Dike intrusion numerical simulation by Discrete Element Method: Implication for eruption conditions

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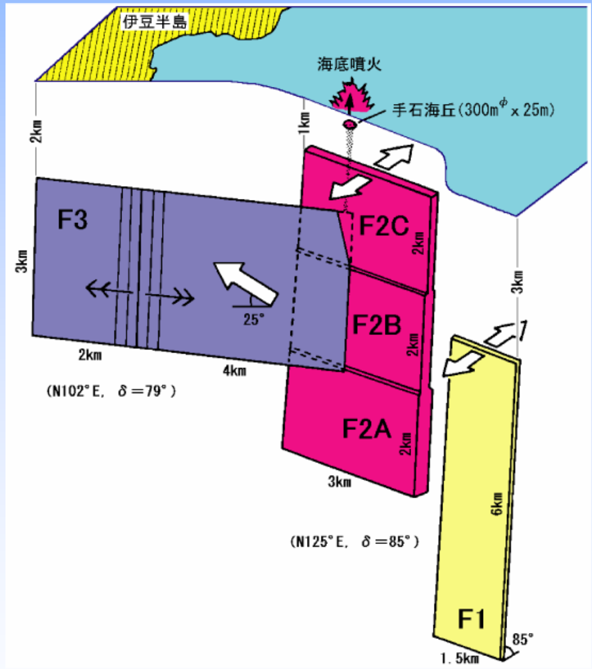
1. Background & Objectives
2. Modeling
3. Simulation results
4. Conclusions & Future works

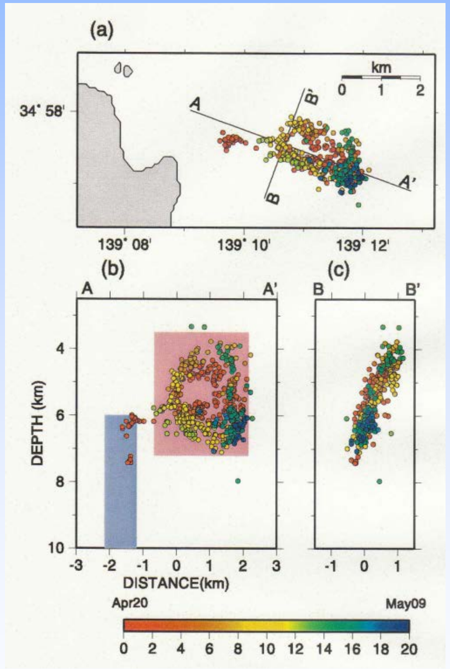
1.Background & Objectives

Recent high-density seismic and ground deformation observation

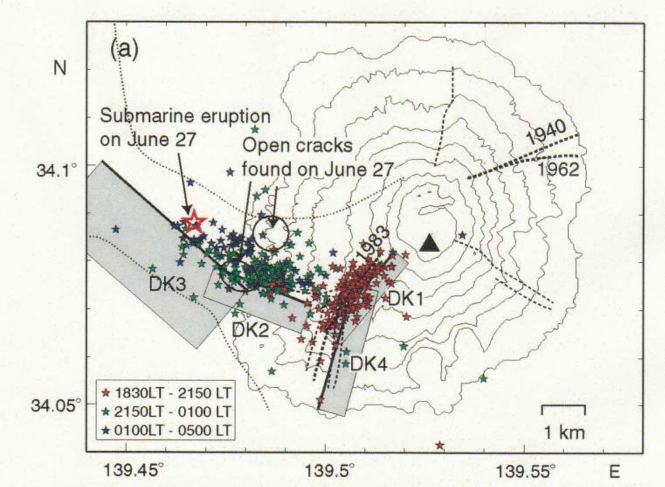
Detection of precise subsurface magma migrations



1989 Off-Ito swarm
(Okada & Yamamoto,1992)



1998 Off-Ito swarm
(Morita et al.,2005)



2000 Miyakejima volcano
(Ueda et al., 2006)

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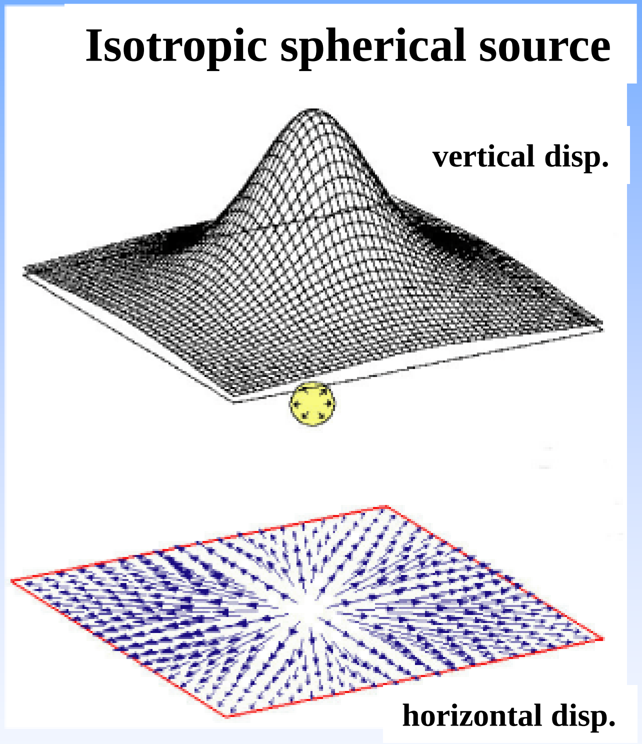
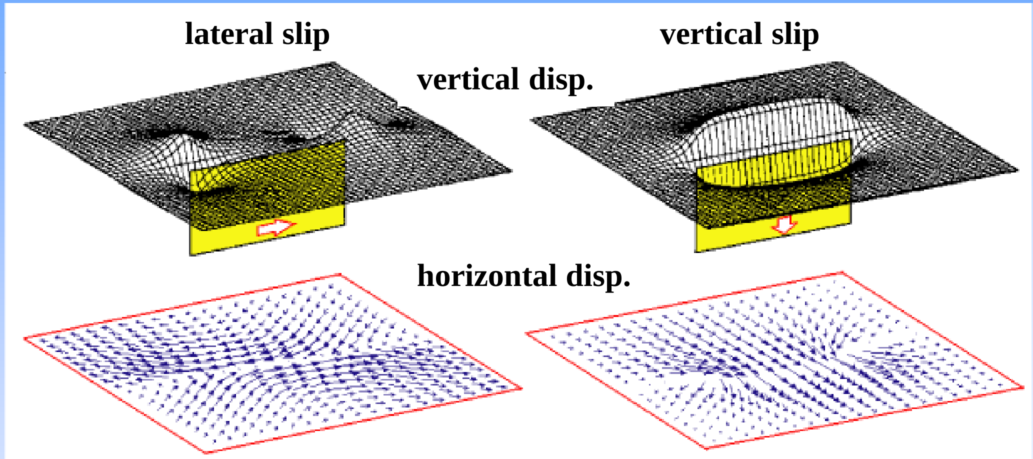
Standard Crustal deformation model

- **Mogi model (1958)**



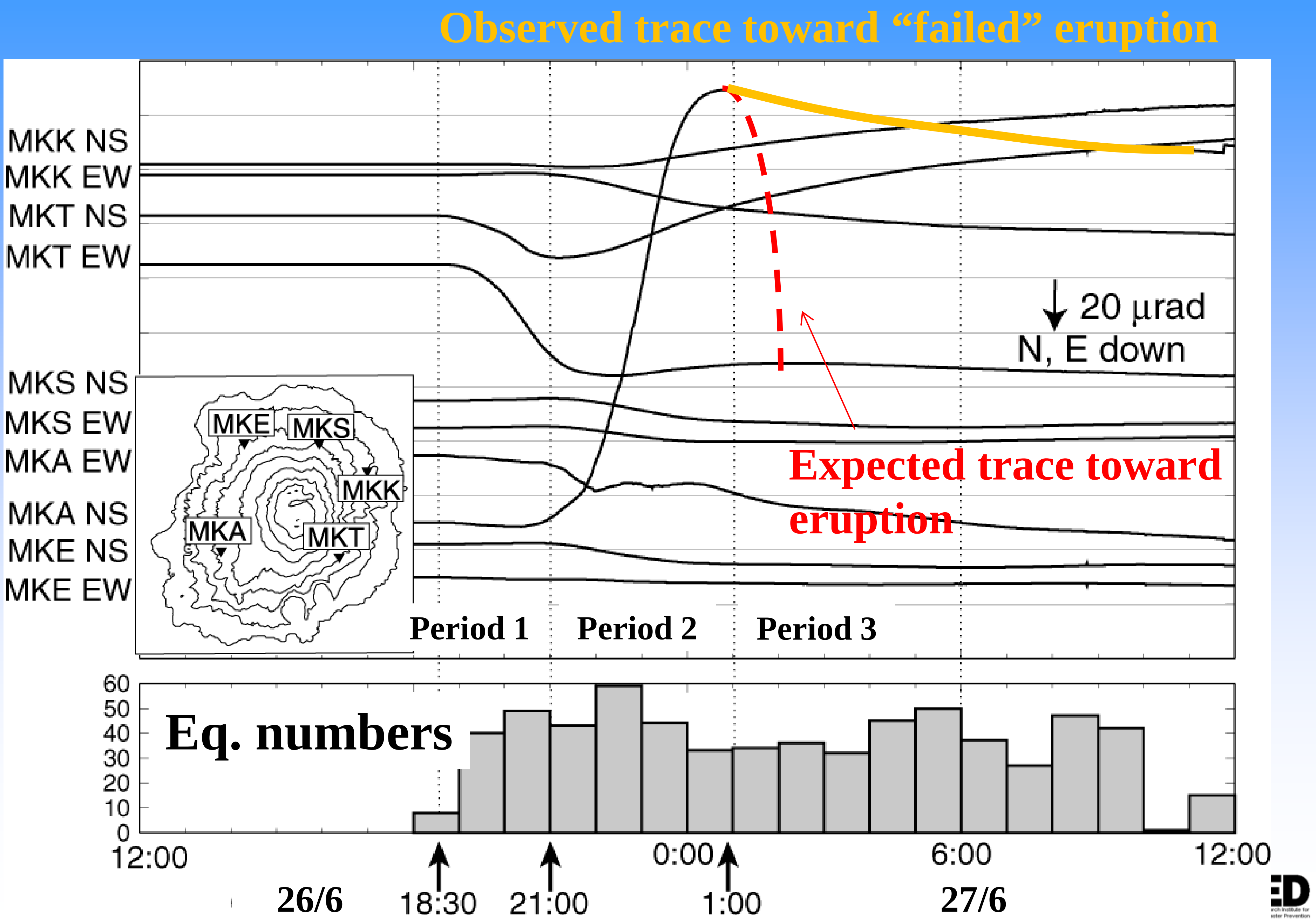
- **Okada model (1985,1992)**



Applicable condition

- **isotropic & homogeneous media**
- **elastic deformation (no fractures)**

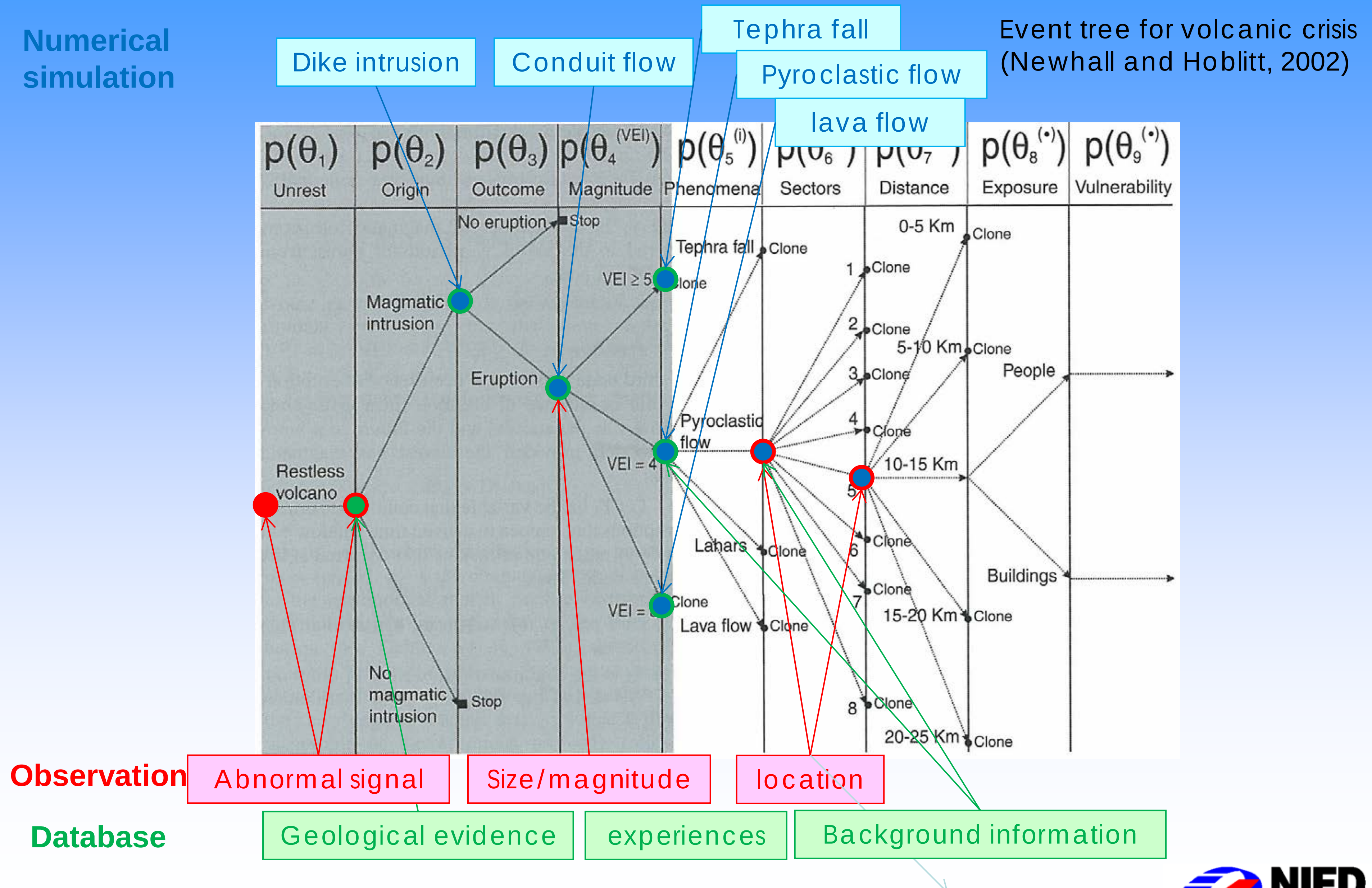
Tilt record during the 2000 Miyakejima eruption



Still we have many questions…

- What determines "eruption" or "failed eruption"?
- How physical properties, initial and boundary conditions control eruption?
- Where VT earthquakes occur ?
  (crack tip? Surroundings?)

Judgment at Event tree branch



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Objectives

- **Quantitative and dynamic modeling of dike intrusions**
  - **Geometry dependency**
  - **Elastic deformation and fracturing**
  - **Coupling of liquid and solid**
  - **Effect of gravity**
  - **Anisotropic and heterogeneous media**
  - **Effects of 3D stress-field (regional and/or local)**

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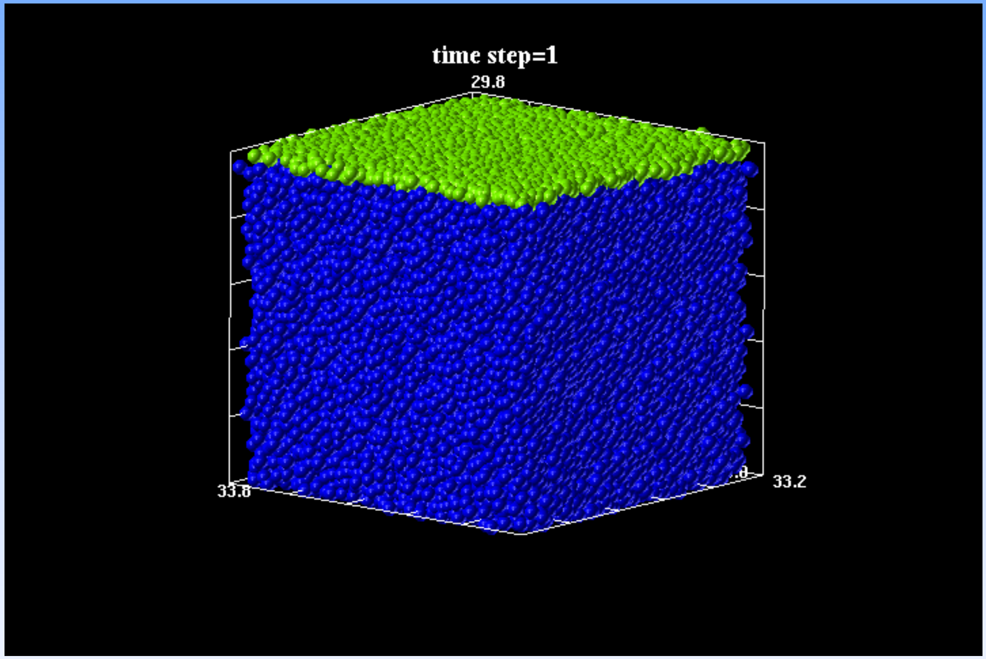
2. Modeling

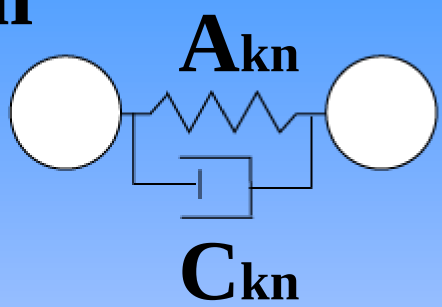
DEM(Discrete Element Method)



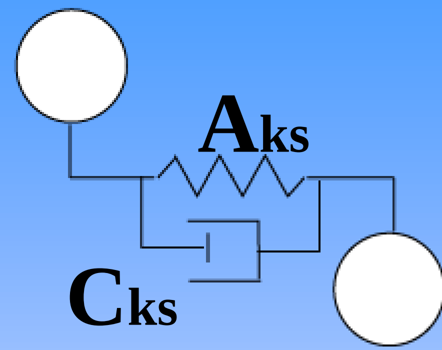
- Continuous media are modeled by particles (discrete elements) connected by visco-elastic springs

Formulation of stress & fracture

normal



shear



Spring coefficient: A_{kn}
Damping coefficient: C_{kn}

Spring coefficient: A_{ks}
Damping coefficient: C_{ks}

Threshold distance

$$D > D_{th}$$

Mohr-Coulomb Criterion

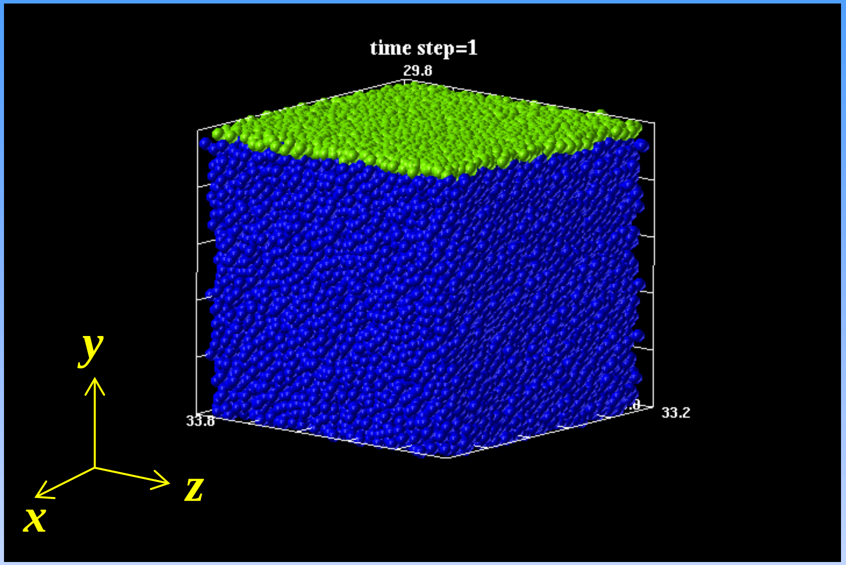
$$t = C + \sigma_n \tan \phi$$

Default values	Density [kg/m3]	A_{kn} [Pa]	C_{kn} [Pa s]	A_{ks} [Pa]	C_{ks} [Pa s]
Mainbody	2.5E3	5.0E5	1.0E4	1.25E4	5.0E3
Magma	2.0E3	2.5E5	5.0E3	6.25E3	2.5E3

Numerical calculation procedures

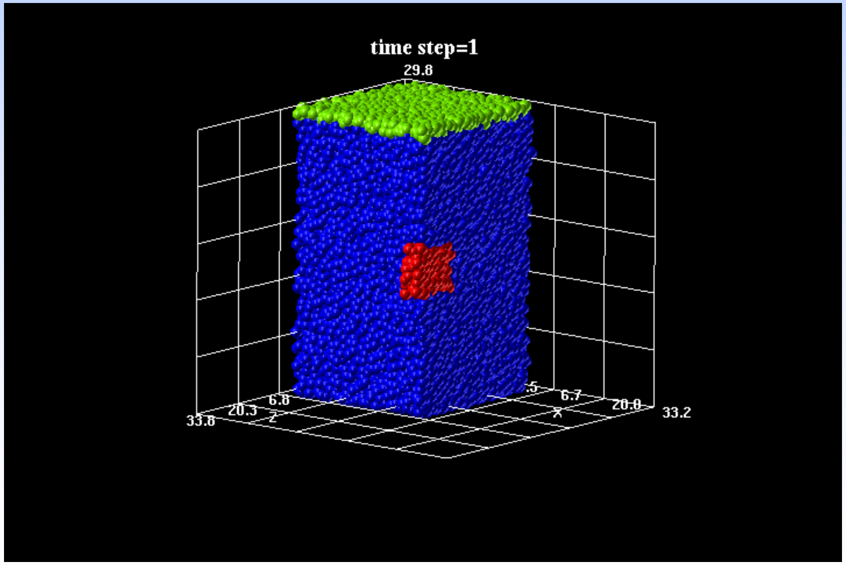
Gravity packing

- Region: 30 x 30 x 30 m
- Generation 100,000 Particles with random size and position
- Gravity packing



Assign magma particles

- Assign magma particles at (-5,-5,-2) – (5,5,2)
- Set low density, bulk modulus etc.



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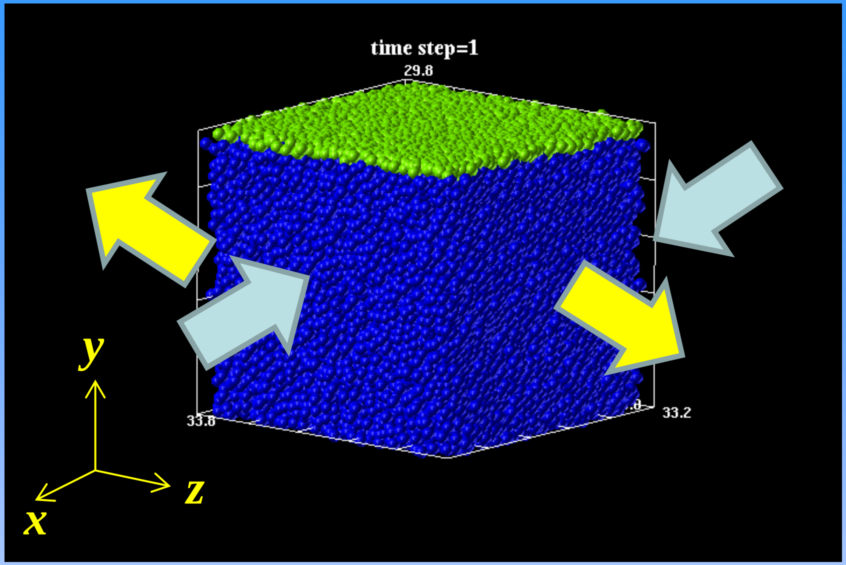
Assign Boundary Conditions

- **Set stresses for boundary particles**

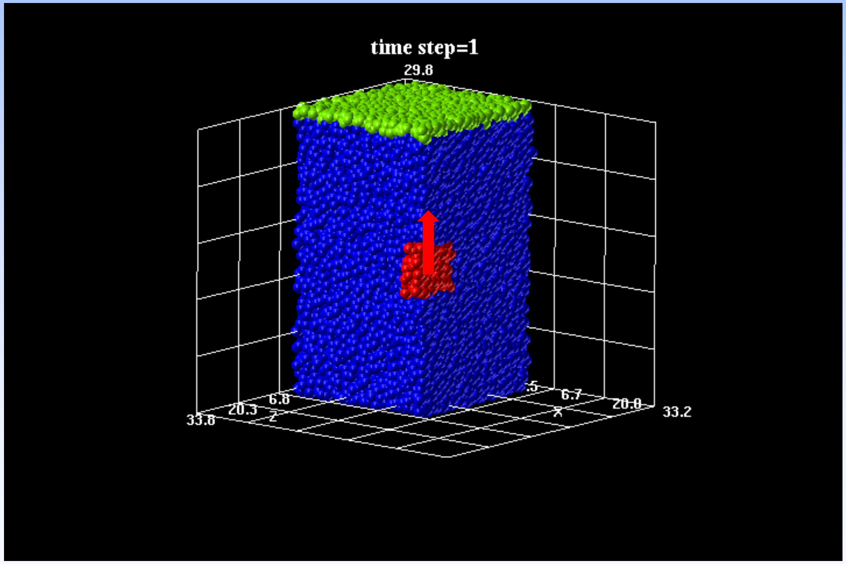
σ_{zz} = -1.0E6 Pa

σ_{xx} = 1.0E6 Pa



Assign Initial Conditions

- **Set initial velocity / excess pressure for magma particles**



Start !

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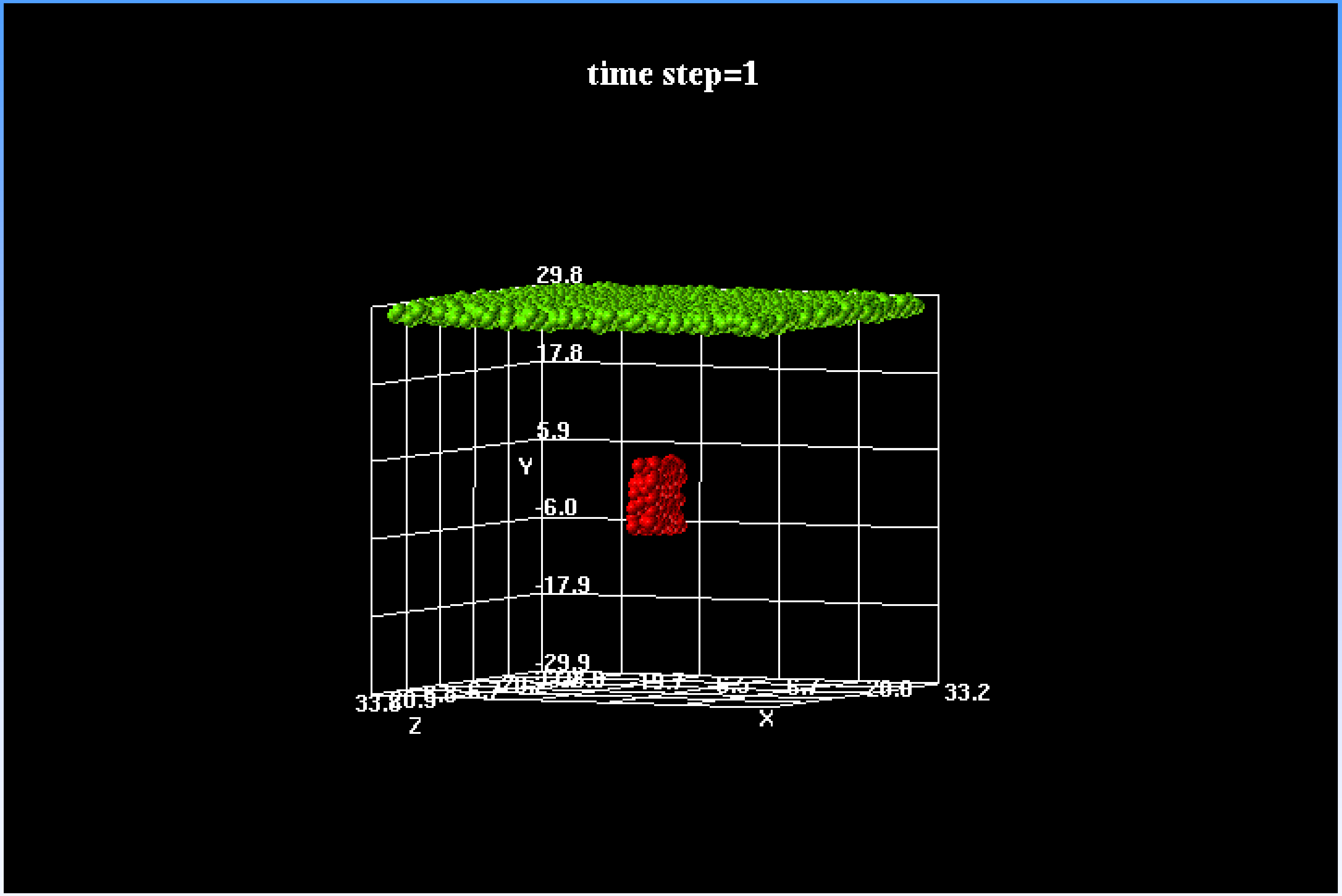
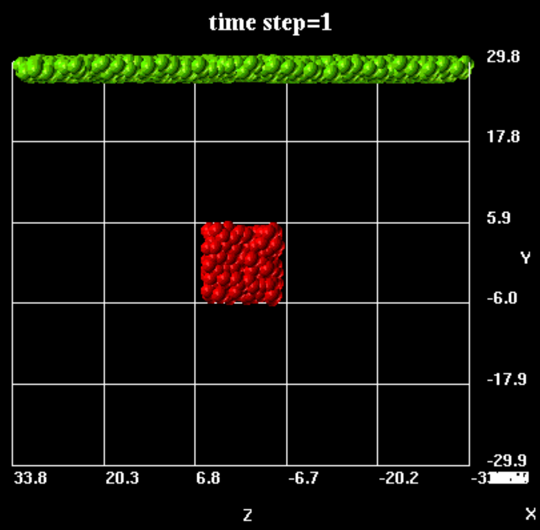
3. Simulation results



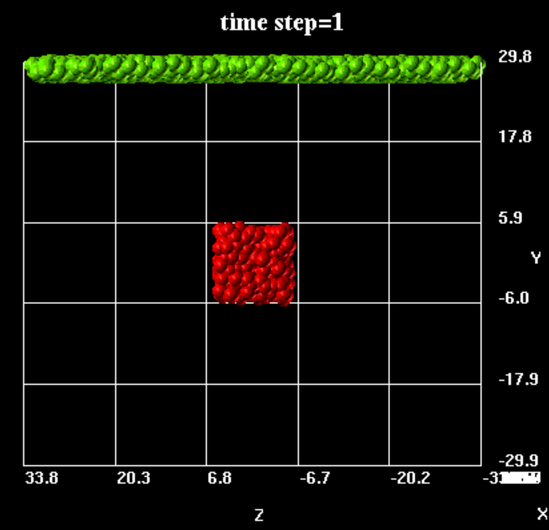
- Initial plate dike -> diapir shape
- Deformation of ground surface

Dependency on Normal damping coefficient: C_{kn} [Pa s]

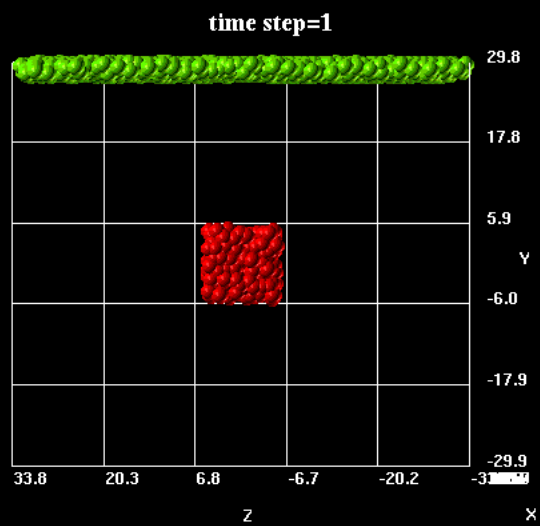
Case 1
5.0E3



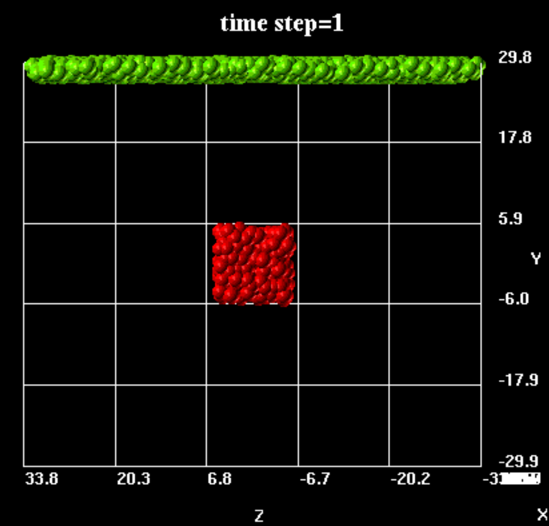
Case 2
7.5E3



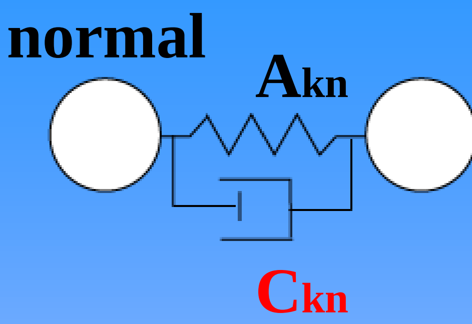
Case 3
1.0E4



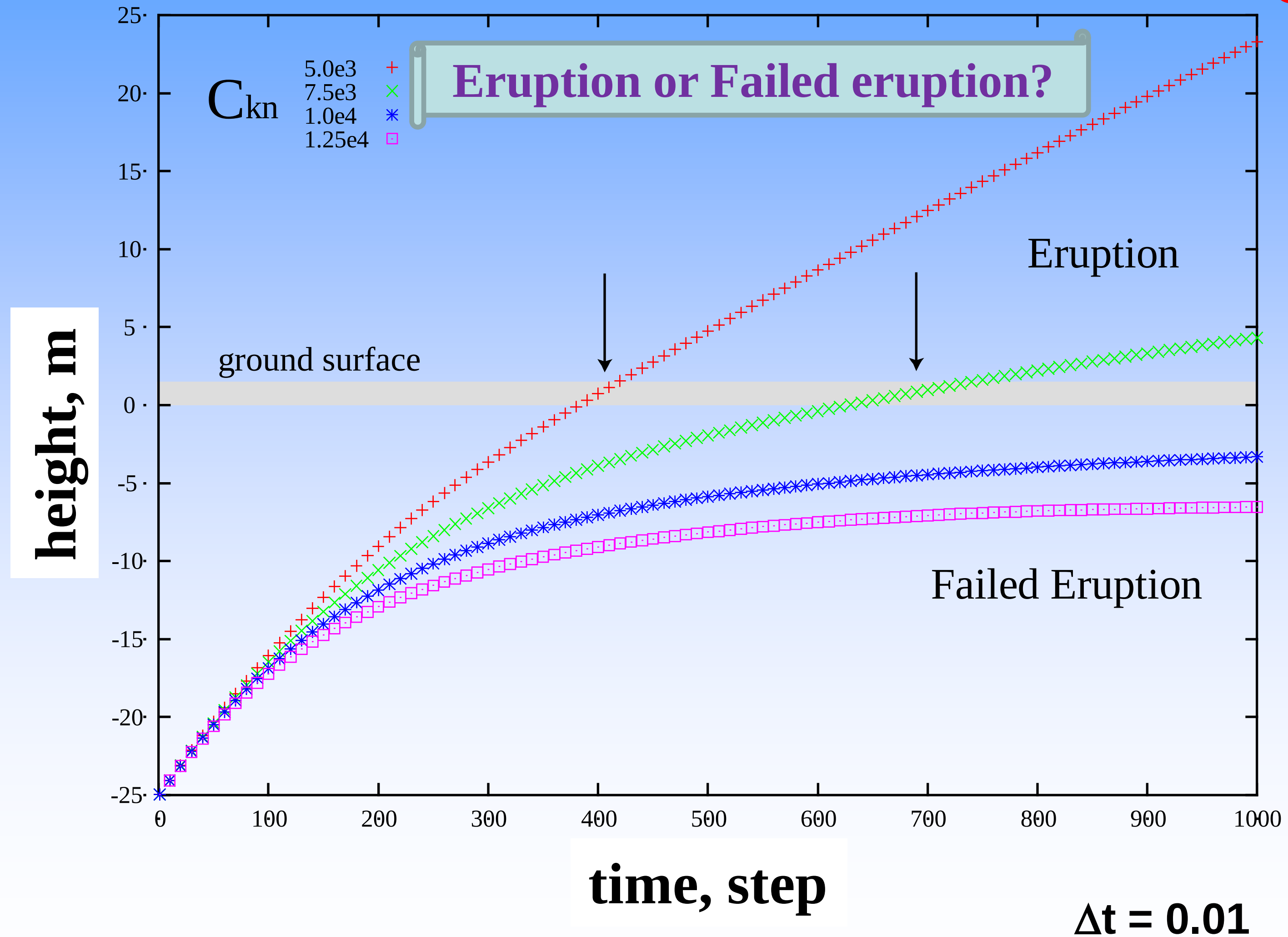
Case 4
1.25E4



Dependency on parameters



Normal damping coefficient: C_{kn}



Case 1
5.0E3 Pas

Case 2
7.5E3 Pas

Case 3
1.0E4 Pas

Case 4
1.25E4 Pas

$\Delta t = 0.01$

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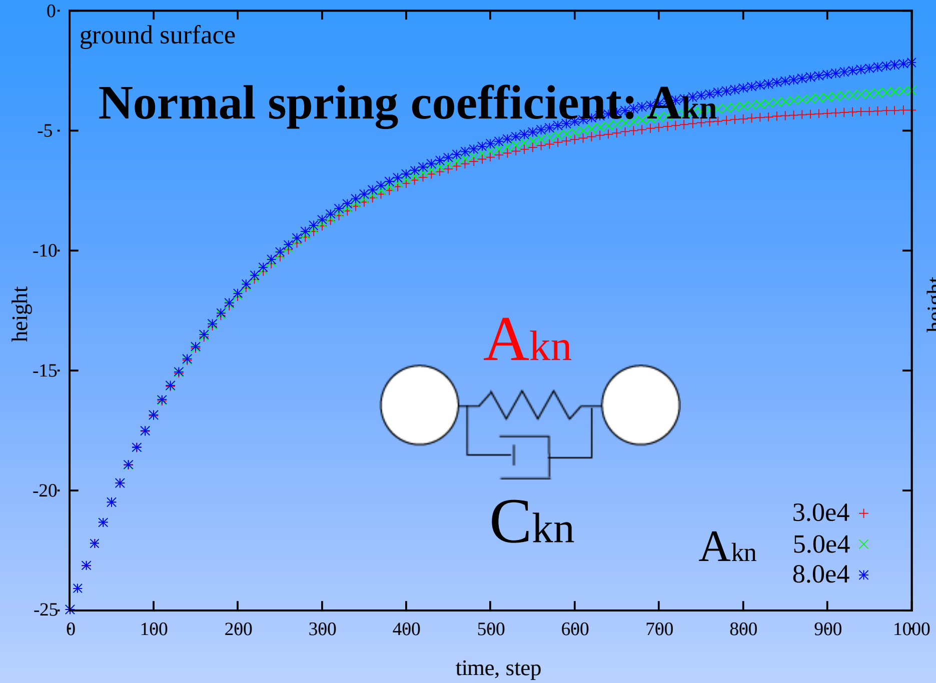
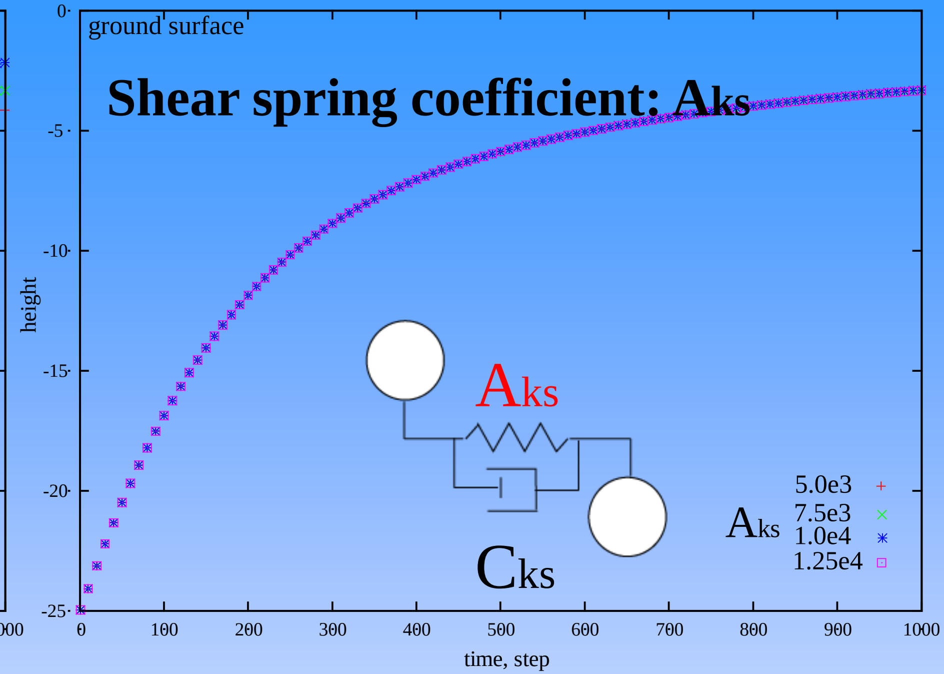
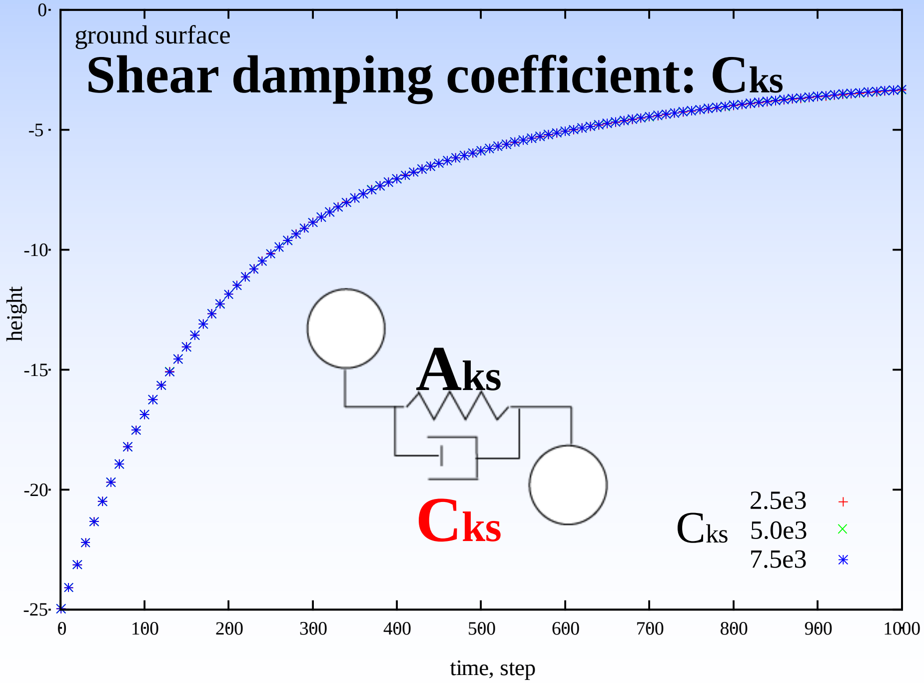
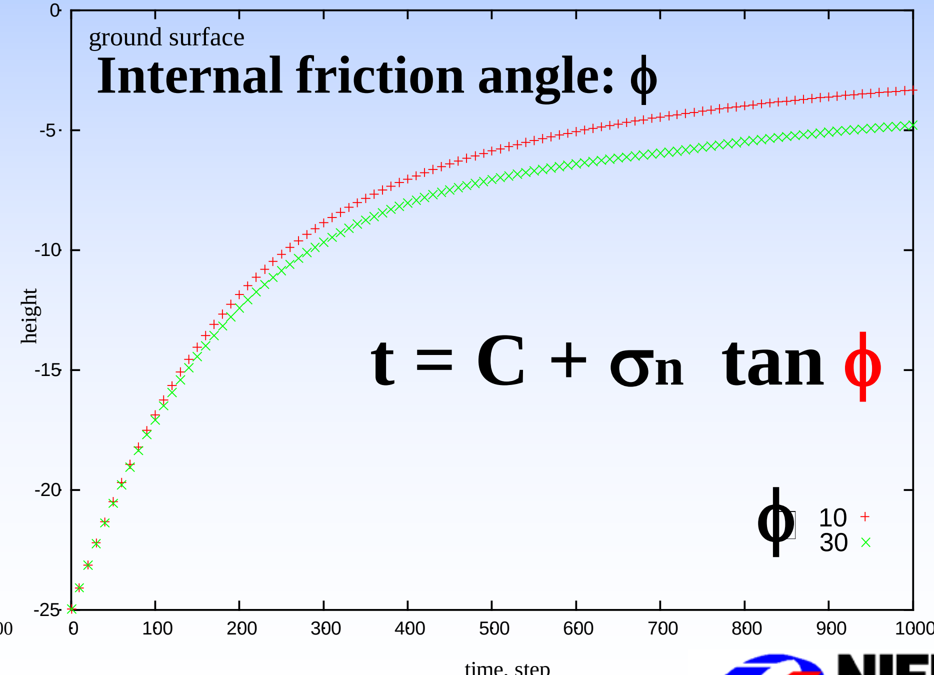
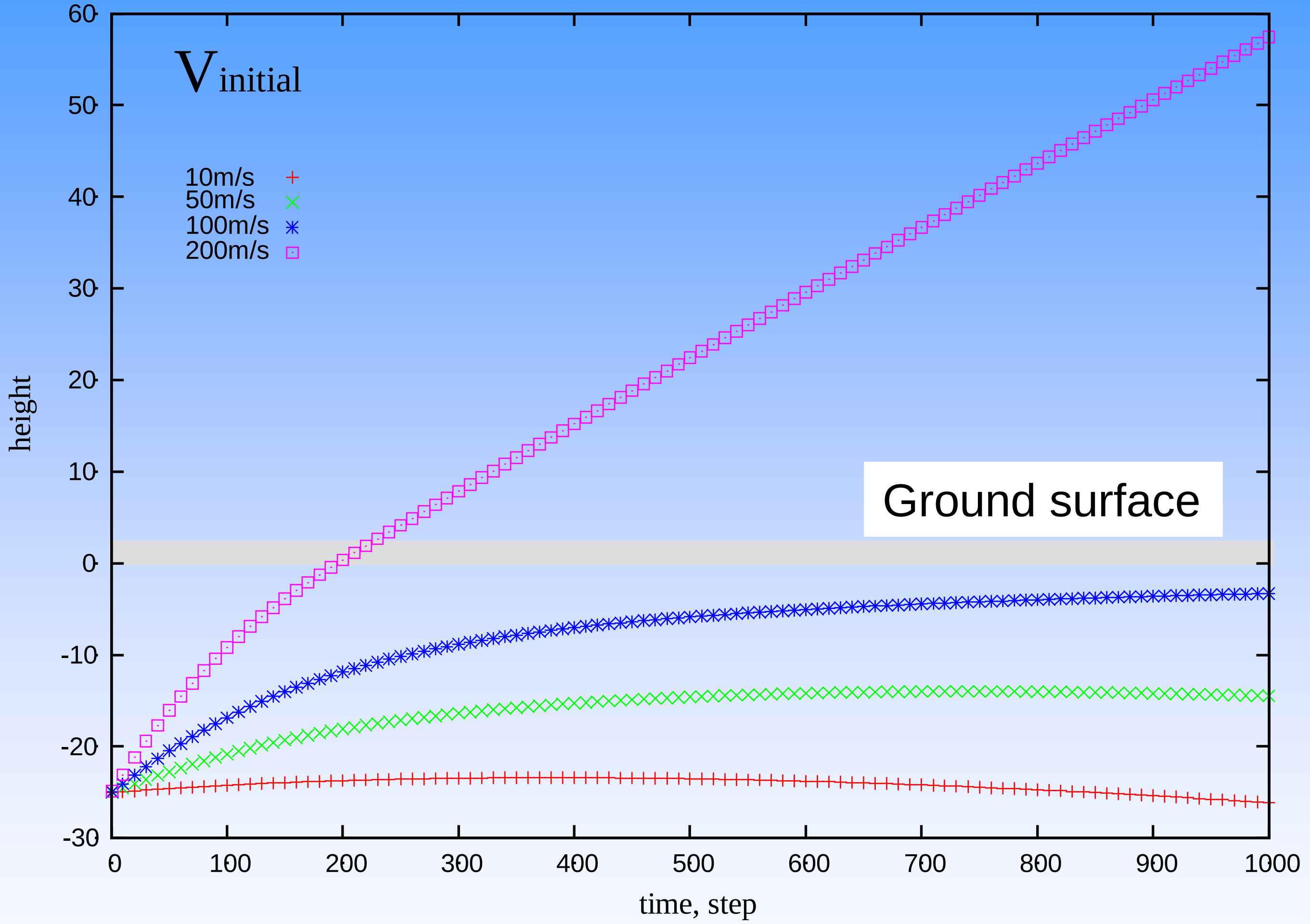

ground surface
Normal spring coefficient: Akn
Akn
Ckn
Akn
3.0e4
5.0e4
8.0e4
height
time, step
0
-5
-10
-15
-20
-25
0 100 200 300 400 500 600 700 800 900 1000


ground surface
Shear spring coefficient: Aks
Aks
Cks
Aks
5.0e3
7.5e3
1.0e4
1.25e4
height
time, step
0
-5
-10
-15
-20
-25
0 100 200 300 400 500 600 700 800 900 1000


ground surface
Shear damping coefficient: Cks
Aks
Cks
Cks
2.5e3
5.0e3
7.5e3
height
time, step
0
-5
-10
-15
-20
-25
0 100 200 300 400 500 600 700 800 900 1000


ground surface
Internal friction angle: ϕ
t = C + σn tan ϕ
ϕ
10
30
height
time, step
0
-5
-10
-15
-20
-25
0 100 200 300 400 500 600 700 800 900 1000

Initial Condition : Velocity or Excess pressure



200m/s (4.0eE7 Pa)

100m/s (2.0eE7 Pa)

50m/s (1.0eE7 Pa)

10m/s (2.0eE6 Pa)

Δt = 0.01

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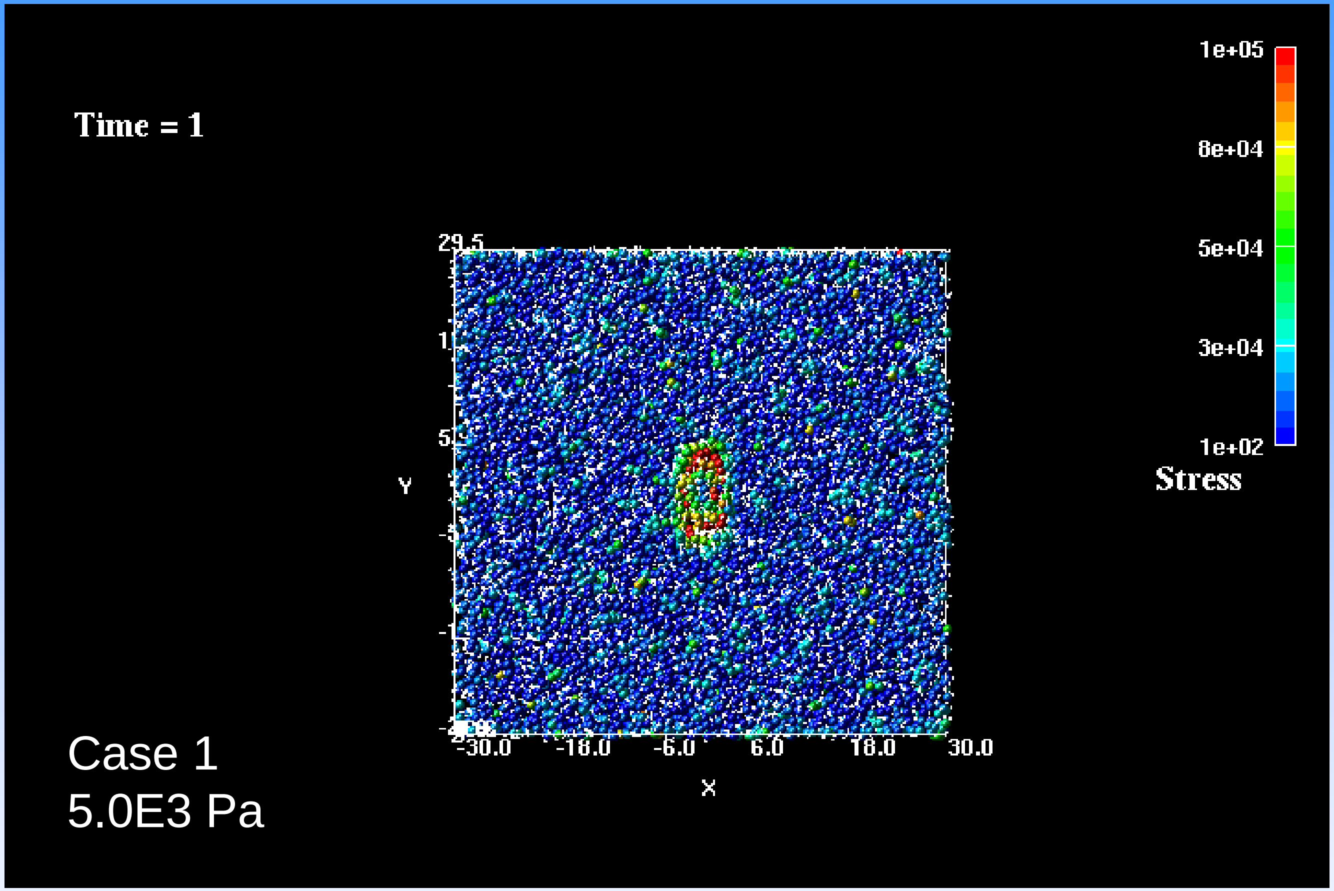
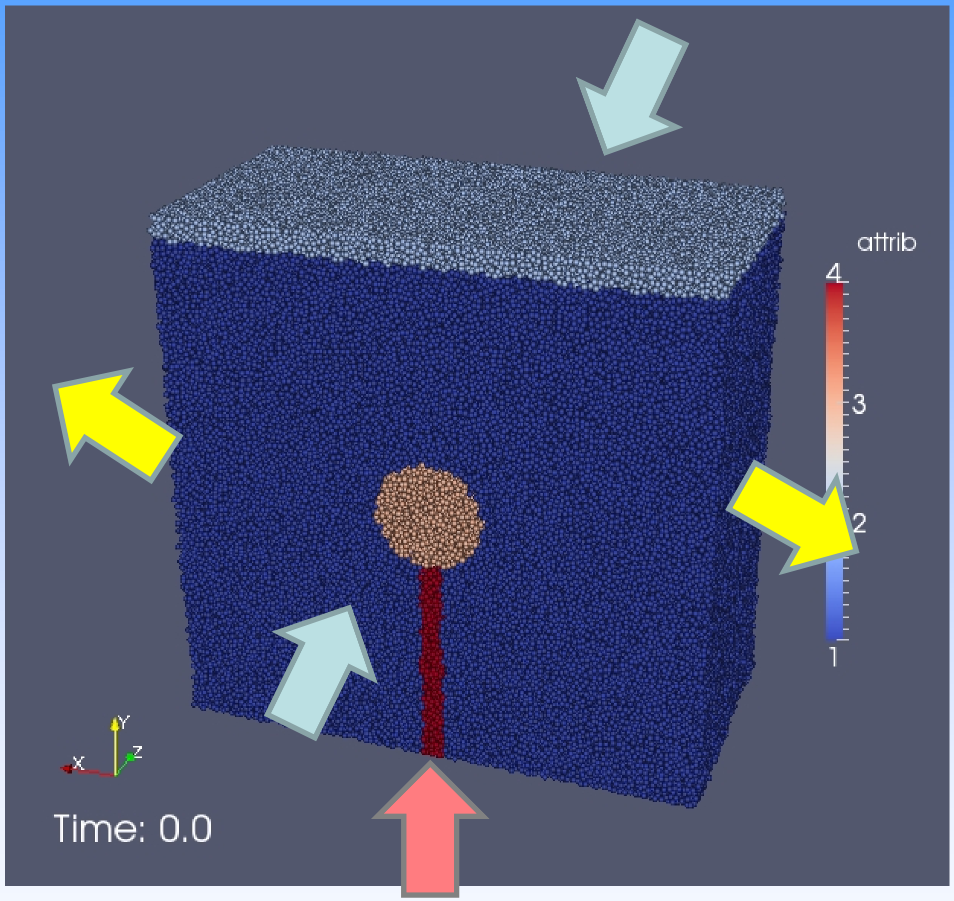
Stress distribution



Identification of stress concentrations and drops

VT earthquakes

Model case 2



1,000,000 particles

10km x 10 km x 10km cubic region
(i.e. diameter – 100m)

Gravity: -y direction

Initial condition

ΔP at the bottom of magma dike

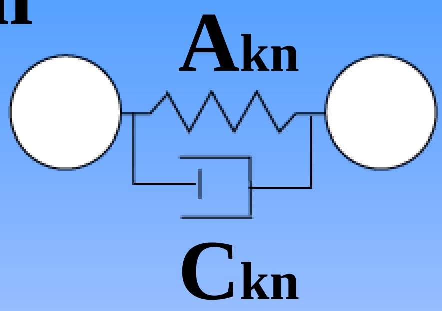
Boundary conditions

σ_{xx} = 1.0E8 Pa σ_{zz} = -1.0E8 Pa

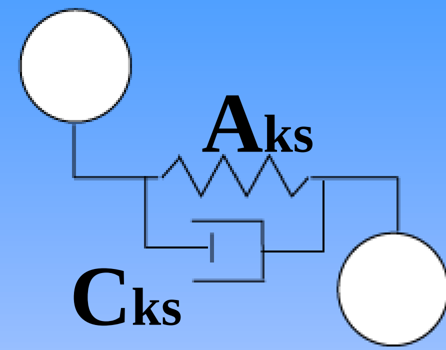
ΔP＝2.7E7Pa

Formulation of stress & fracture

normal



shear



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Spring coefficient: A_{ks}
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Threshold distance

$$D > D_{th}$$

Mohr-Coulomb Criterion

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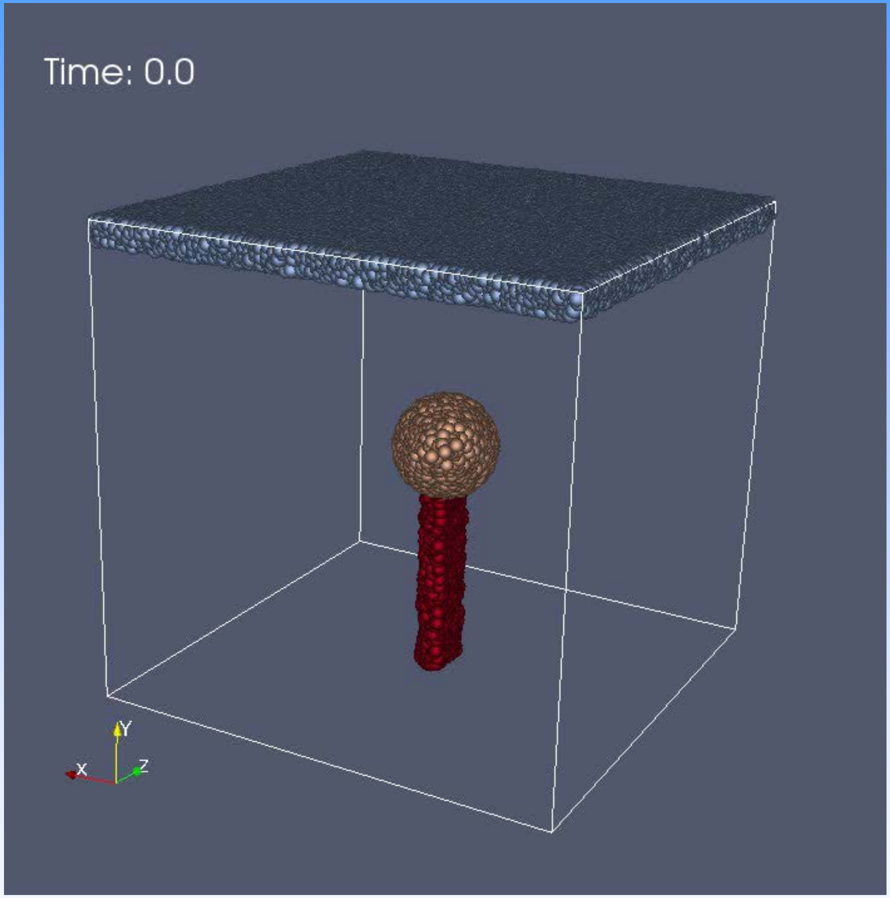

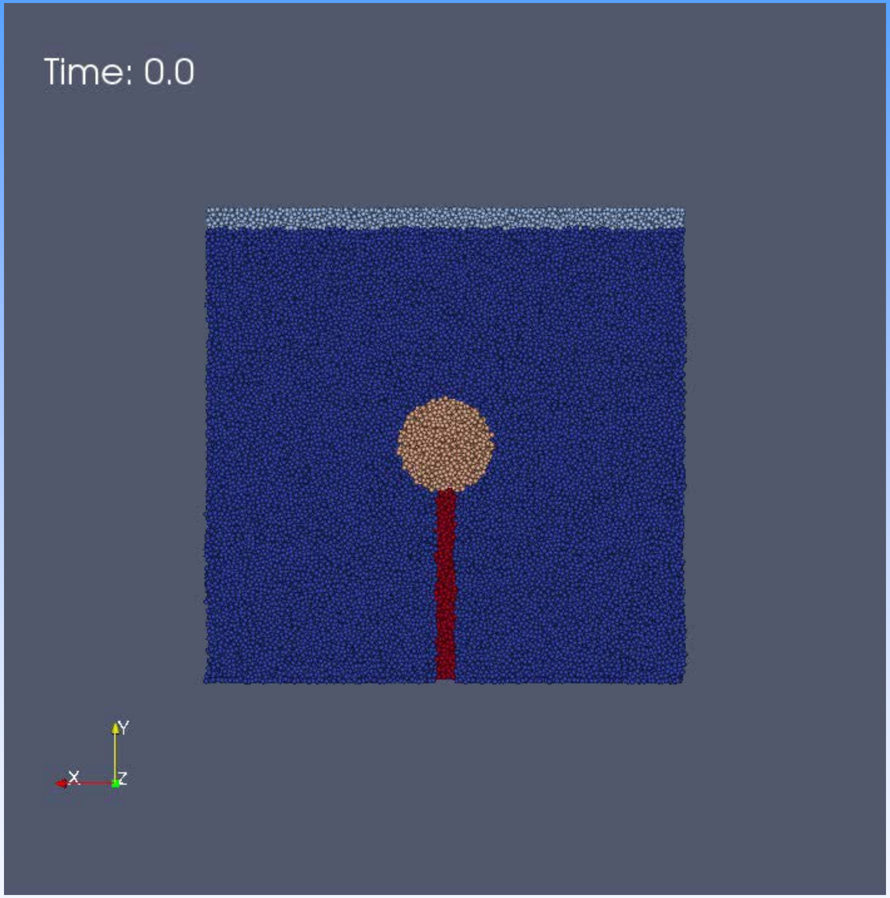

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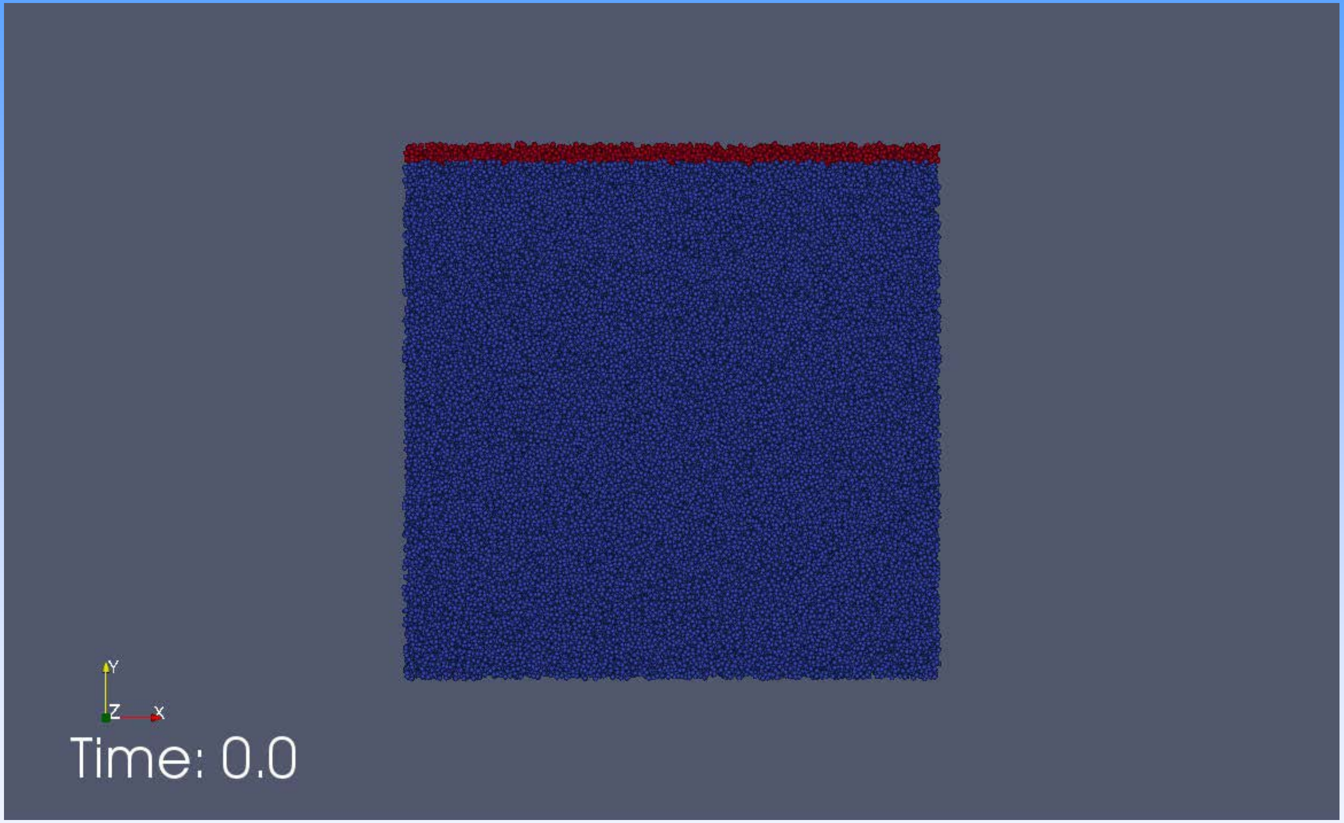
Gravity packing



Spring & dashpot coeff.--- Macro / Micro

Conclusions

- DEM modeling successfully simulate magma migration beneath a volcano, including the effect of fracture, 3D stress field, initial pressure, etc. (threshold of eruption / failed eruption)
- We used 1,000,000 particles (1 particle – 100m in 10x10x10 km^3)… The excess pressure to initiate the migration is about 10^{11} Pa … This is too huge.
- This may be due to the too big particles. We must increase the number of particles to about 1,000,000,000.
- In addition, under the realistic elastic properties, we need very large excess pressure. This means, we must include the effect of phase change (i.e., rapid increase of volume) must be included.

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Future works

- Multi-scale analysis (10e-3 – 10e3 m)
  - Relation between macro-micro physical properties
- Application the model to observation data
- Normalization of the formulation
- Bubbling of magma due to depressurization

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