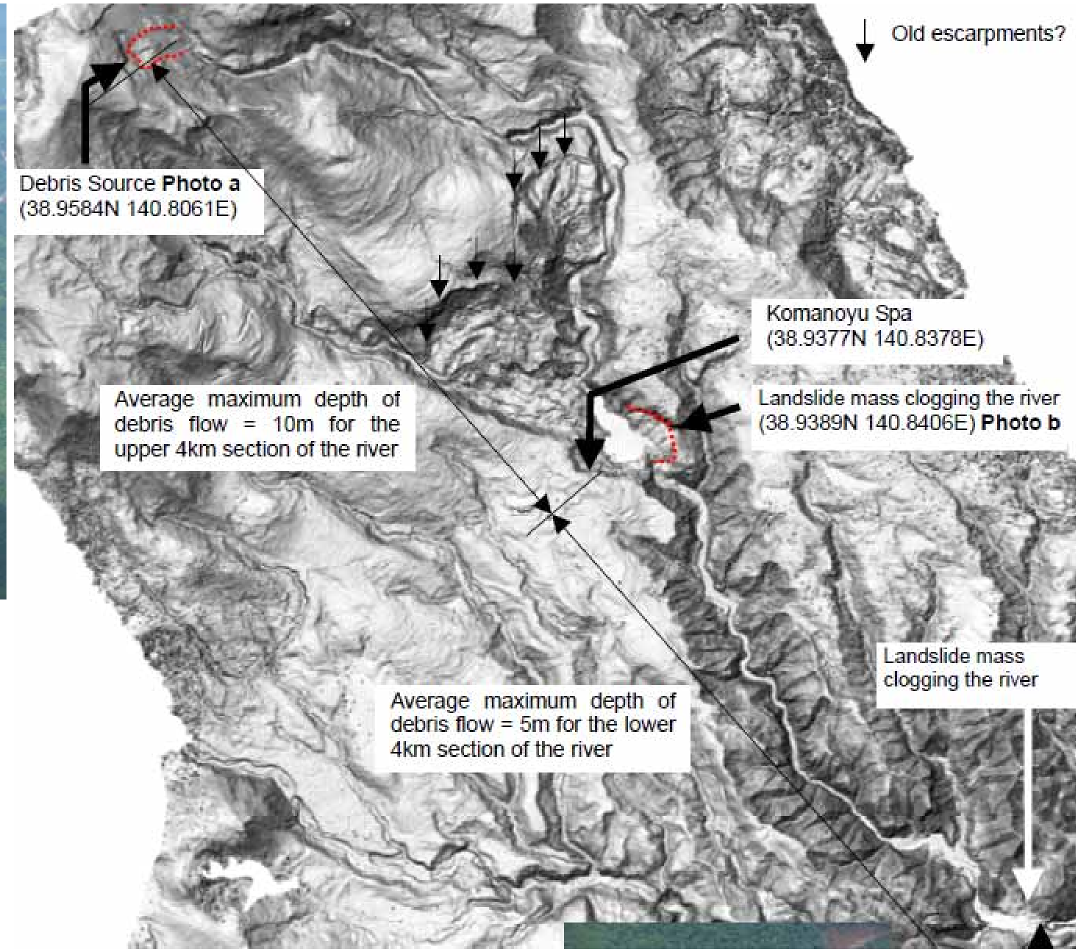
East Yokoyama landslide (Gifu) 2006

Landslide width=150m, Total slid volume=50,000 m^3
People noticed some symptoms, set video cameras, and performed quick survey of material parameters (c, ϕ, density) to check if the river at the bottom will be banked up or not?

Chuetsu offshore earthquake (Niigata) 2007

M=6.6, depth=17km
Liquefaction in Kashiwazaki city
Kashiwazaki-Kariwa nuclear power plant was slightly damaged.
Slope failure near JR Omigawa Station.
→Shinetsu line was stopped for two months.

Iwate-Miyagi Nairiku earthquake 2008



Konagai Lab., Univ. of Tokyo

M=7.2, depth=8km
Total damage = 1.4 billion dollars
Upstream slopes of Aratozawa dam was collapsed.
Debris flow run down 10km along Dozo river that killed 7 people.

Hofu mudslide (Yamaguchi pref.) 2009

http://www.mlit.go.jp/river/sabo/0907doshasaigai.html

Heavy rain (100mm/hr) during the end of a rainy season in Japan triggered a lot of debris flows some of which went down to the settlement. (death toll: 30, casualties: 43)

Unsolved issues for sediment-related disaster prevention

1) Various geo-materials (clay, sand, water contents, etc.)

2) Various disturbance (rain, earthquake, weathering, etc.)

3) Complicated dynamic behavior
   (localization, liquefaction, erosion and deposition)

4) Prediction of large deformation
   volume and travel distance of collapsed soil mass
   impact forces and resulting structural damage

5) Subsequent events and risk analyses
   landslide dams, damage to transportation, etc.

Classical limit analysis

- Mohr-Coulomb yield criterion (c, **ϕ**)

  +

- Rigid-perfectly plastic model

  +

- Equilibrium of continu

  ↓

- limit analysis

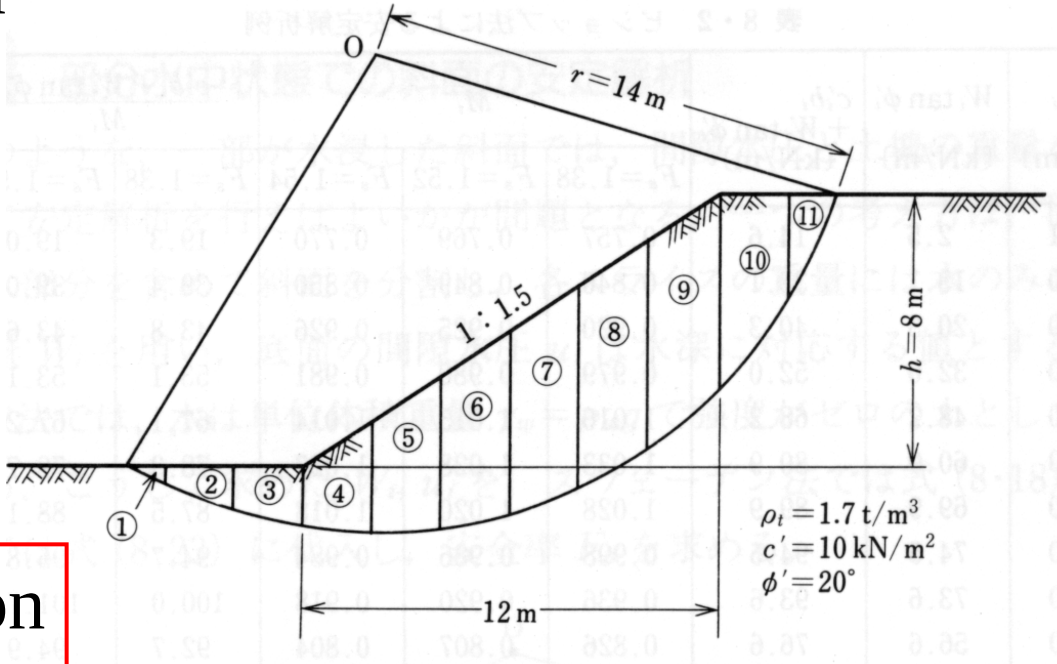


図 8・7　安全率計算の例として用いた斜面とすべり円弧

The resulting deformation cannot be discussed.

Computer simulation methods

FEM

*Well-established simulation method for continuum.

*Mesh distortion due to large deformation should be dealt with additional re-meshing process.

*Discrete materials with "meeting and parting (erosion and sedimentation)" behavior is not easy to simulate.

DEM

*Simulation method for discrete particles

*Particle interaction model in place of constitutive model.

Particle methods

*Discretization of continuum by virtual particles.

*Any types of constitutive equation can be used.

GOOD ALTERNATIVE TO FEM

Particle methods (meshless methods)

FMM (Free Mesh Method)
Automatic remeshing FEM

MORE ACCURATE

EFG (Element-free Galerkin method)
Continuum quantities are interpolated into background mesh nodal points
Simultaneous linear equations obtained from weak-form equilibrium are solved like FEM

SPH (Smoothed Particle Hydrodynamics)
Continuum quantities are solved for each particle with smoothing approximation
Equation of motion is solved for each particle like DEM

MORE APPLICABLE

2. Application of SPH into simulations of slope failure

SPH

*Developed by Lucy(1977), Gingold & Monaghan(1977)
for compressible fluid
→Applied into elasto-plastic solid (Cleary et al. 2002)

*A kind of meshless method for continuum
suitable for the large deformation analysis

*Constitutive equation is plugged in the simulation
Classical Elasto-plasticity
Micromechanics-based model
etc.

*Explicit time-marching scheme
(like DEM, MD)

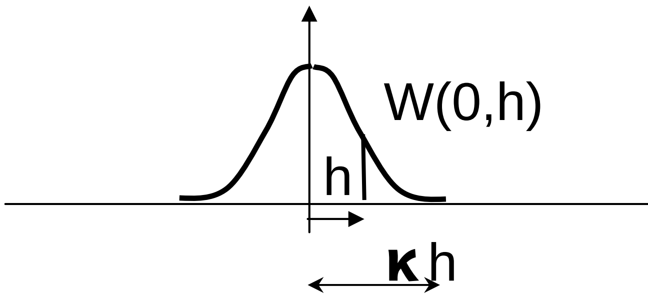
Kernel approximation

Using the following identity

$$f(\boldsymbol{x}) = \int_\Omega f(\boldsymbol{x}')\delta(\boldsymbol{x}-\boldsymbol{x}')d\boldsymbol{x}'$$

$$\delta(\boldsymbol{x}-\boldsymbol{x}') = \begin{cases} 1 & (\boldsymbol{x}=\boldsymbol{x}') \\ 0 & (\boldsymbol{x}\neq\boldsymbol{x}') \end{cases}$$

$$W = 0 \ at \ |\mathbf{x}-\mathbf{x}'| > \kappa h$$



δ is replaced by smooth (weighted) function W

$$f(\boldsymbol{x}) \cong \int_\Omega f(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}',h)d\boldsymbol{x}' \equiv \langle f(\boldsymbol{x}) \rangle$$

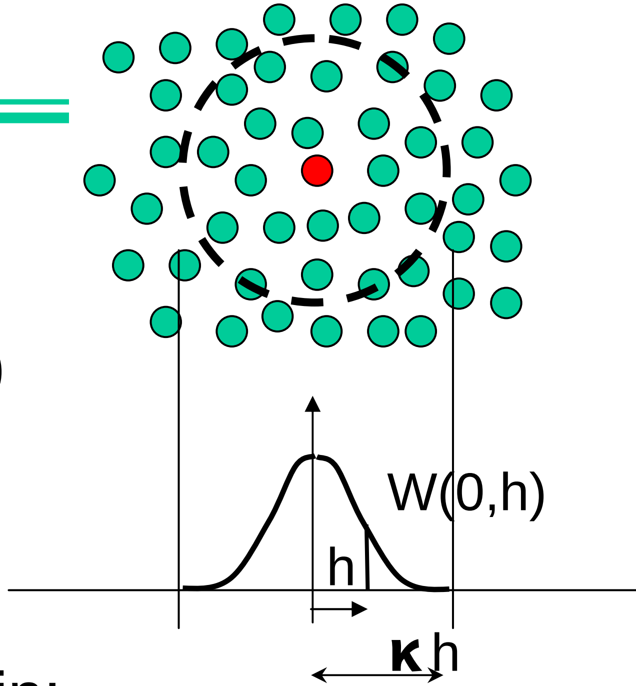
$$\int_\Omega W(\boldsymbol{x}-\boldsymbol{x}',h)d\boldsymbol{x}' = 1$$

Taylor expansion gives the information on accuracy

$$\langle f(\mathbf{x}) \rangle = f(\mathbf{x}) + O((\kappa h)^2)$$

$\kappa h: effective\ length$

Particle approximation



- Each material point (SPH particle) keeps the continuum quantities (stress, strain, density, internal variables)

Integral → summation on f(x) in the domain:

$$f(\boldsymbol{x}) \cong \int_{\Omega} f(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}',h)d\boldsymbol{x}' \equiv \langle f(\boldsymbol{x}) \rangle \Rightarrow \langle f(\boldsymbol{x}^i) \rangle = \sum_{j=1}^{N} \frac{m^j}{\rho^j} f(\boldsymbol{x}^j) W^{ij}$$

its derivative:

$$\left\langle \frac{\partial f(\mathbf{x})}{\partial x_\alpha} \right\rangle = -\int_{\Omega} f(\mathbf{x}') \frac{\partial W(\mathbf{x}-\mathbf{x}',h)}{\partial x_\alpha} d\mathbf{x}' \approx -\sum_{j=1}^{N} \frac{m^j}{\rho^j} f(\mathbf{x}^j) \frac{\mathbf{x}^i - \mathbf{x}^j}{r} \frac{\partial W^{ij}}{\partial r}$$

Time marching scheme

at a time *t*

1. Calculate density

$$\rho_0{}^i = \sum_{j=1}^{N} m^j W^{ij}$$

2. Calculate deformation rate

$$D^i_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{N}\left(\frac{m^j}{\rho^j} v^j_\alpha \frac{\partial W^{ij}}{\partial x_\beta} + \frac{m^j}{\rho^j} v^j_\beta \frac{\partial W^{ij}}{\partial x_\alpha}\right)$$

3. Calculate stress rate from C.E.

$$\dot{\sigma}^i_{\alpha\beta} = C_{\alpha\beta\gamma\delta} D_{\gamma\delta}$$

4. Calculate Interparticle force

$$f^i_\alpha = \frac{1}{\rho^i}\sum_{j=1}^{N}\frac{m^j}{\rho^j}\sigma^j_{\beta\alpha}\frac{\partial W^{ij}}{\partial x_\beta}$$

5. Solve equation of motion for each particle

$$\frac{\partial v^i_\alpha}{\partial t} = f^i_\alpha + g_\alpha$$

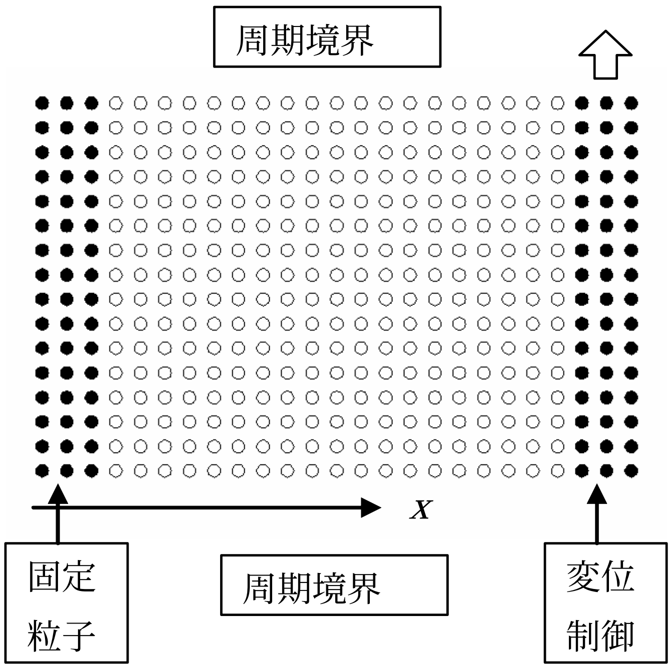
→Latest position

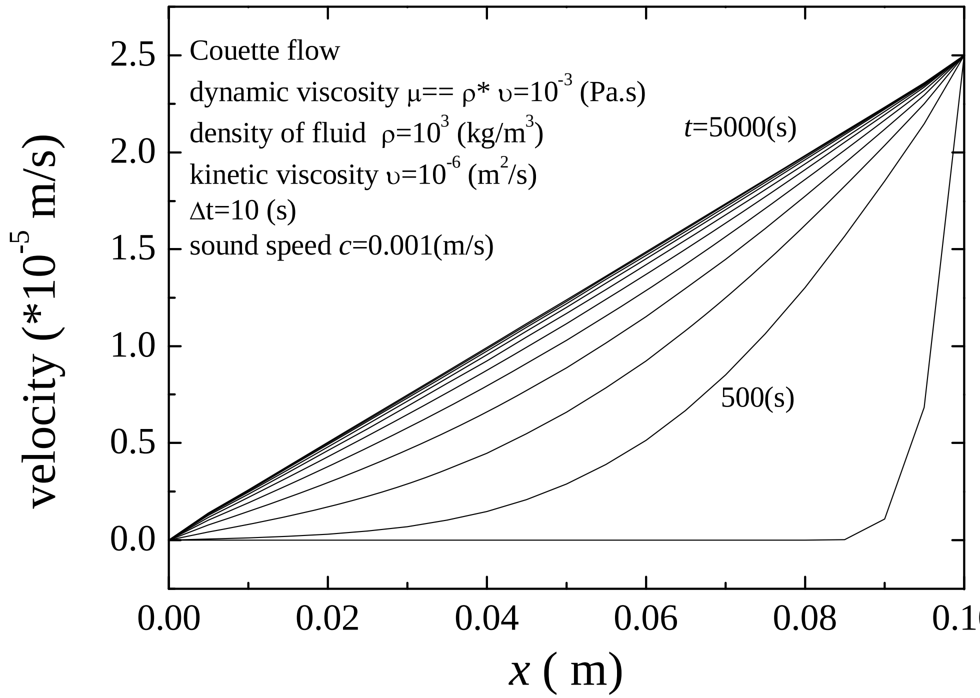
Next time step

the higher-order deformation mode (particle fluctuation) is included.

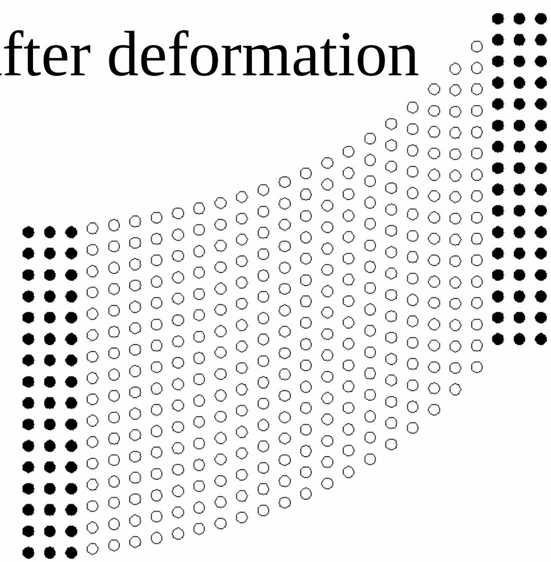
18

Numerical verification: simple shear of viscous fluid





After deformation



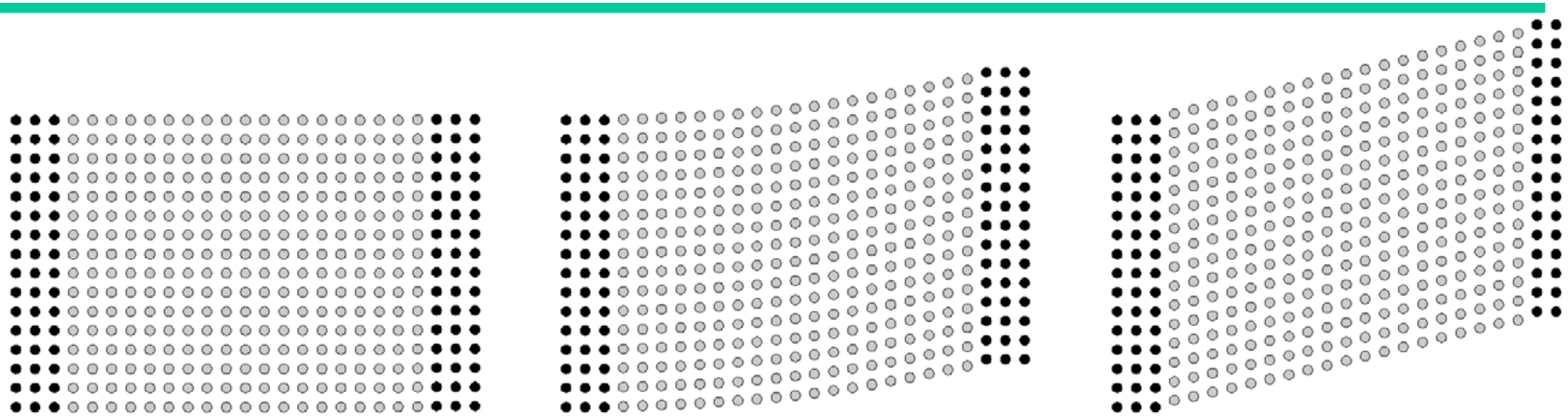
specimen width =10cm

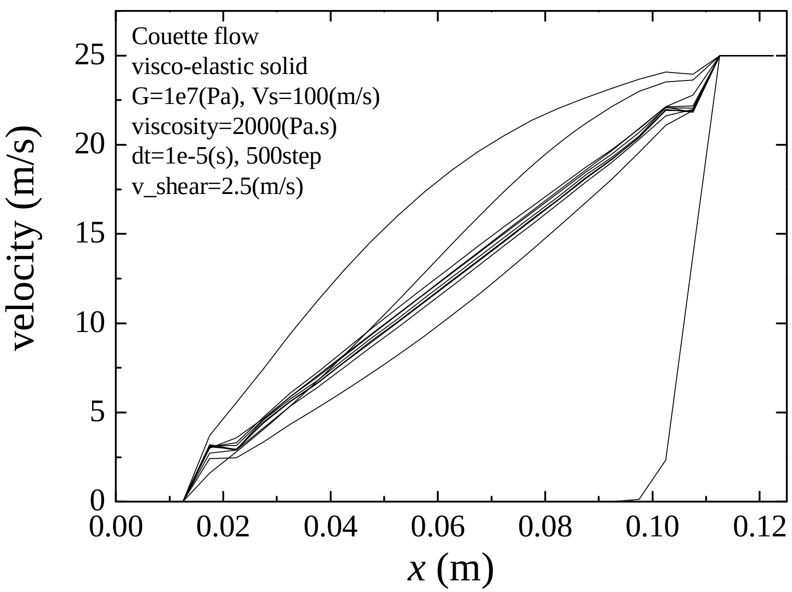
Viscosity of water is assumed.

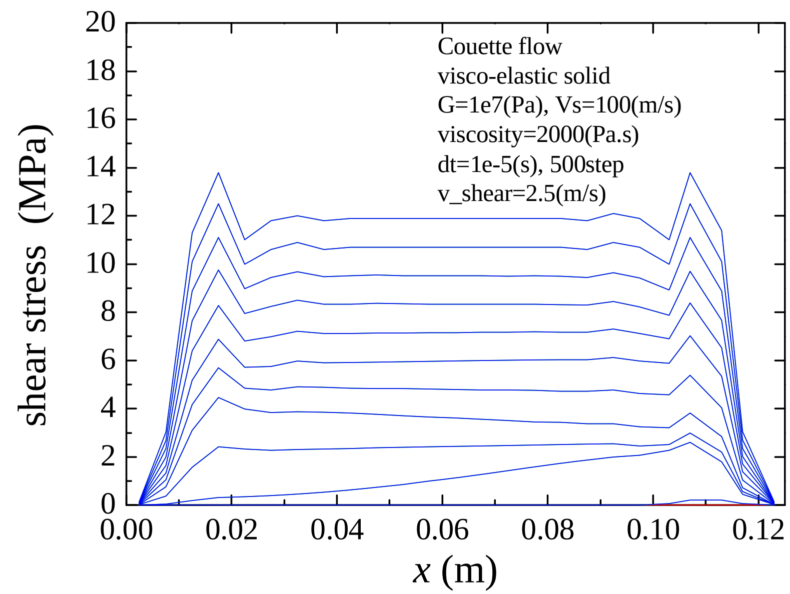
(ν_f=10^{-3}(Pa.s))

Good agreement with analytical solution.

Simple shear of visco-elastic solid



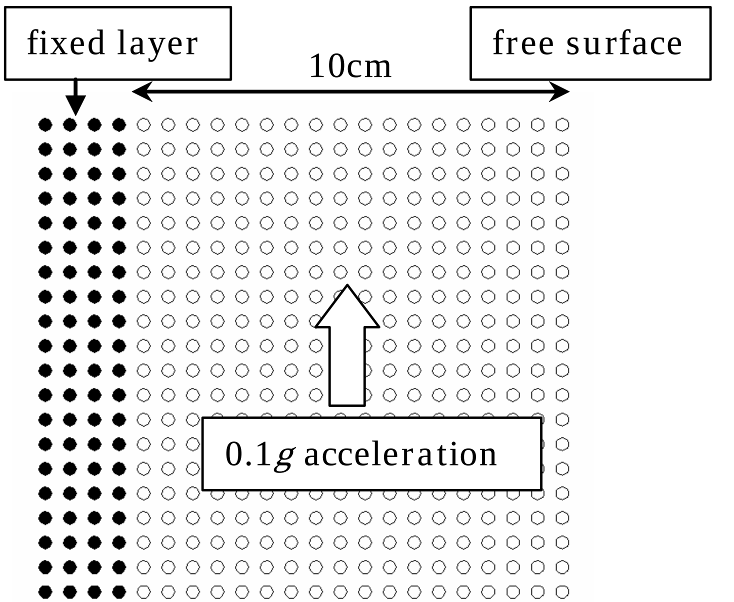




G=10(MPa), Vs=100(m/s), Poisson ratio=0.25, ν_f =2000(Pa.s)

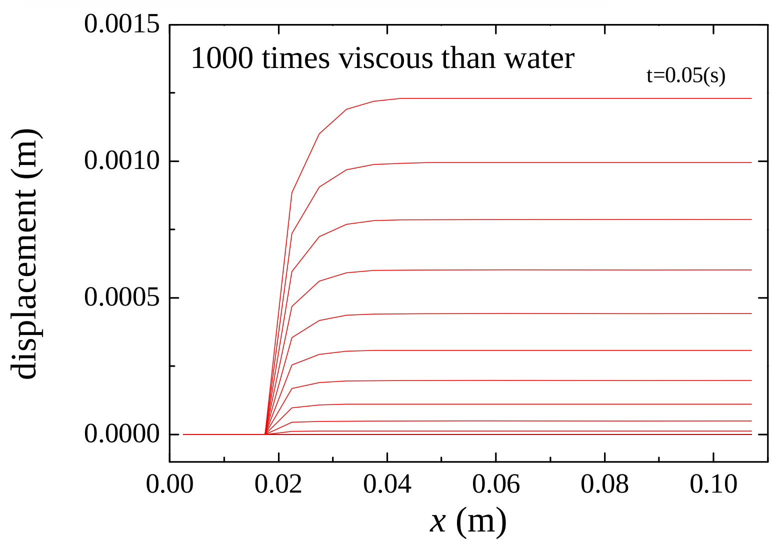
Good result except for boundary layers

Flow of 1D slope

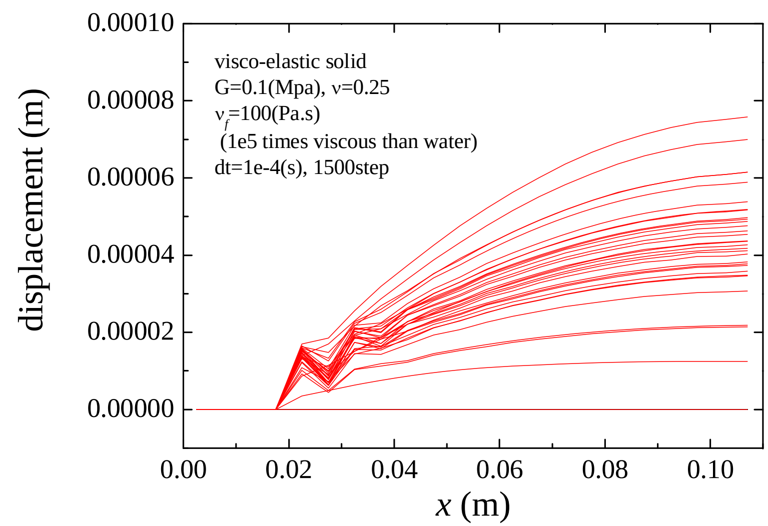


Bundary layer thickness is affected by effective length

Damped oscillation in visco-elastic solid is well simulated.



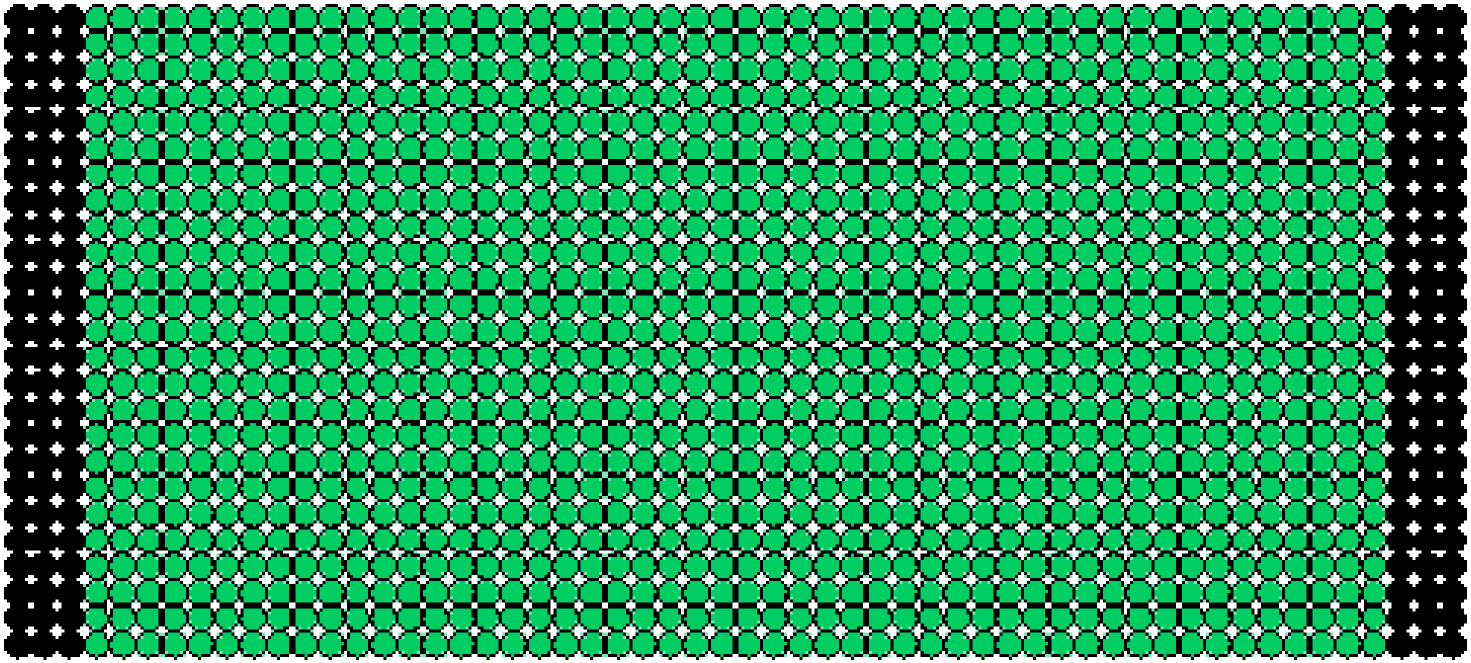
viscous fluid (ν_f=100(Pa.s))



visco-elastic solid (ν_f=100(Pa.s))

Particle fluctuation

Biaxial compression test: elastic material, no damping



Particle fluctuation leads to the computational degradation.

Particle velocity correction

Interparticle forces in SPH is more like those in liquid molecule
(The constraint from the close neighbors is not strong)

To avoid this particle fluctuation,
particle velocity field is “smoothed” in the SPH sense.
(Monaghan, 1994)

$$v(\boldsymbol{x}^i)^{corrected} = v(\boldsymbol{x}^i) - \varepsilon\left[v(\boldsymbol{x}^i) - \left\langle v(\boldsymbol{x}^i)\right\rangle\right] = v(\boldsymbol{x}^i) - \varepsilon\sum_{j=1}^{N}\frac{m^j}{\rho^j}(v(\boldsymbol{x}^i) - v(\boldsymbol{x}^j))W^{ij}$$

Smoothed velocity field

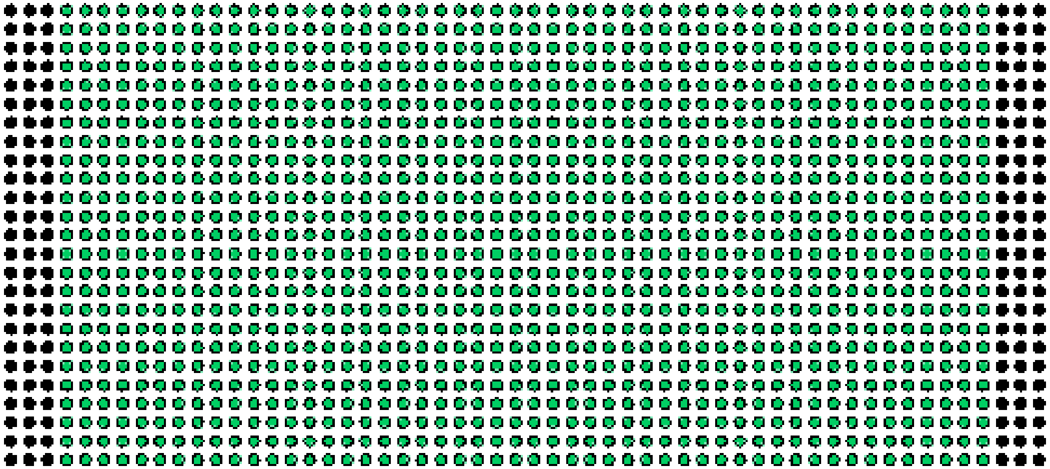
How to determine the parameter ε ?

homogeneous failure: $\varepsilon = 1 \Rightarrow v^{corrected}(\mathbf{x}^i) = \left\langle v(\mathbf{x}^i)\right\rangle$

23

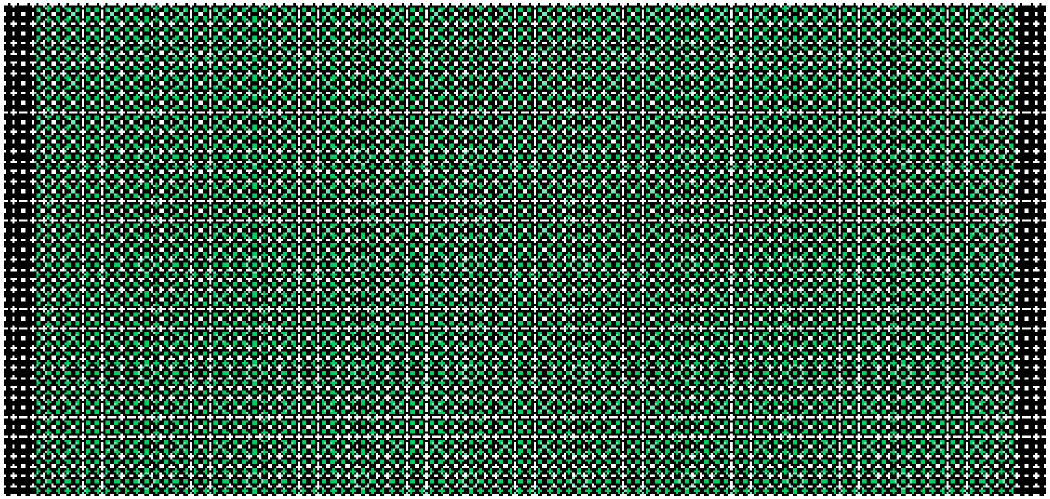
Slope surface failure: we have to tune ε

Biaxial compression with
*Mises yield criterion
*associate flow rule
*no hardening



50by25

particle in blue
is in plastic regime

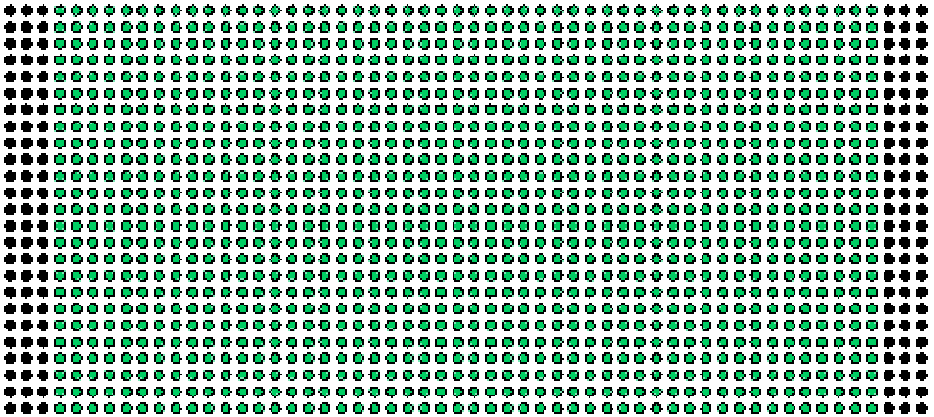


100by50

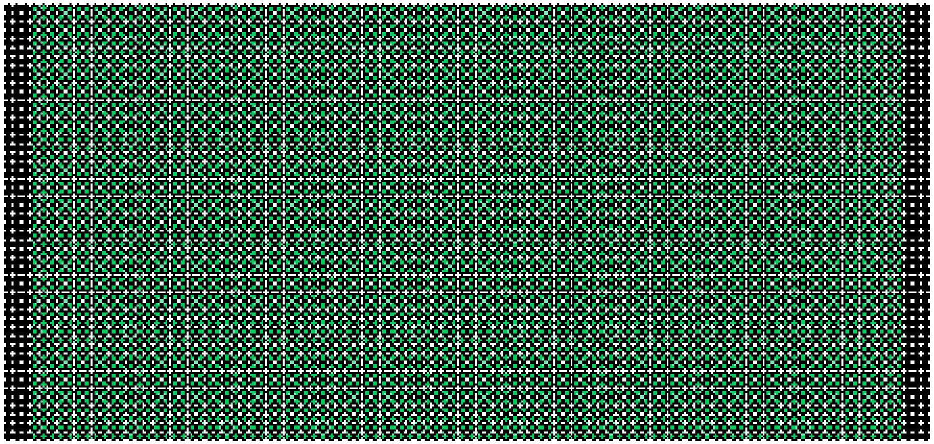
Shear band thickness depends on the effective length

24

with
Drucker-Prager
criterion
(Φ=25(deg.))



50by25

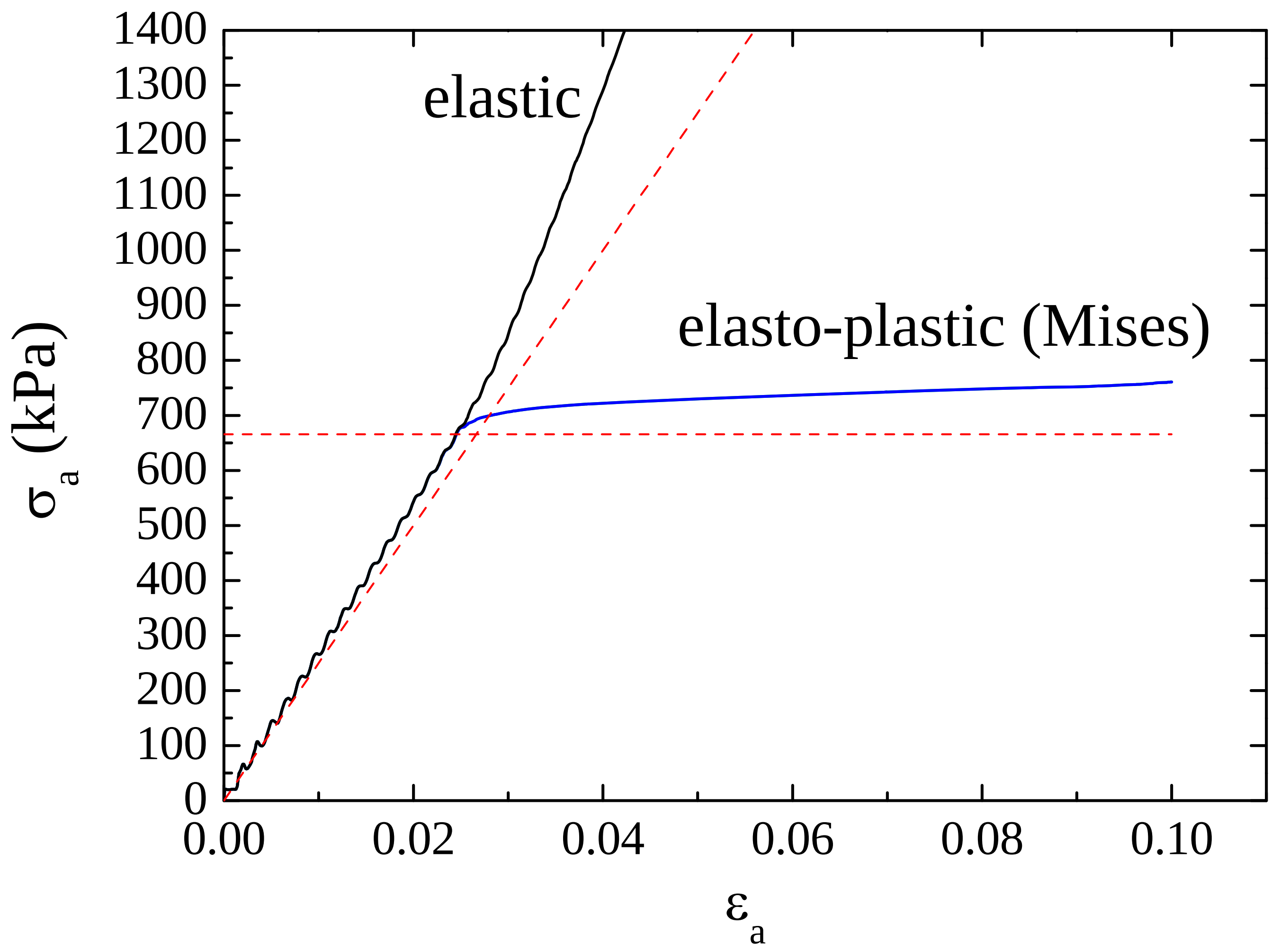


100by50

shear band inclination: $$\alpha = \frac{\pi}{4} + \frac{\phi}{2}$$

25

Overall stress-strain relationship

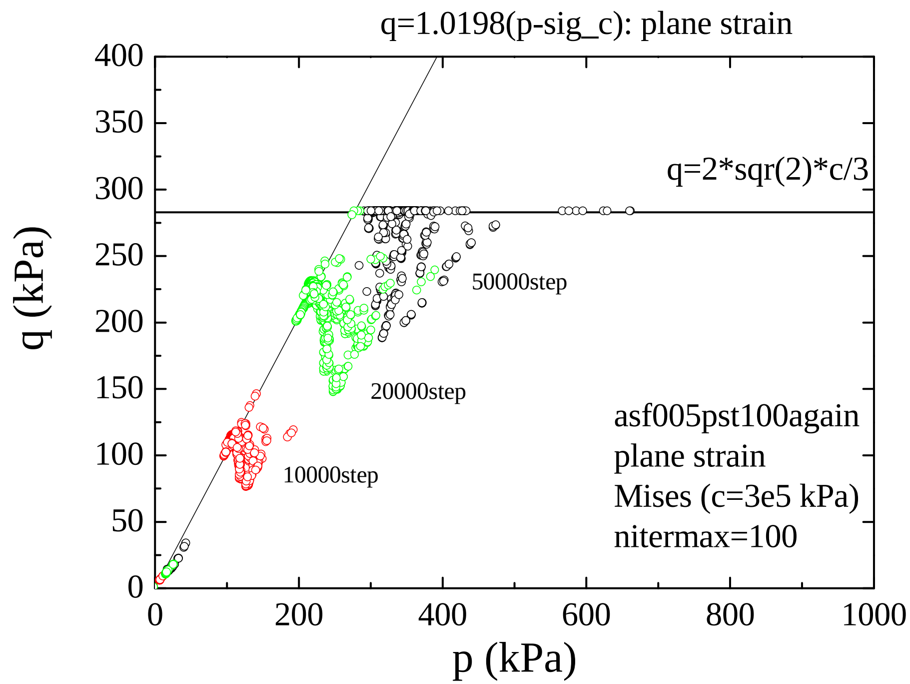


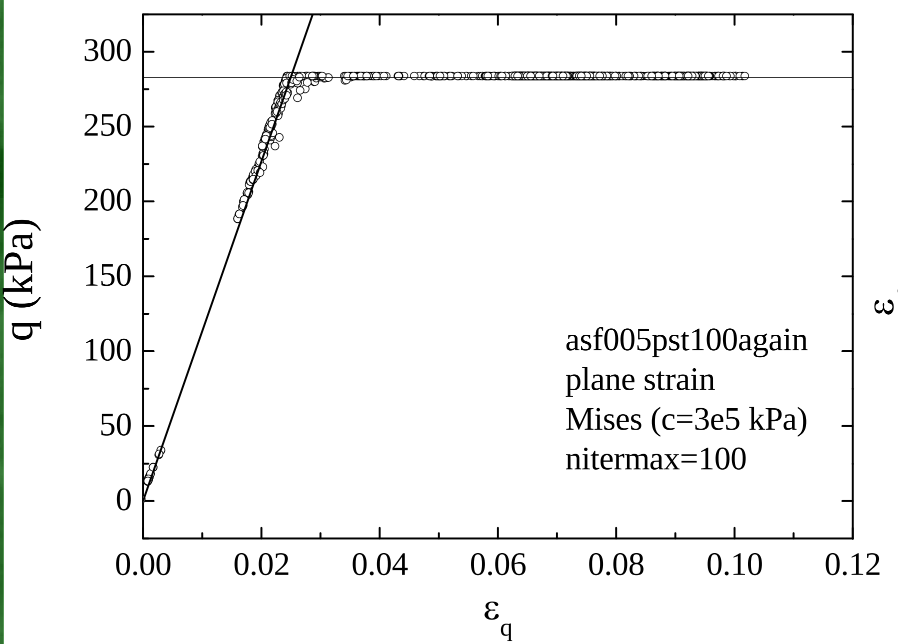
26

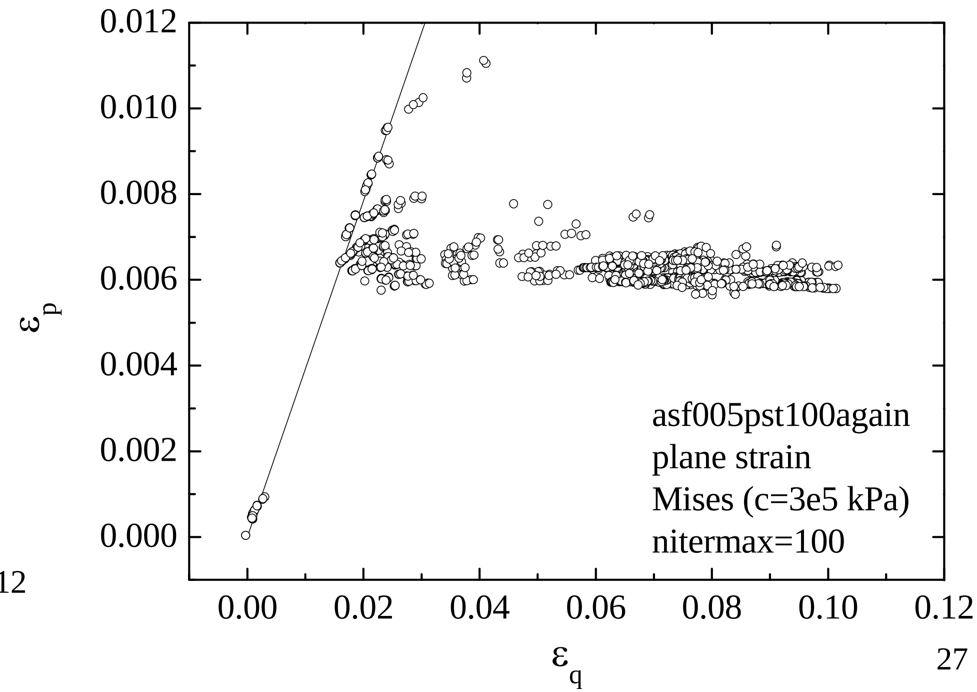
particle-wise behavior (with Mises criterion)

*Classical return mapping algorithm is adopted.

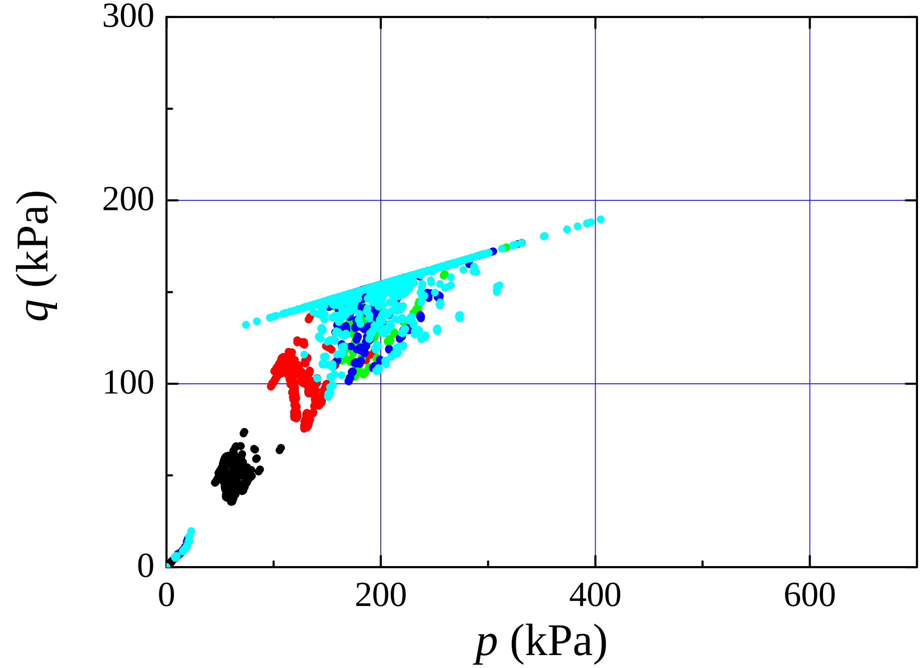
*Particles close to boundary are in a different stress condition

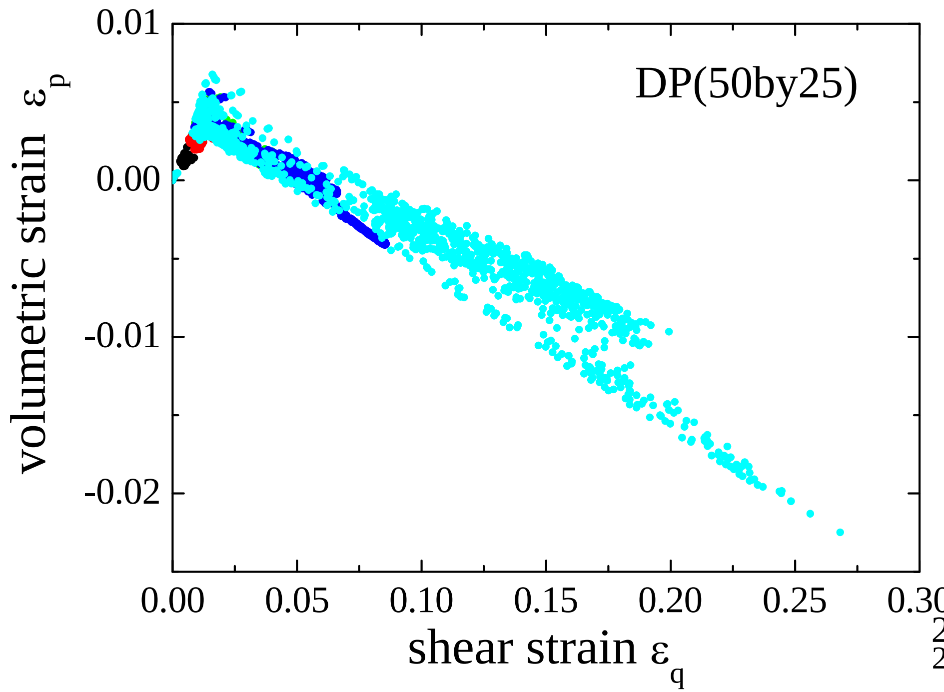






particle-wise stress path (with DP criterion)



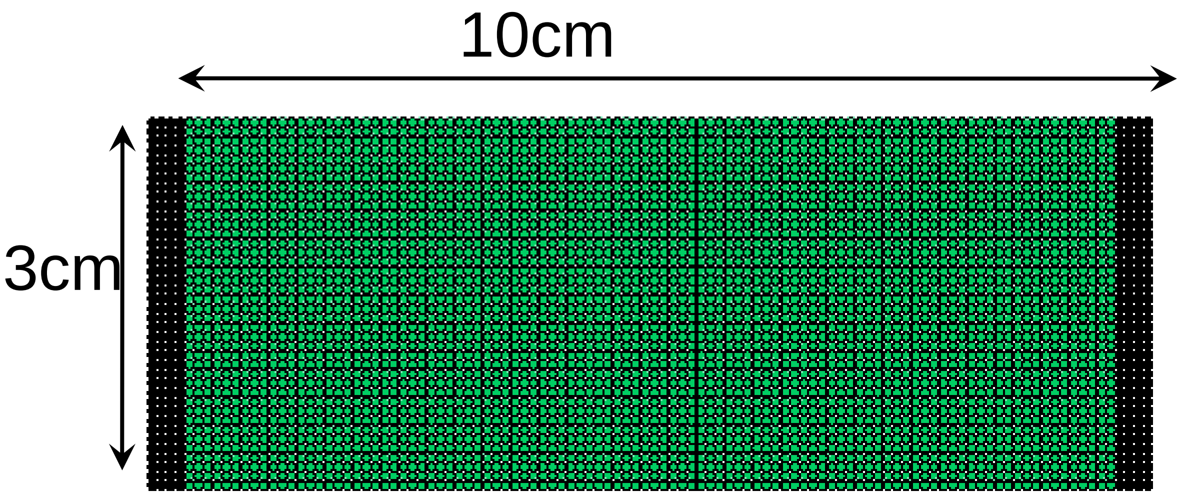


Noticeable dilation

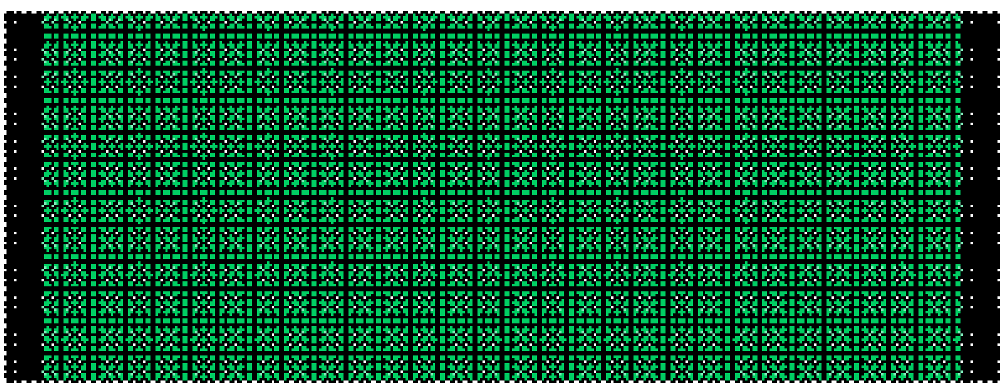
No residual state

28

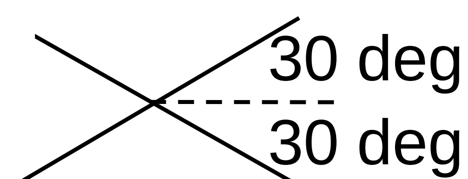
Numerical tests (2) Biaxial tension



Mises
elasto-plastic
no hardening

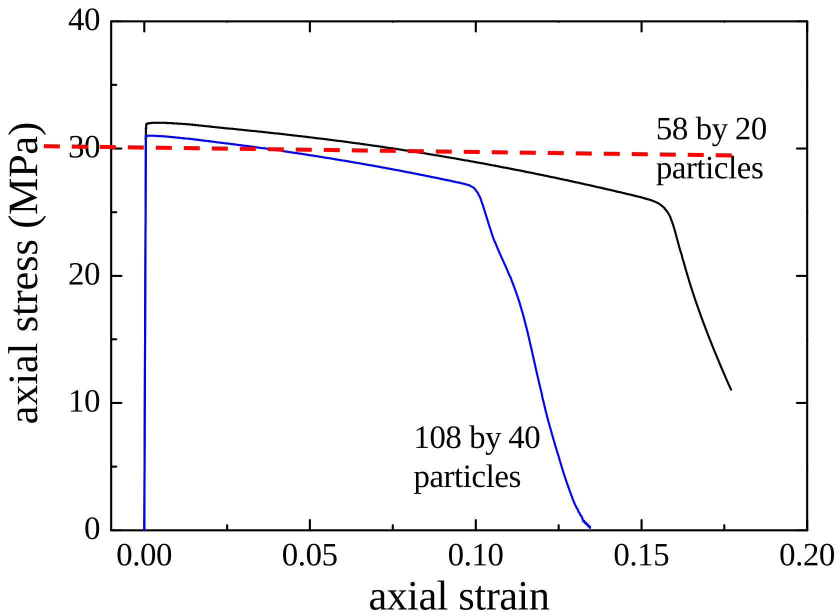


Asaro’s
2D
double slip
model
no hardening

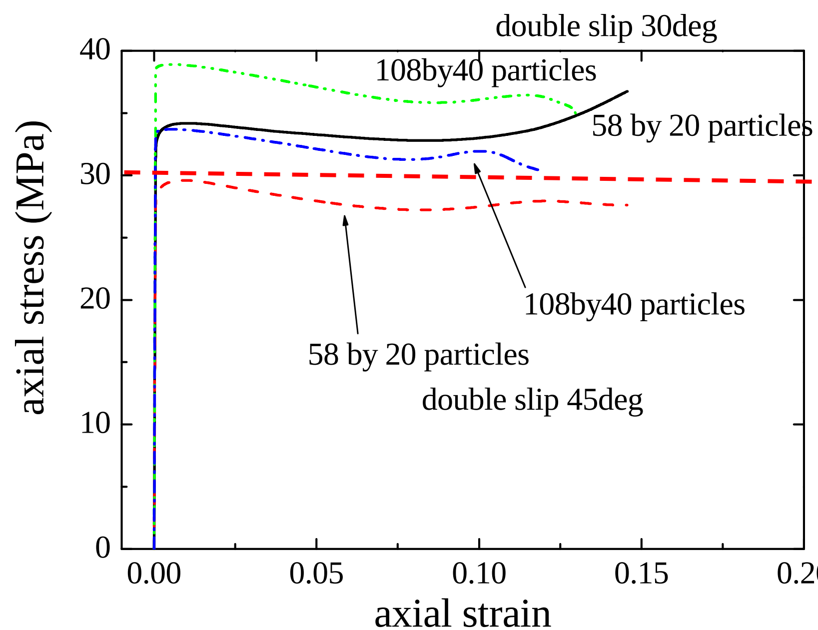


Overall stress-strain

Mises elasto-plastic

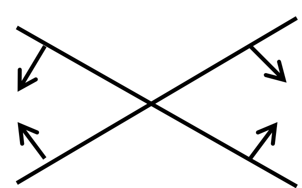


2D double slip model



softening due to the enlargement of particle spacing →final separation

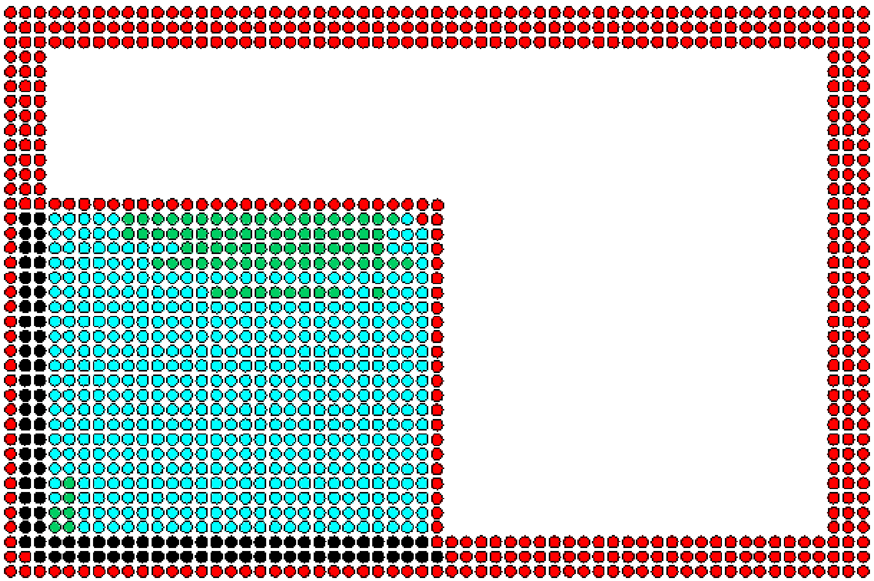
hardening due to the rotation of slip plane



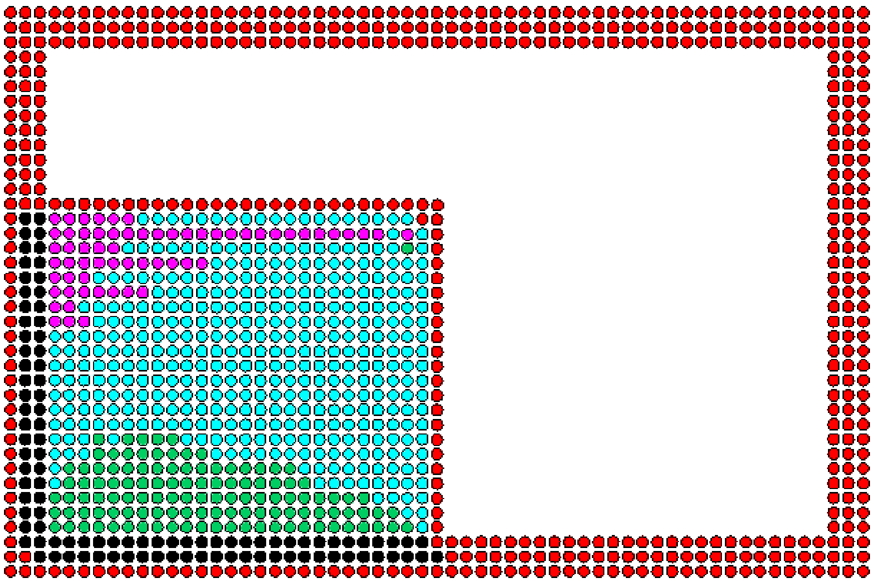
Numerical example (3): dam-break

ε=0.1

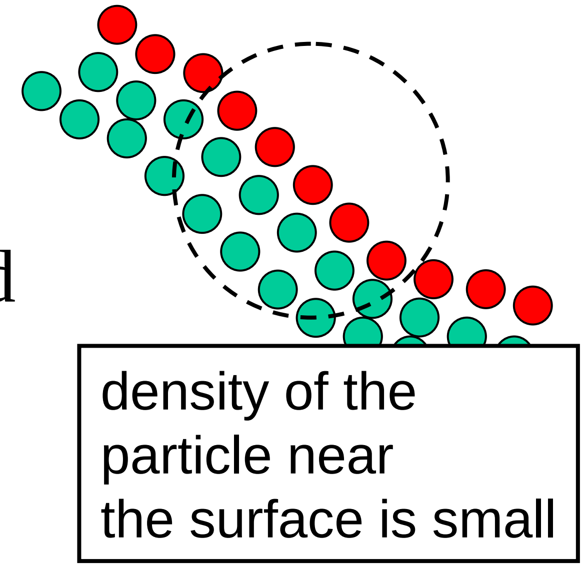
Mises type



D-P type(Φ=40deg.)

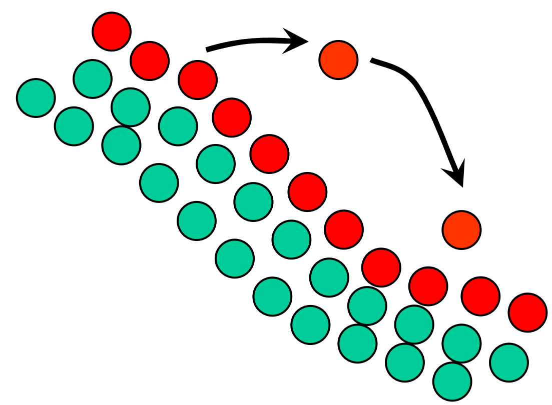


Treatment of particle “meeting and parting”



Simple treatment:
Stress in SPH particle vanishes when the density is below the threshold

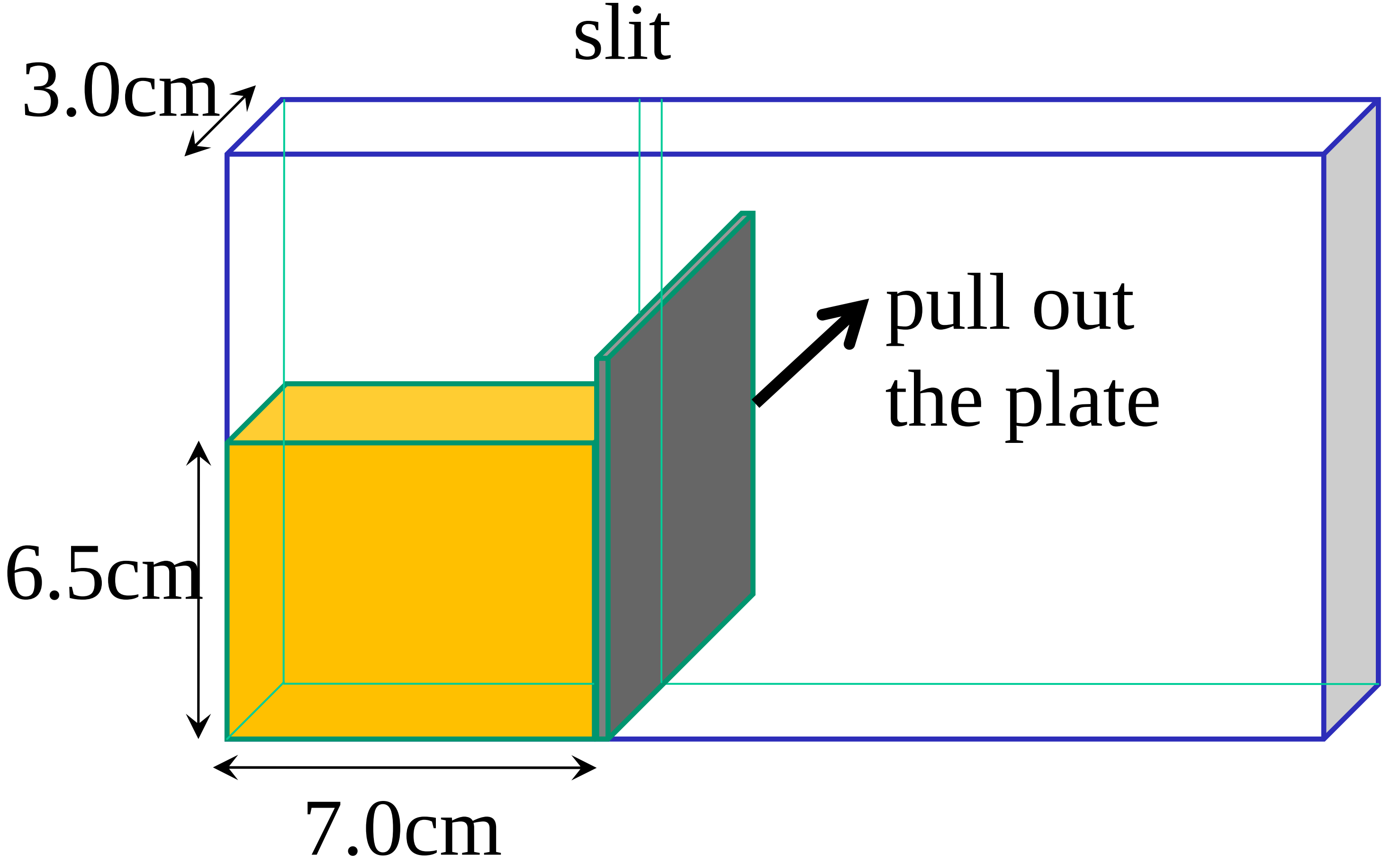
Note:
Interparticle force acting on the particle does not vanish
(because it is computed from the stress of the neighboring particles)



Solitary particles move only by gravity.
If they join to others, they become a part of continuum again.

32

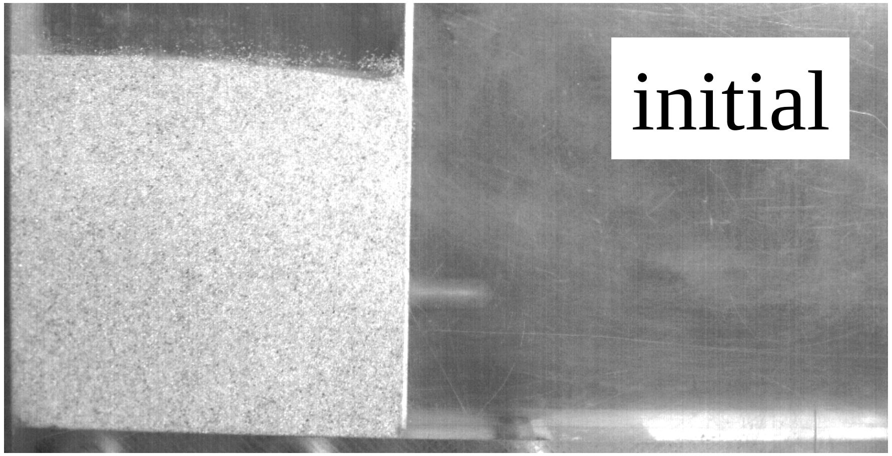
Experimental validation

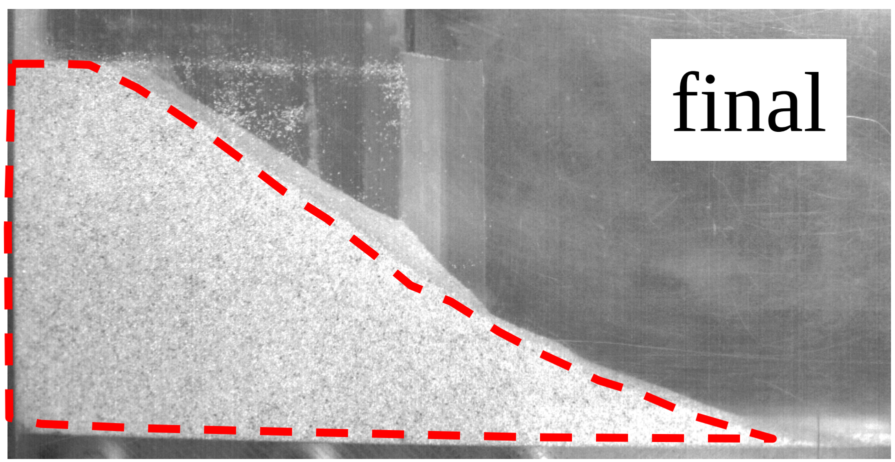


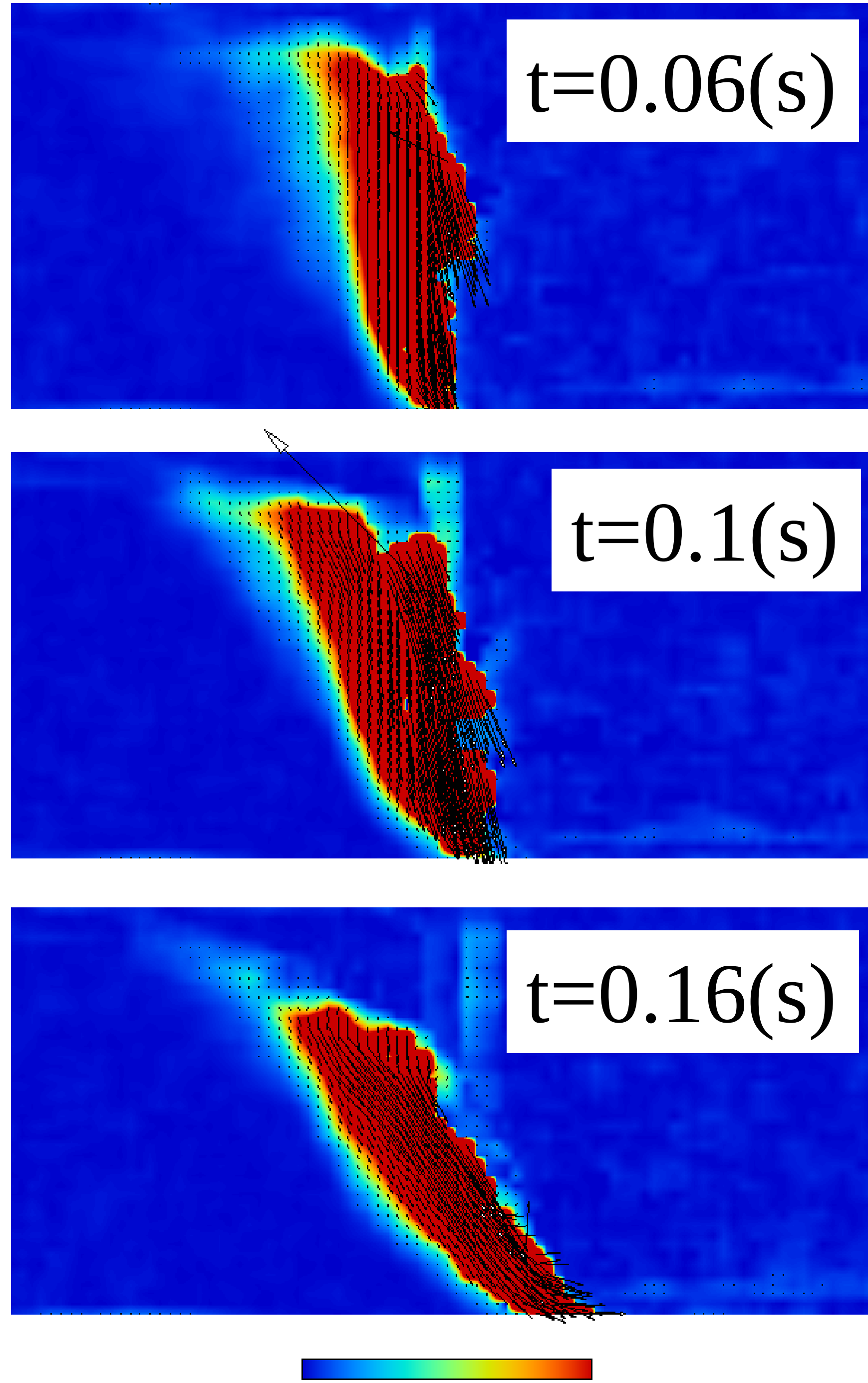
dry Toyoura sand, loose packing(e=0.92)

33

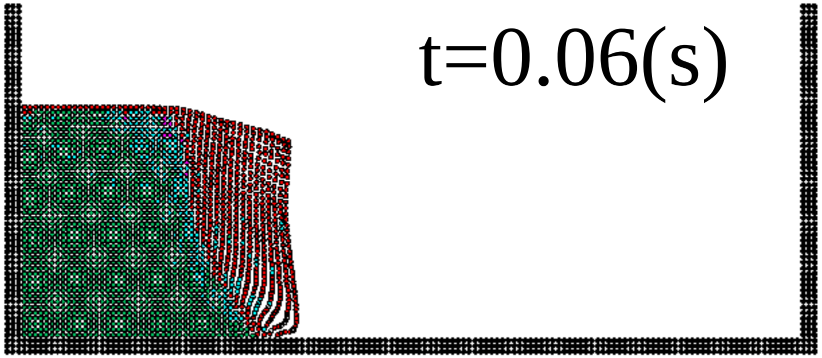
loose(e=0.92)

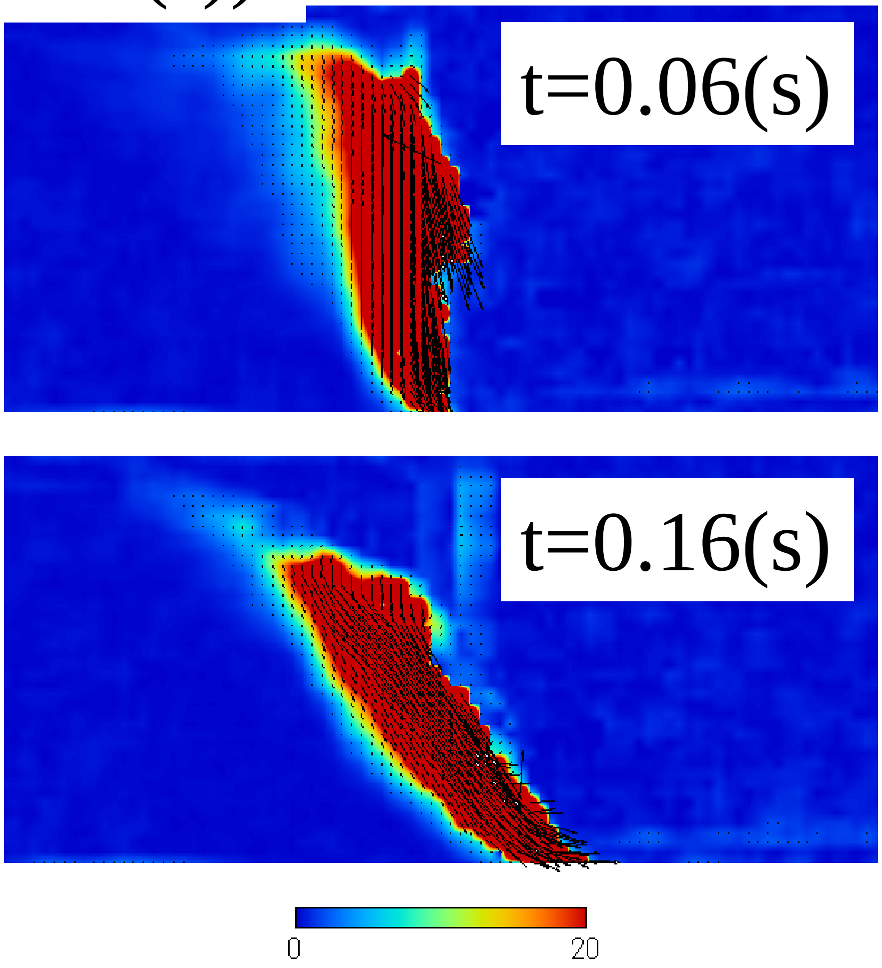


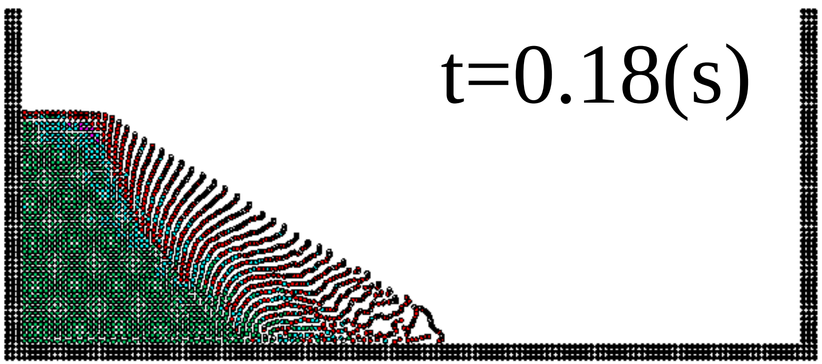


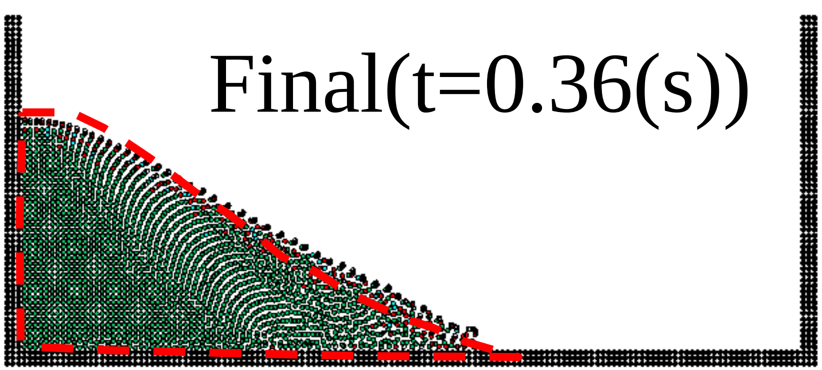


SPH: D-P model (Final(t=0.36(s))





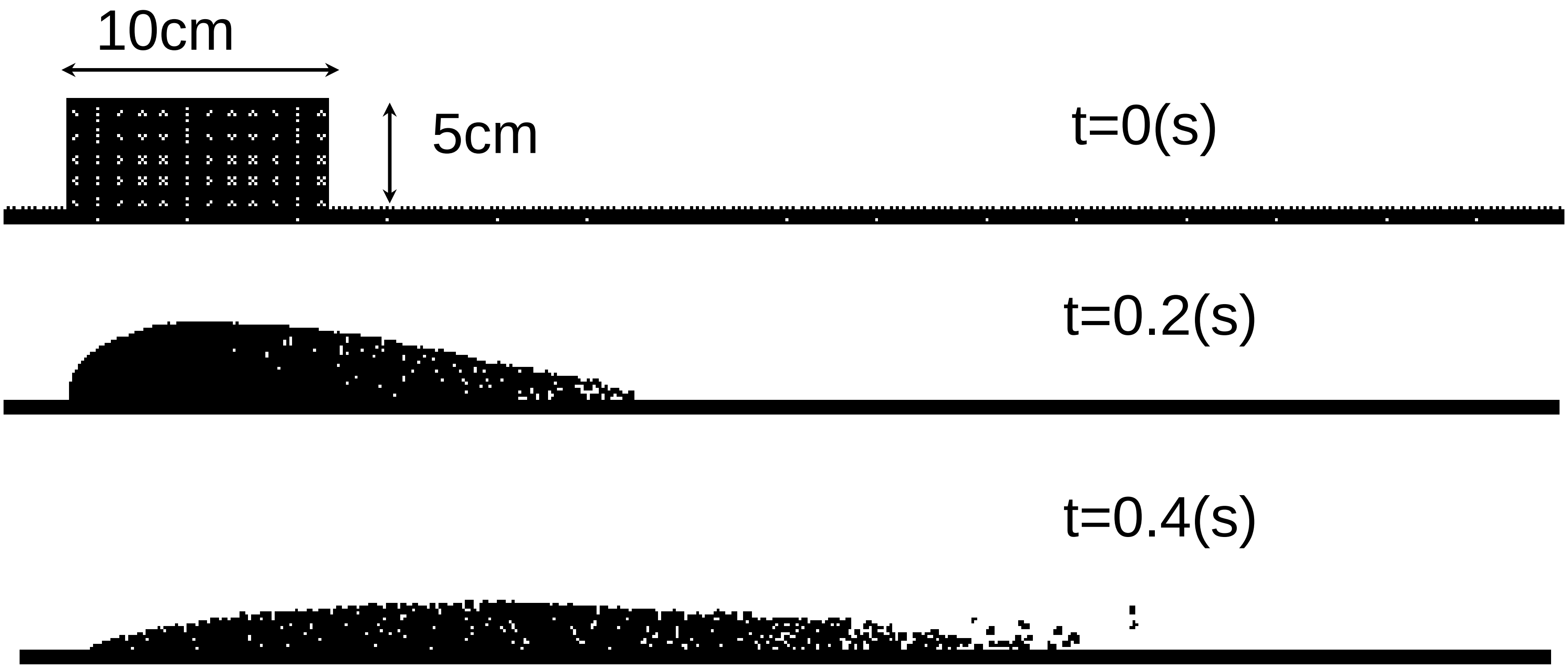




$\phi = 35°,\ c = 0,\ \varepsilon = 0.1$

35

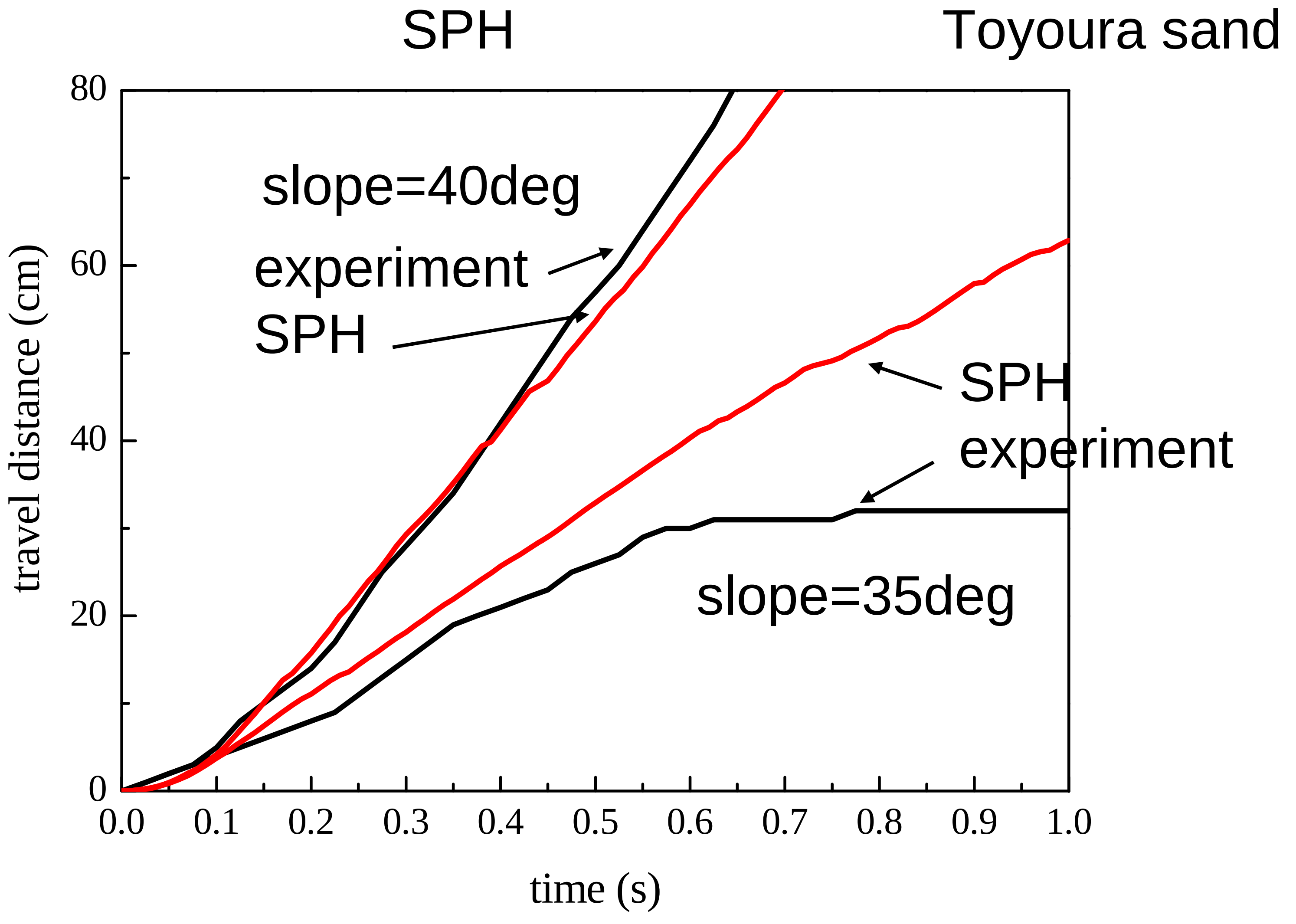
validation(2) Dry granular flow



inclination of slope=40deg.

ϕ=35(deg.), ε=0.1

validation(2) Dry granular flow



Comparison with limit analysis

FELLENIUS METHOD

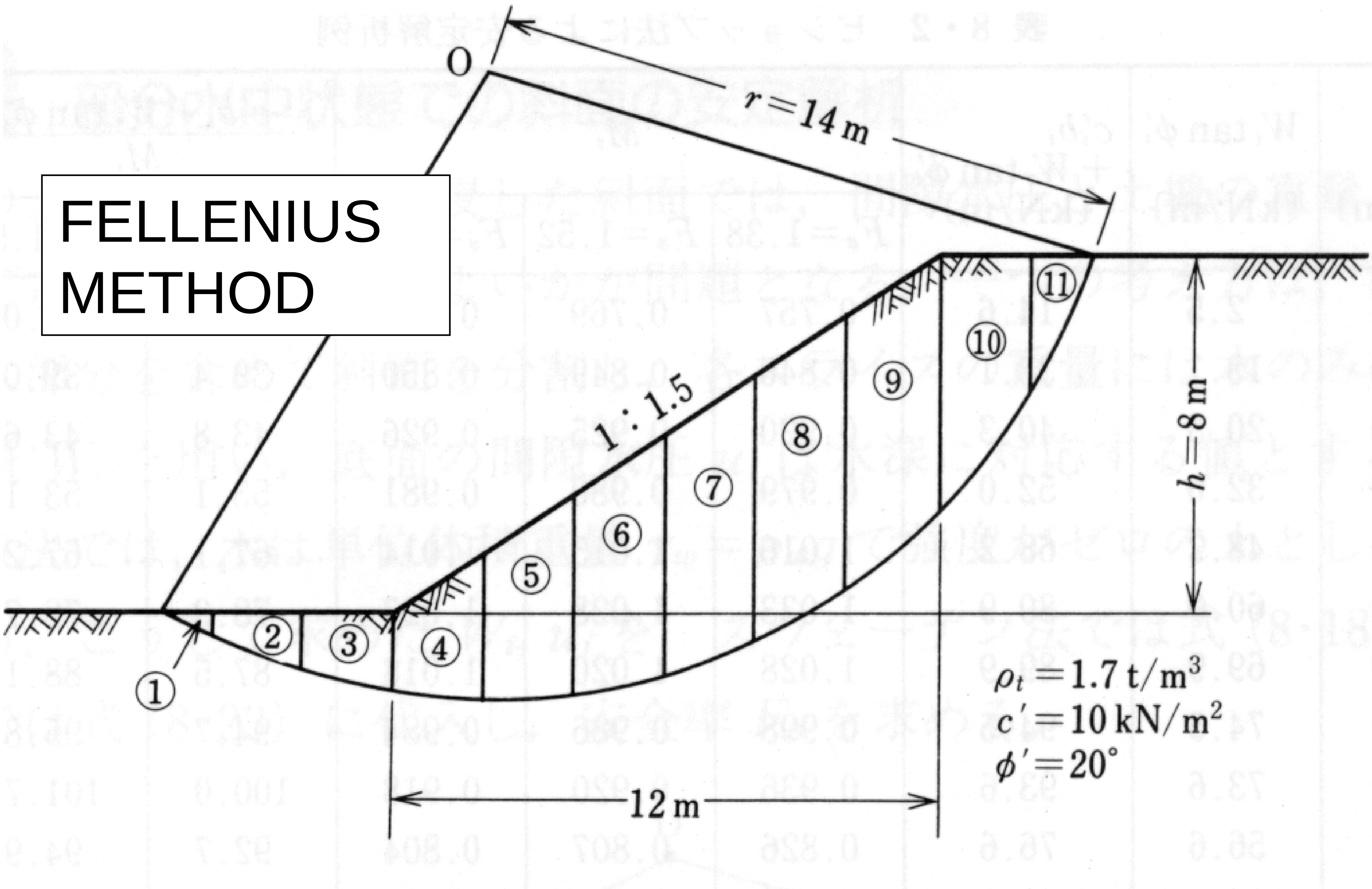
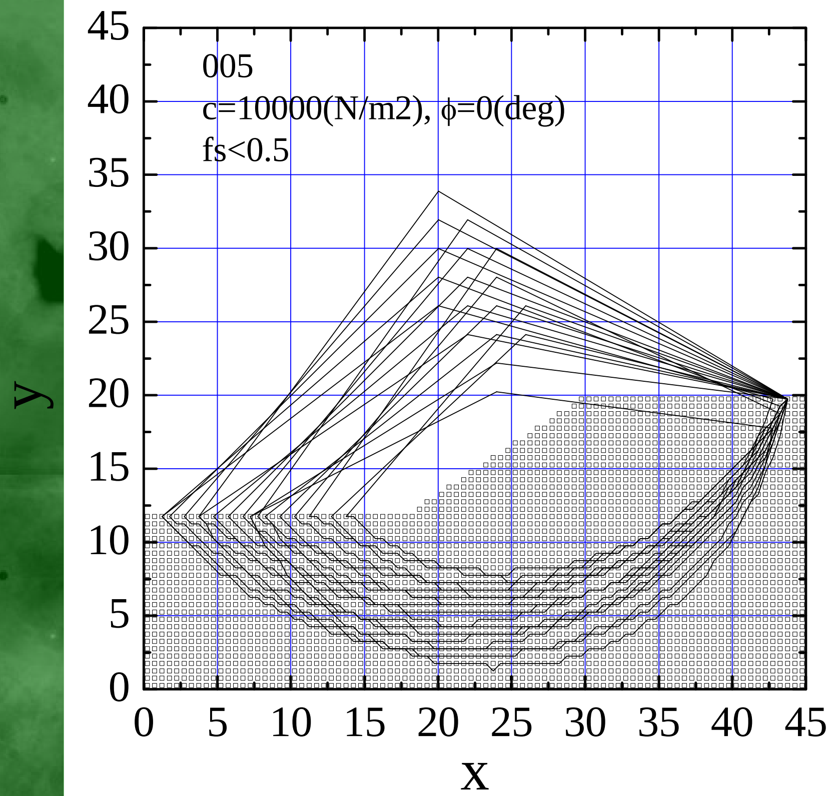


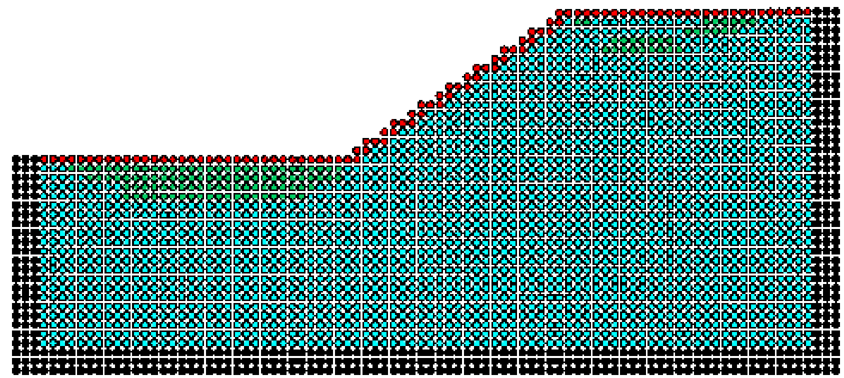
図 8・7　安全率計算の例として用いた斜面とすべり円弧

38

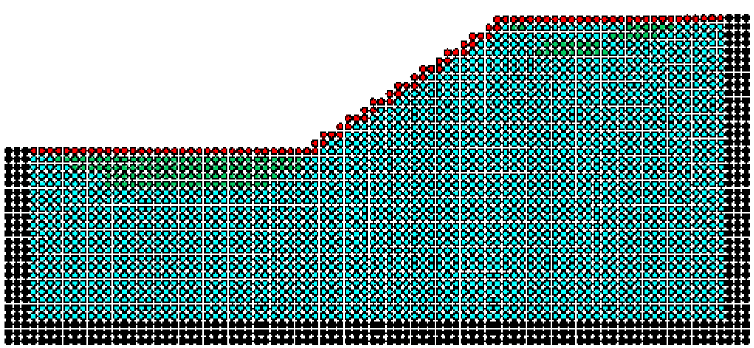
Mises type： Φ=0(deg)



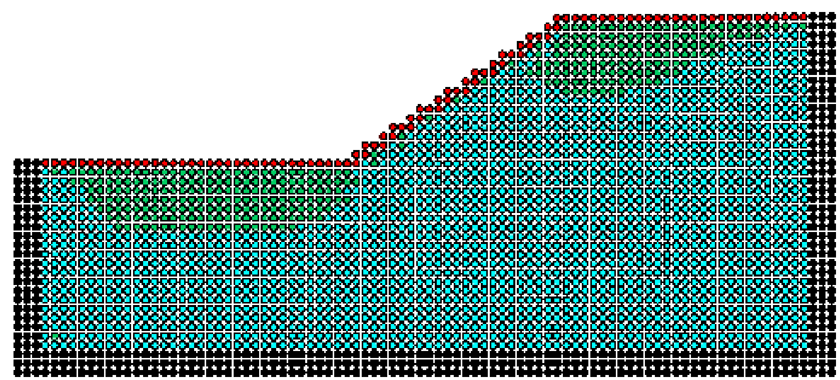
$$c = 10(kPa),\ \varepsilon_{xsph} = 0.01$$



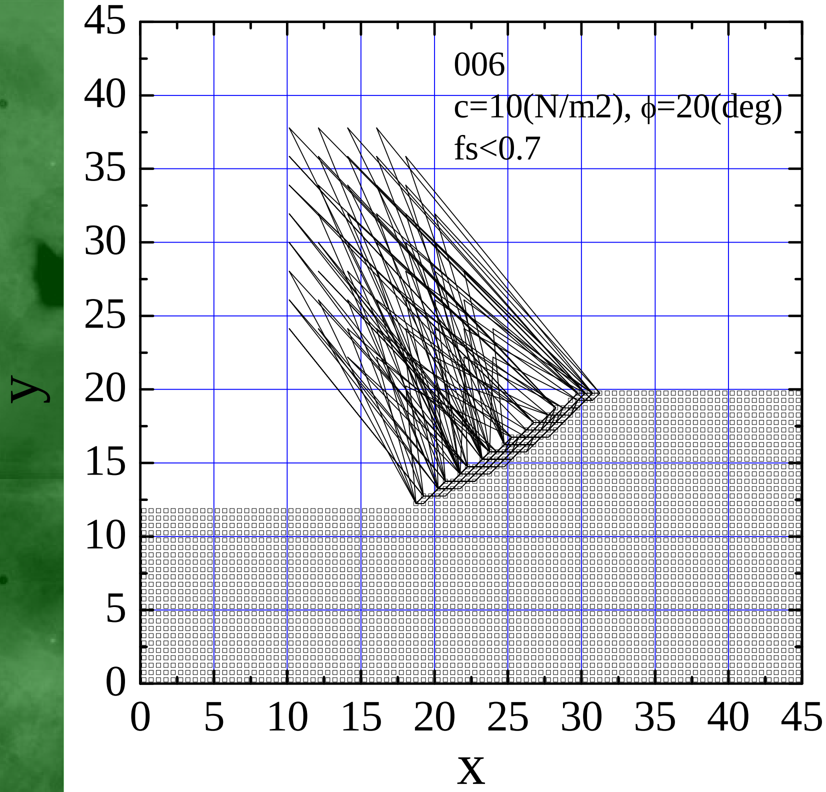
$$c = 10(kPa),\ \varepsilon_{xsph} = 0$$



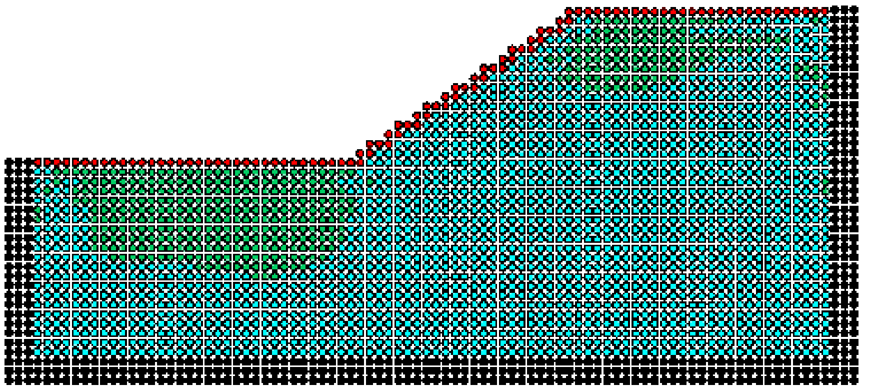
$$c = 20(kPa),\ \varepsilon_{xsph} = 0$$



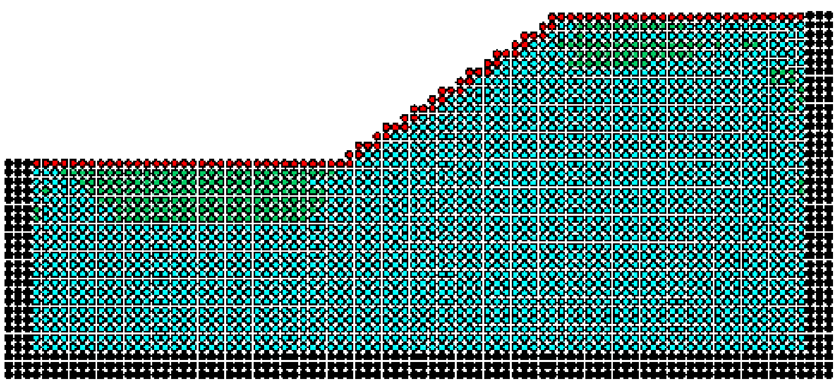
DP type：c　0, Φ=15-25(deg.)



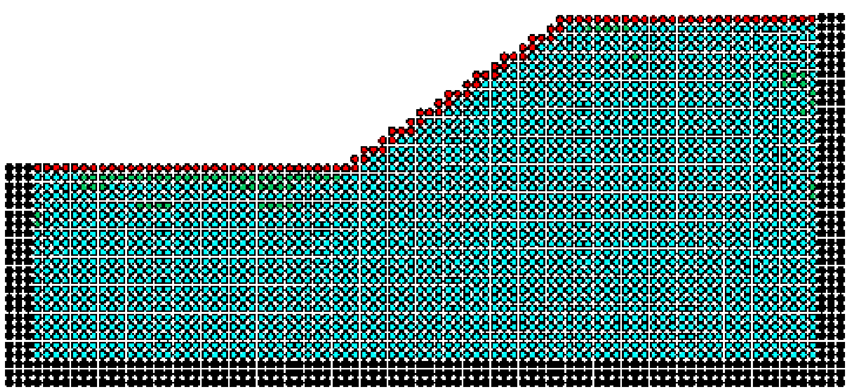
$\phi = 25(\text{deg}),\ \varepsilon_{xsph} = 0$



$\phi = 20(\text{deg}),\ \varepsilon_{xsph} = 0$



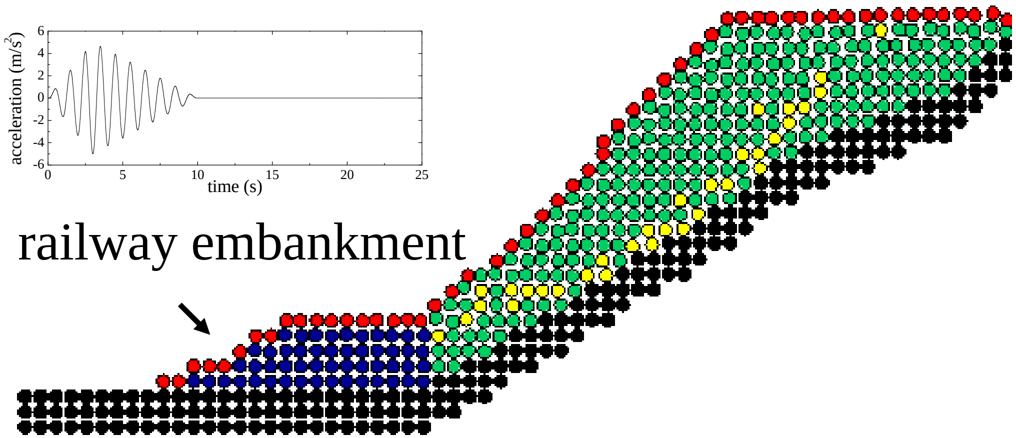
$\phi = 15(\text{deg}),\ \varepsilon_{xsph} = 0$



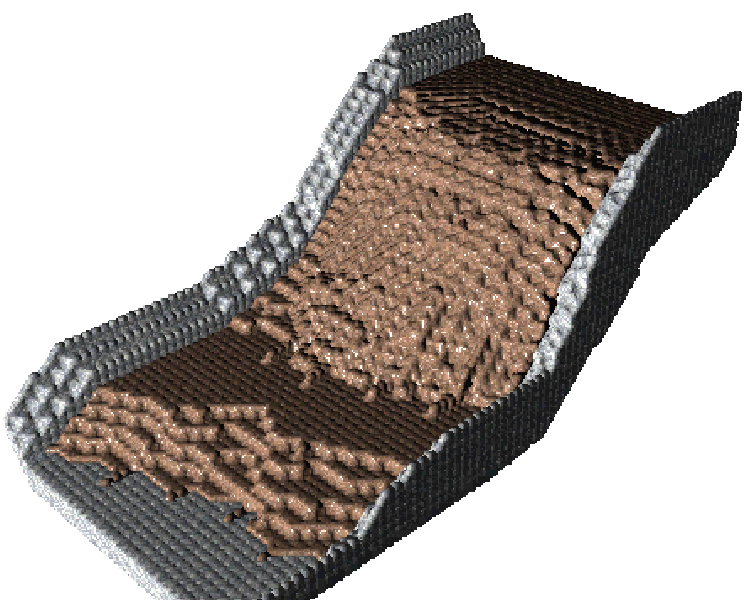
Application to actual slope failure

Offshore Chuetsu earthquake(2007)

1Hz a_{max}=500(gal), c=40(kPa), ϕ=10(deg.)



railway embankment



The railway embankment downstream was collapsed possibly due to the impact of the slid soil mass.

The large deformation analysis is essential to the stability of the downstream structure.

Points to keep in mind in slope failure simulation

Flow speed is affected by the particle velocity correction factor ε in slope failure, because the surface movement takes the lead in slope failure.

However, if ε is set to 0, the particles are fluctuated so much that the impact force cannot be evaluated correctly.

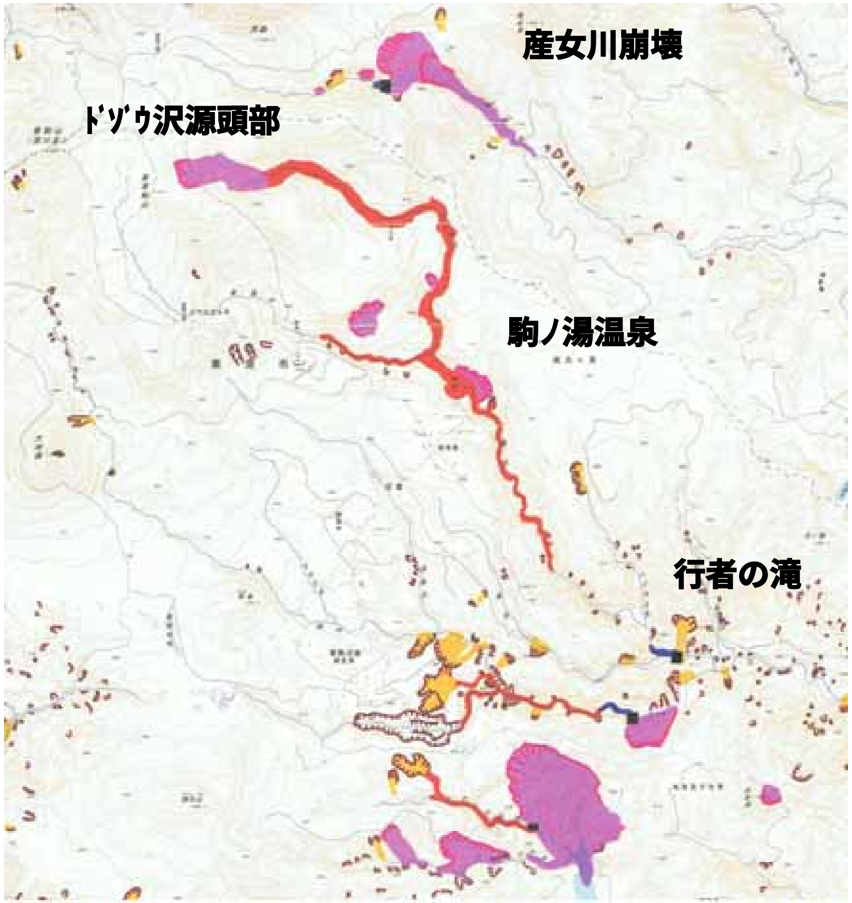
Therefore, simulation with ε=0 should be done at first,

and then increase ε within the range that it does not affect the overall flow velocity too much.

3. A simplified particle method for the simulation of debris flow

Debris flow: long travel distance

Iwate-Miyagi earthquake (2008)
Debris flow travels down 4.8km
during 10 min. (30km/hr)



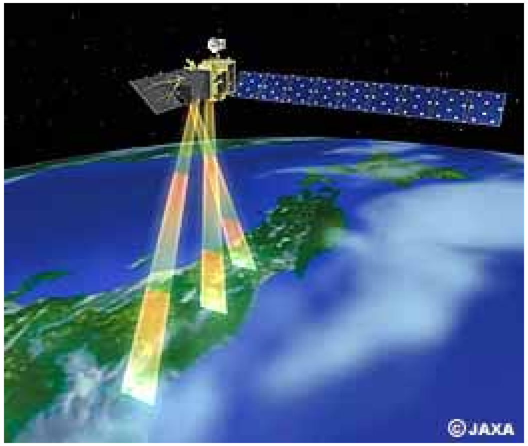
PWRI

SPH cannot deal with such behavior because of computational limitation.

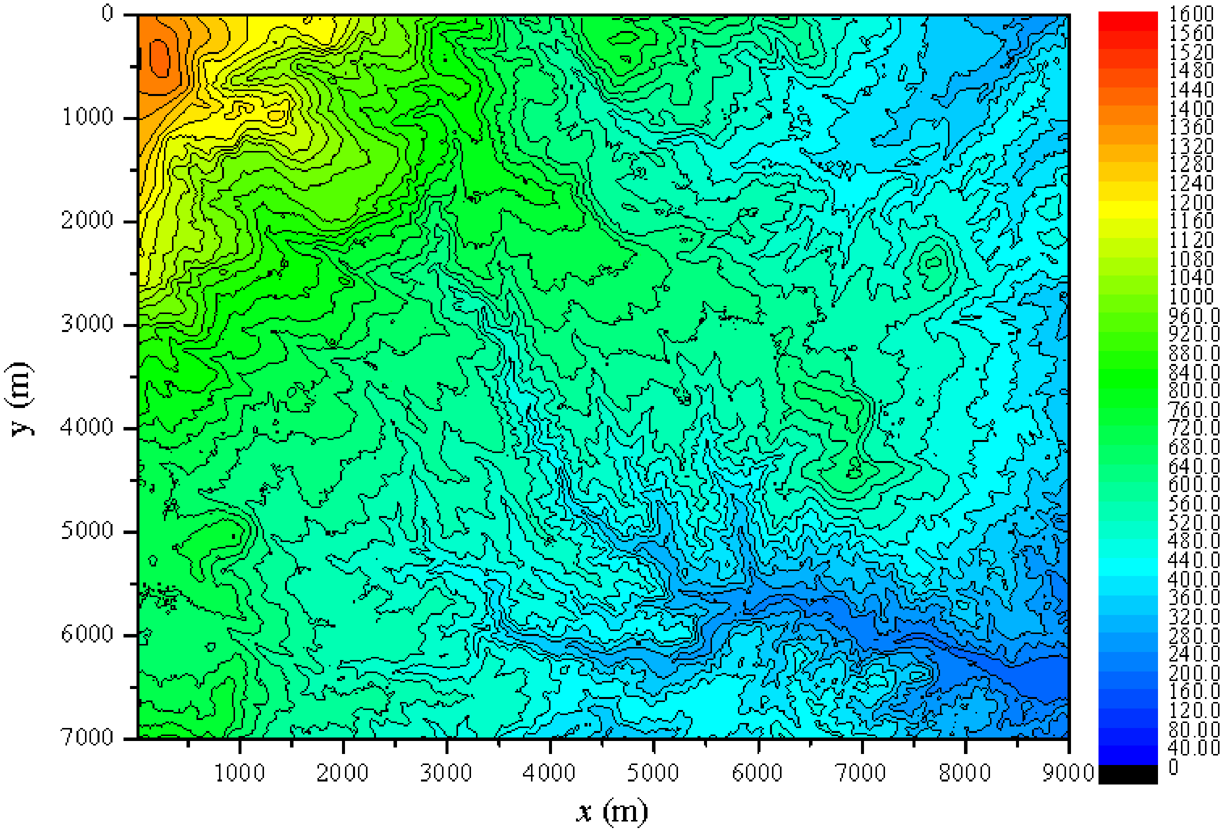
⇒ a simplified method is proposed.

Geographical information from satellite “ALOS”

Stereographical images obtained from PRISM sensor in “ALOS(Daichi)” enables to construct DSM with 2.5m mesh.



PRISM sensor



Formulation of the proposed model

■2D shallow water equation

$$\frac{\partial h\bar{v}_x}{\partial t}+\frac{\partial h\bar{v}_x^{\,2}}{\partial x}+\frac{\partial h\bar{v}_x\bar{v}_y}{\partial y}=-g\frac{\partial}{\partial x}(h_0+h)-\frac{(\tau_b)_x}{\rho}$$

$$\frac{\partial h\bar{v}_y}{\partial t}+\frac{\partial h\bar{v}_y^{\,2}}{\partial x}+\frac{\partial h\bar{v}_x\bar{v}_y}{\partial y}=-g\frac{\partial}{\partial x}(h_0+h)-\frac{(\tau_b)_y}{\rho}$$

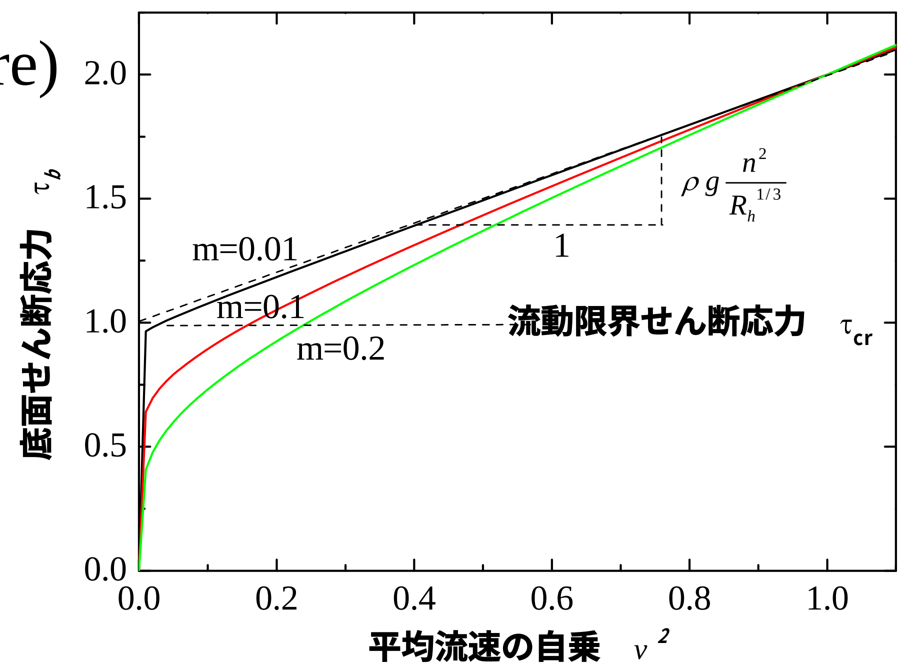
■Shear stress acting on the bottom (Modified Manning rule suitable for the flow of soil-water mixture)

$$\boldsymbol{\tau}_b=\left(\tau_{cr}\|\boldsymbol{v}\|^m+\rho g\frac{n^2}{R_h^{\,1/3}}\|\boldsymbol{v}\|^2\right)\frac{\boldsymbol{v}}{\|\boldsymbol{v}\|}$$

$$\tau_{cr}=\rho g R_h i_{cr}$$

i_{cr} critical slope gradient

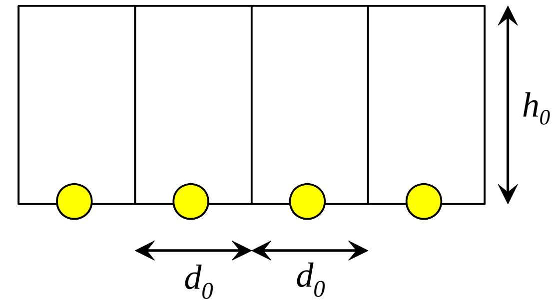
n Manning's coefficient

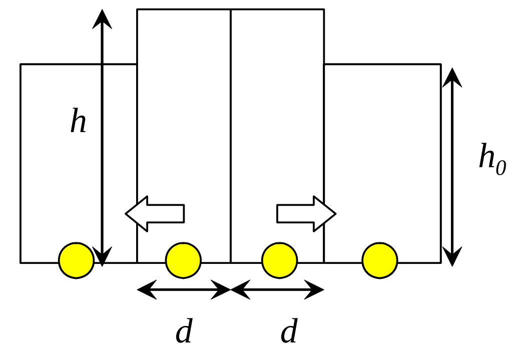


Formulation (cont.)

■pressure due to the soil-water mixture head is modeled with inter-particle force

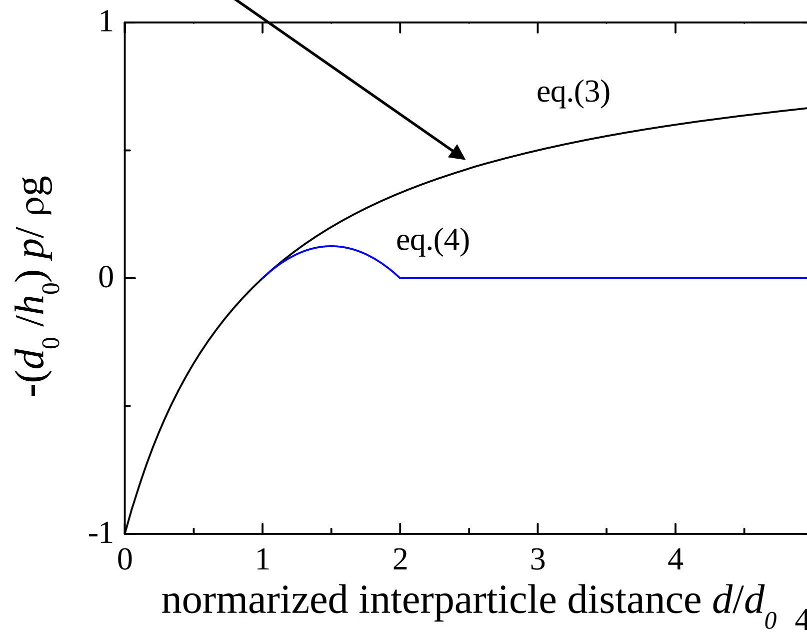
$$\boldsymbol{p} = \rho g \nabla h = \rho g \frac{h_0}{d_0} \left(\frac{1 - \|\boldsymbol{d}\| / d_0}{1 + \|\boldsymbol{d}\| / d_0} \right) \frac{\boldsymbol{d}}{\|\boldsymbol{d}\|}$$





The model is modified to consider the effective length.

$$\boldsymbol{p} = \begin{cases} \rho g \frac{h_0}{d_0} \left(\frac{1 - \|\boldsymbol{d}\| / d_0}{1 + \|\boldsymbol{d}\| / d_0} \right) \frac{\boldsymbol{d}}{\|\boldsymbol{d}\|} & (\|\boldsymbol{d}\| < d_0) \\ -\frac{1}{2} \rho g \frac{h_0}{d_0} \left[\left(\|\boldsymbol{d}\| / d_0 - 3/2 \right)^2 + \frac{1}{8} \right] \frac{\boldsymbol{d}}{\|\boldsymbol{d}\|} & (d_0 \le \|\boldsymbol{d}\| < 2d_0) \\ 0 & (\|\boldsymbol{d}\| \ge 2d_0) \end{cases}$$



No fitting parameter in this model

Summary of material parameters

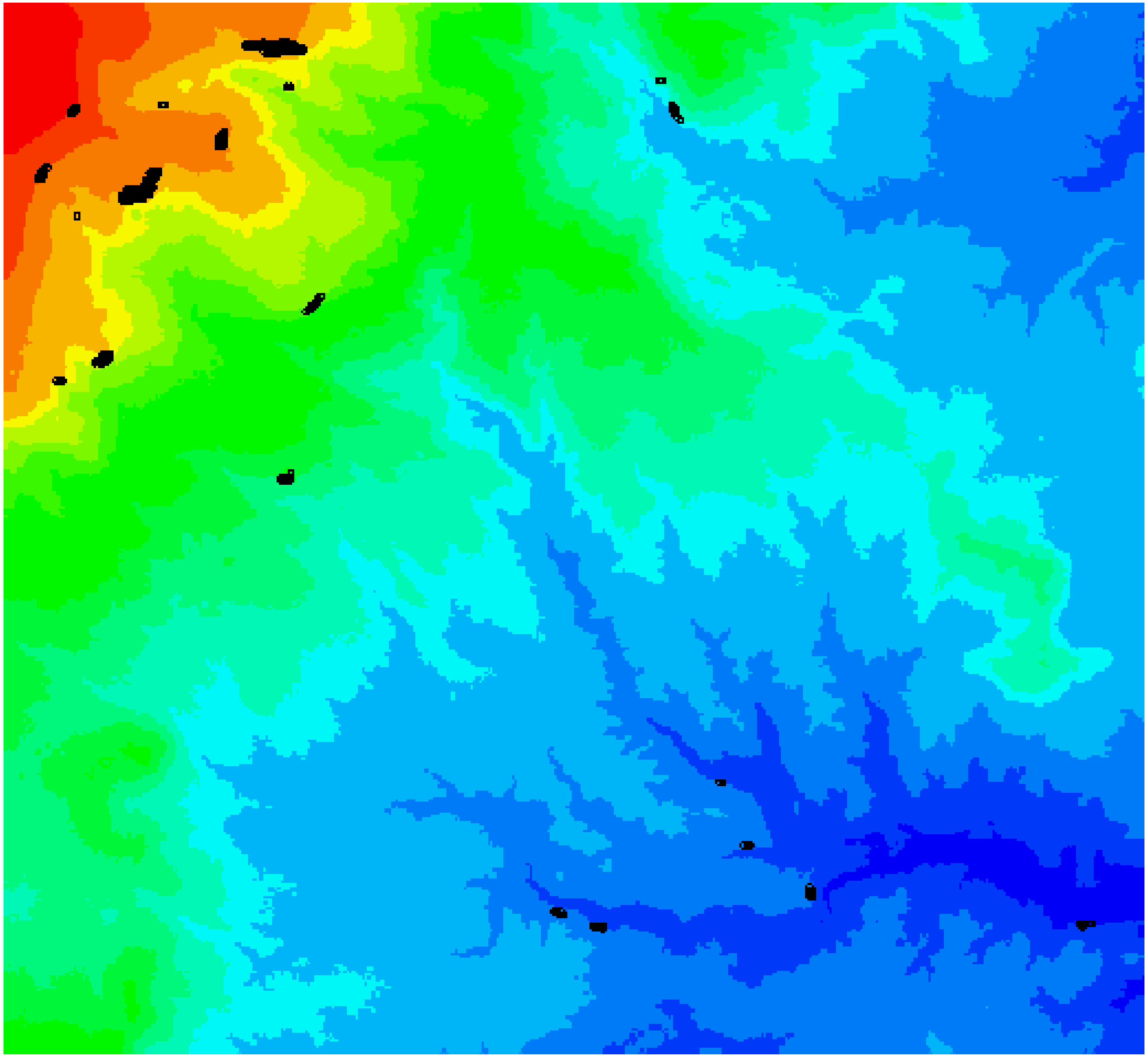
Only two material parameters to describe the sediment flow

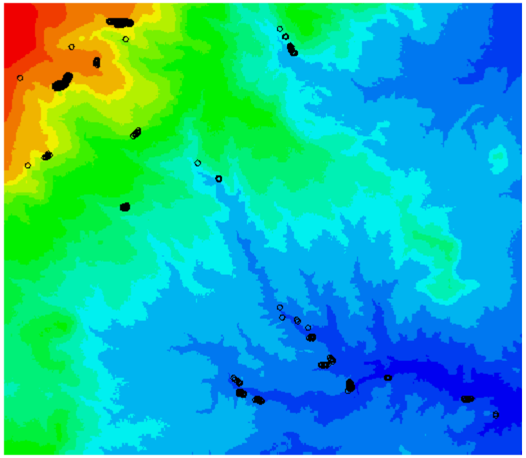
i_{cr} critical slope gradient for the sediment flow
n Manning's coefficient to describe the boundary roughness

i_{cr} If i_{cr}=0, flow does not stop until the slope angle=0
i_{cr} may be a function of flow speed

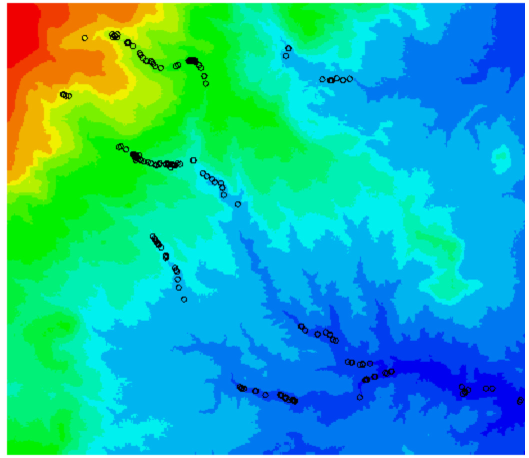
n =0.02〜0.1 (for natural river, based on river engineering)

simulation result n=0.06, i_{cr}=0.15

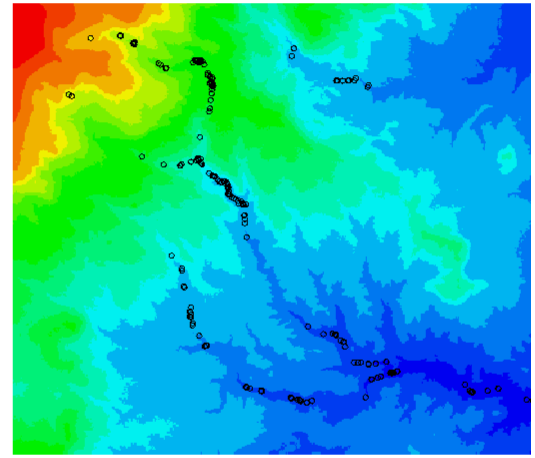




Initial condition



5 minutes later



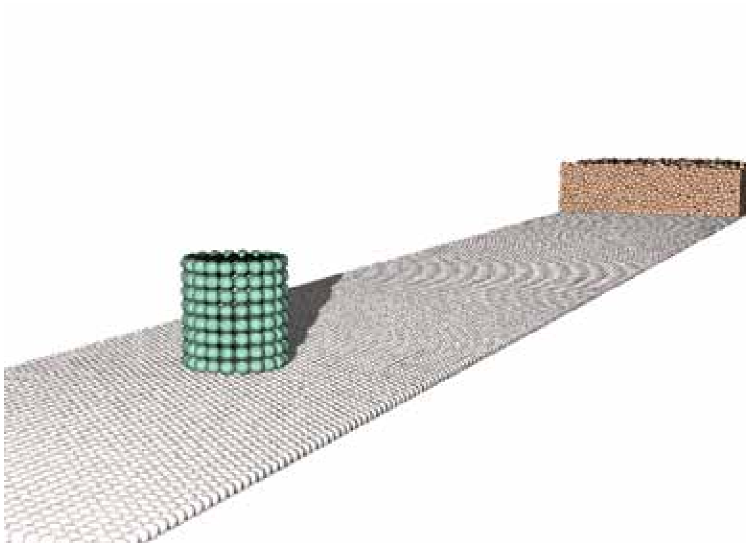
10 minutes later

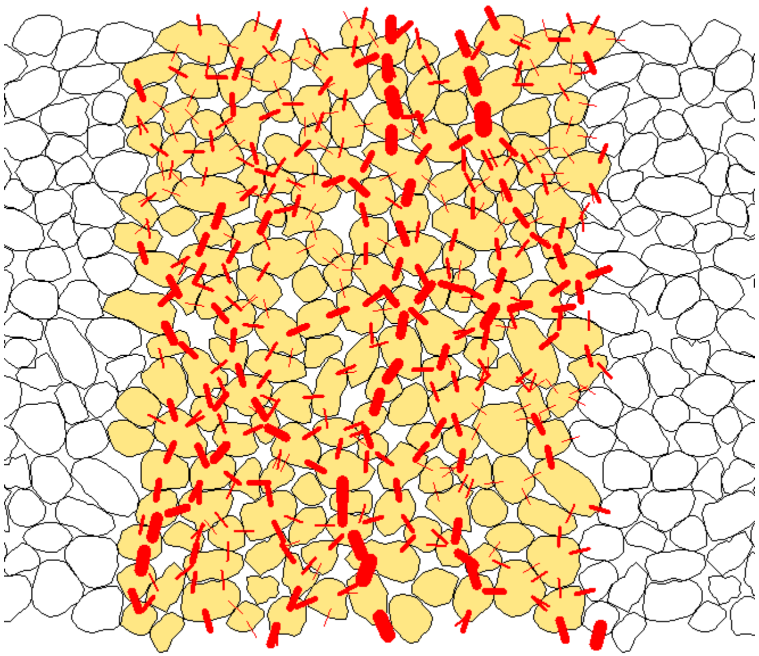
Advantage of this method

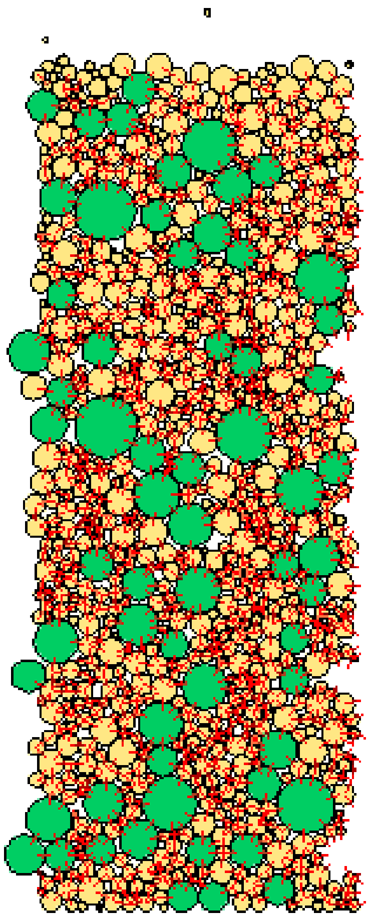
* Easy to handle meeting and parting of the flowing sediment
* No need to pay attention to the mass conservation
  because the particles hold all the continuum quantities.
  (advection term does not include in Lagrange description)
* Easy to add any additional quantities such as
  grain size distribution, water contents, etc.
* Very efficient computation
  (several seconds of computation time for 10 minutes' flow)

4. DEM simulation for rock avalanches

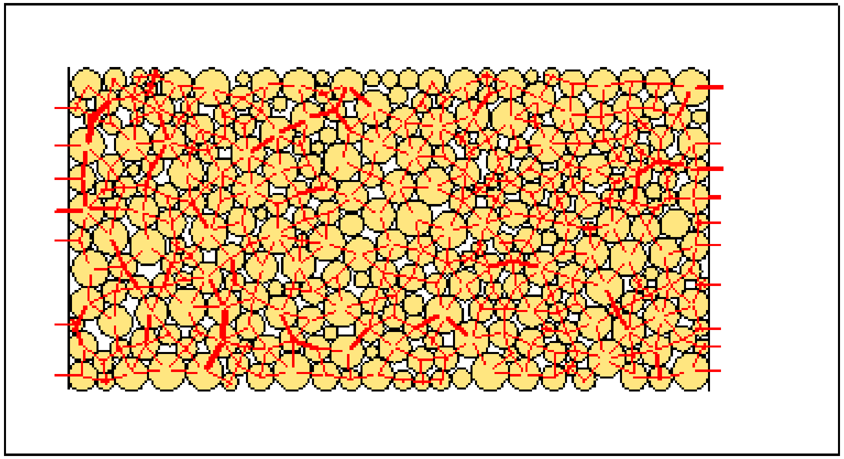
Discrete Element Method for granular materials

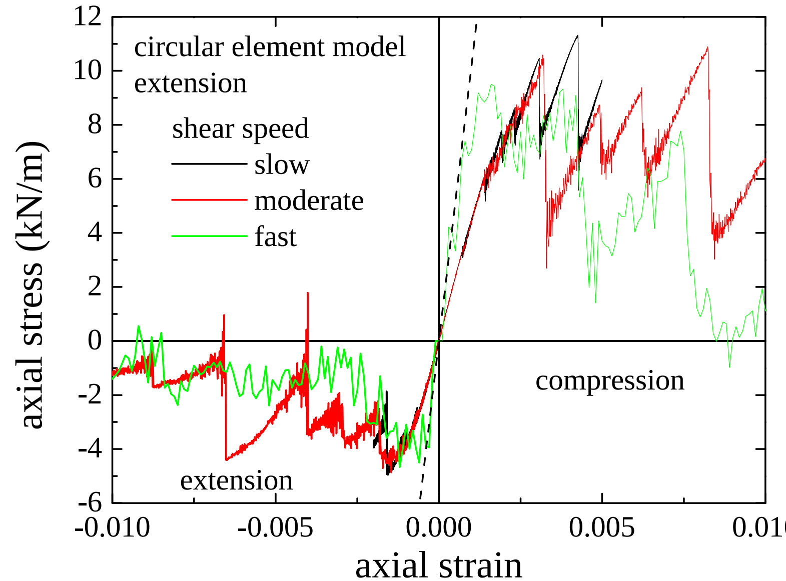


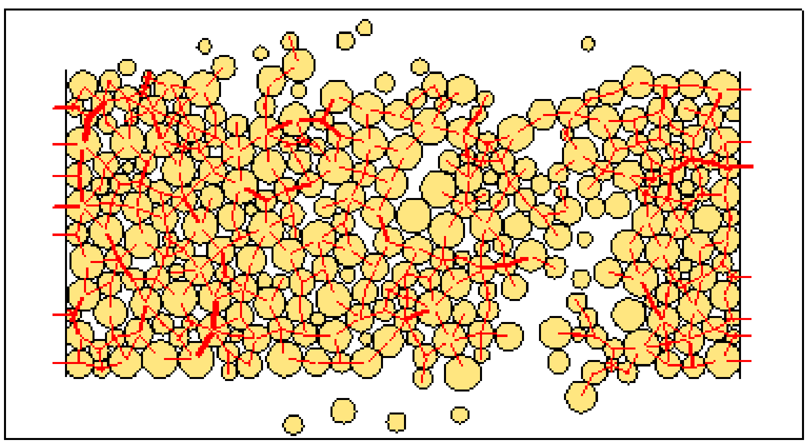




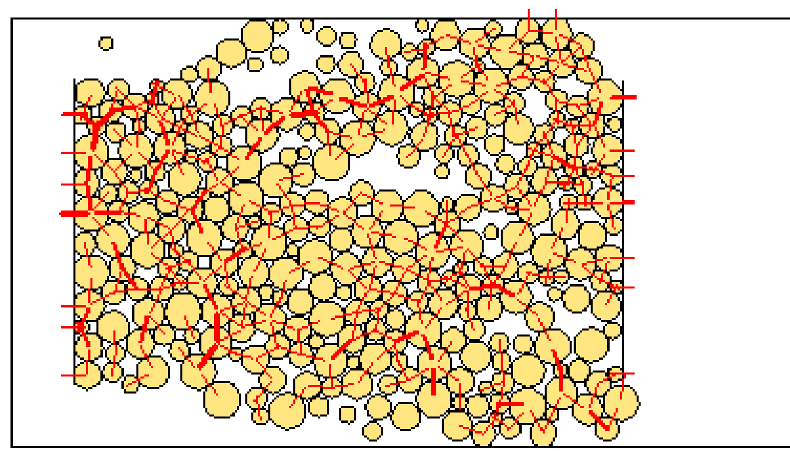
Biaxial test of bonding circles





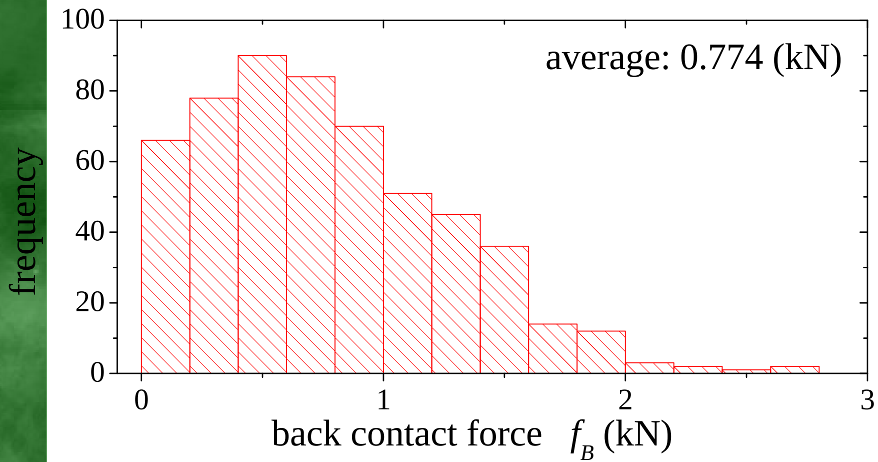


引張り破壊後

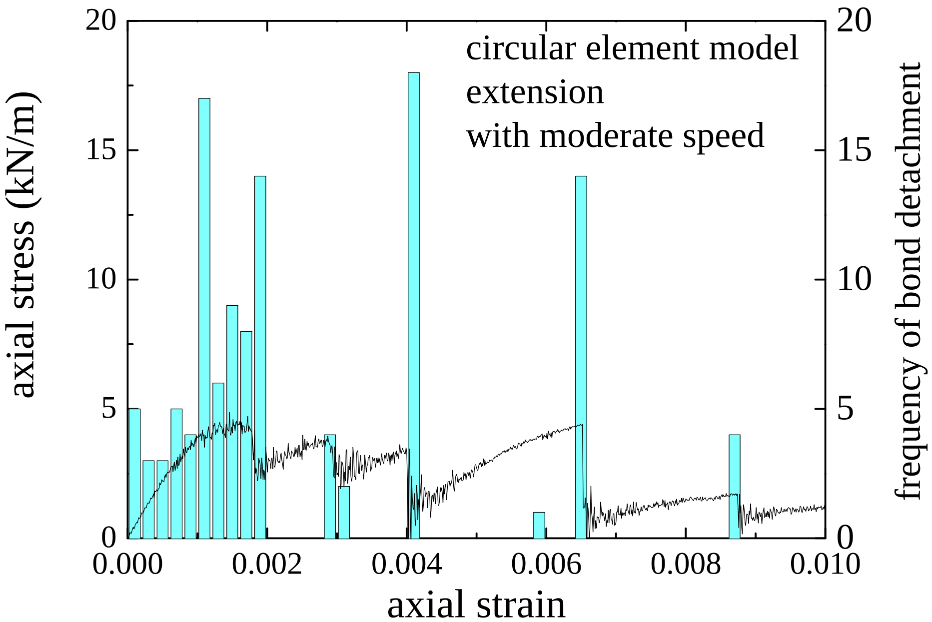


圧縮破壊後

Biaxial test of bonding circles



Initial back-force distribution

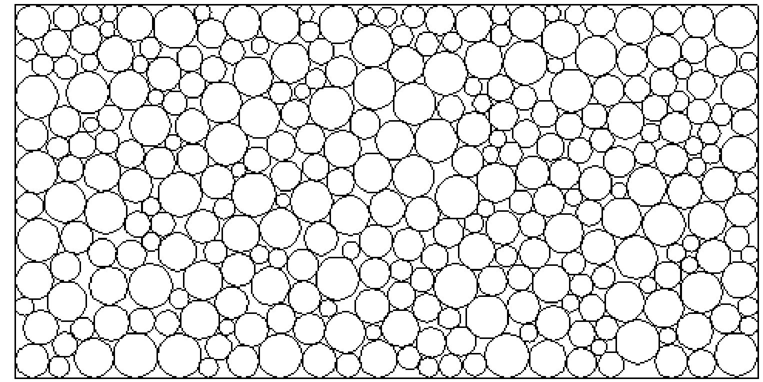


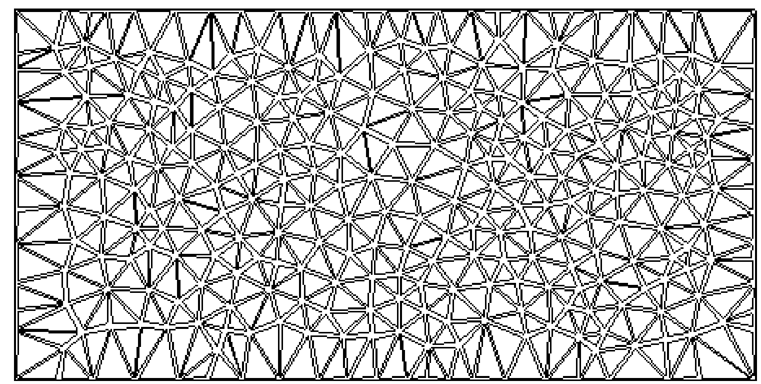
AE reponse

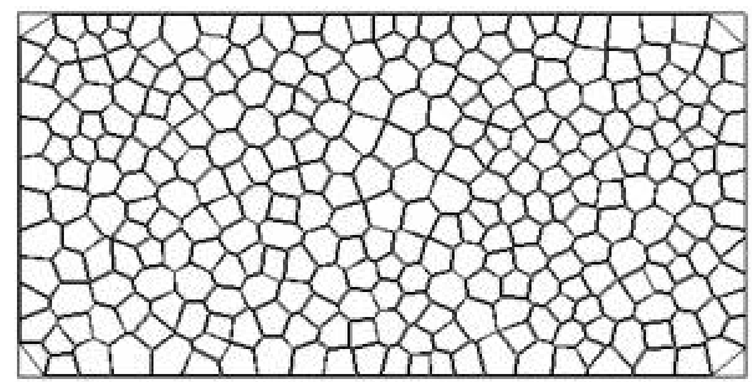
Volonoi tessellation

From the packing structure of circular particles, volonoi tessellation and Delaunay triangulation can be obtained.

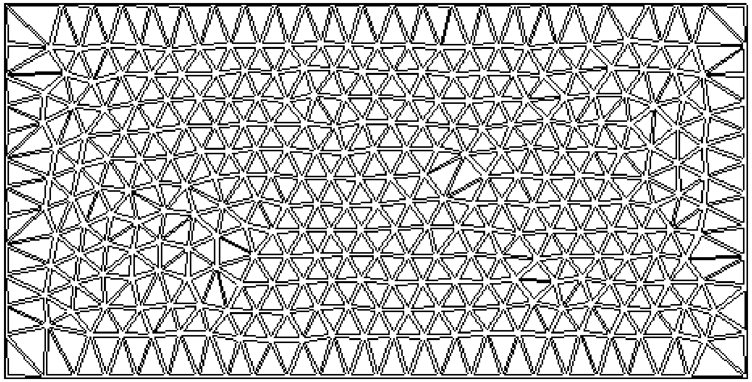
Physics-based tessellation can be possible.

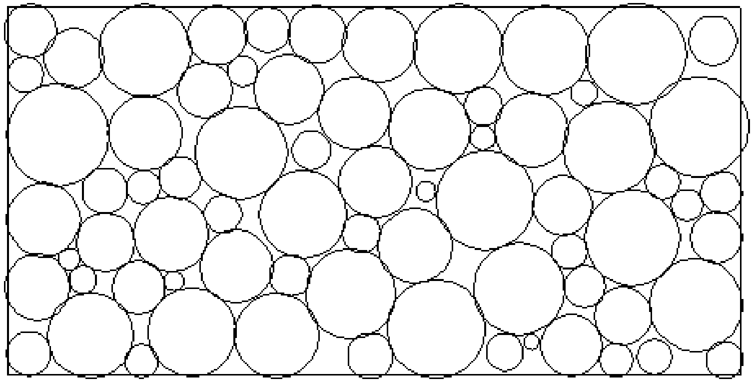


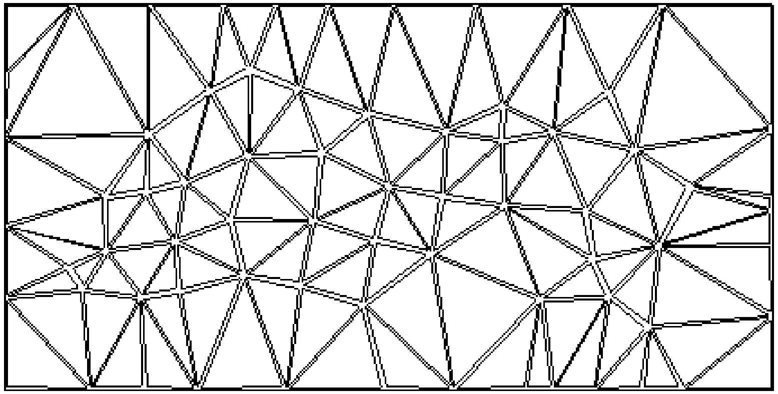




Effect of initial packing

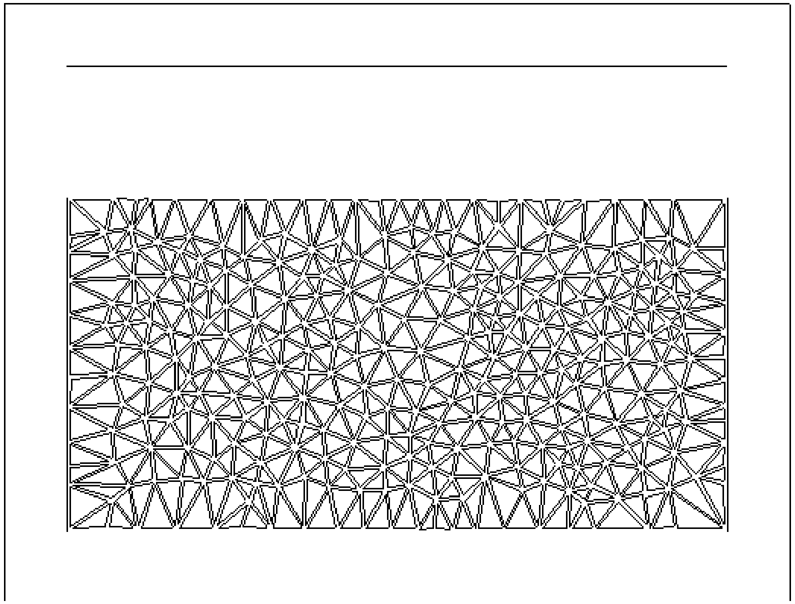


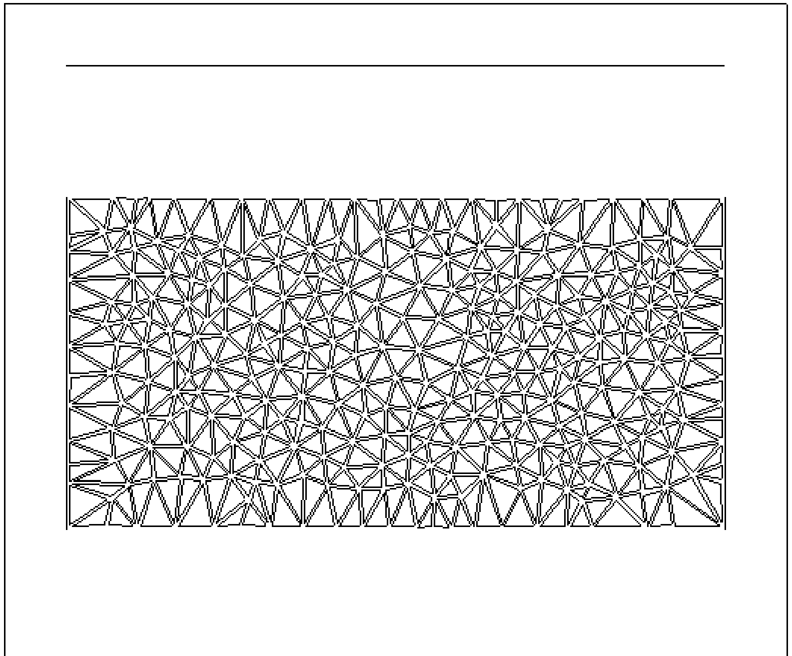


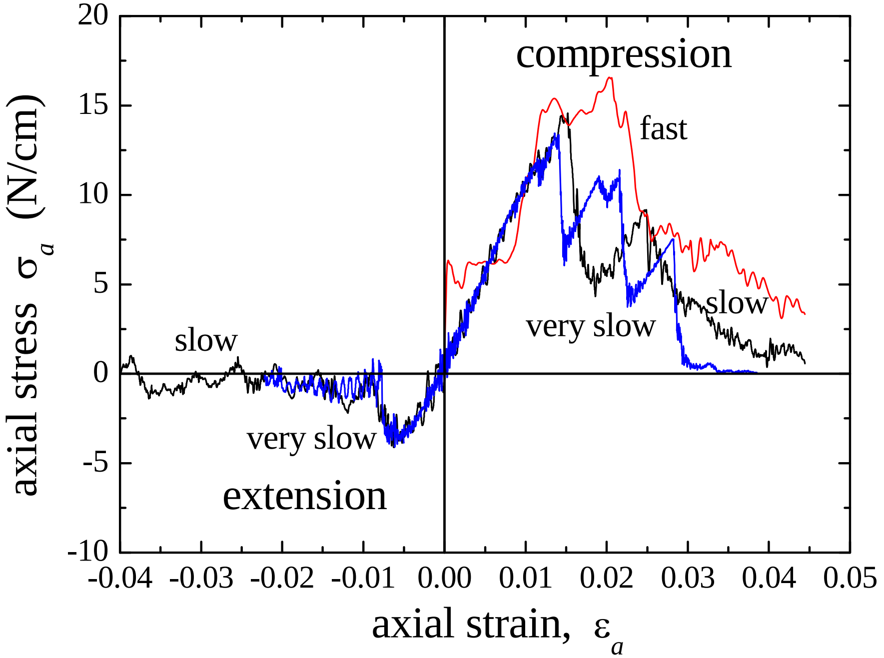


The density and orientation of discontinuous slips can be obtained by packing simulation.

Simulation of rock failure by DEM



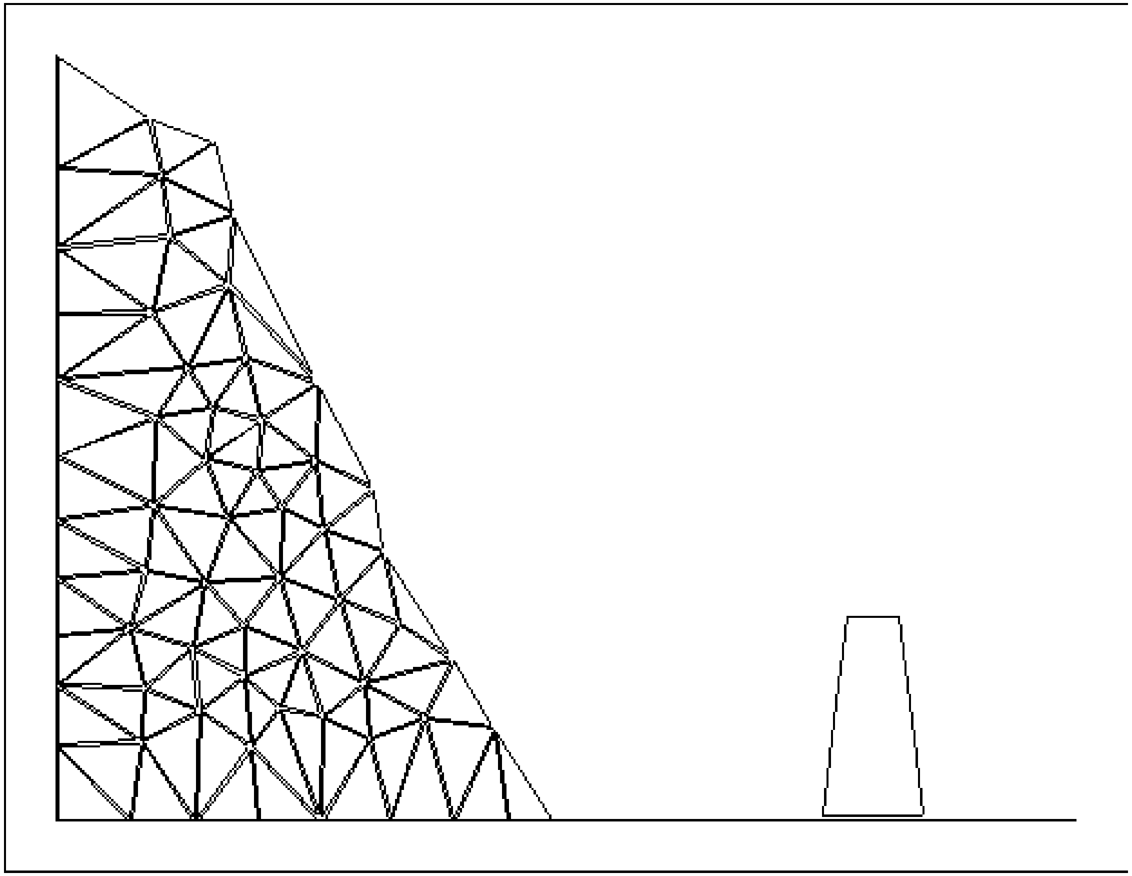




The response is qualitatively in good agreement with experiments.

Rock avalanche simulation with DEM

Rock mass is discretized by Delaunay triangulation



Conclusions

Particle methods are suitable for the simulation of fluid-like behavior of geomaterials.

Various types of modeling methods can be used in particle methods depending on the requirement condition

More detailed information on the material on site is necessary to improve the simulation accuracy.