Research on Bounce Behavior of Spherical Target Marker with Spikes

32th Workshop on JAXA Astrodynamics Symposium and Flight Mechanics

○ Shun YASUDA
Tetsuya KUSUMOTO
Yoshiki SUGAWARA
Osamu MORI

Outline

1. Introduction
2. Method
3. Behavior analysis
    - A) Model without spikes
    - B) Model with spikes
4. Summary

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Sample Return (Hayabusa, Hayabusa2)

Target Marker was used for safe landing

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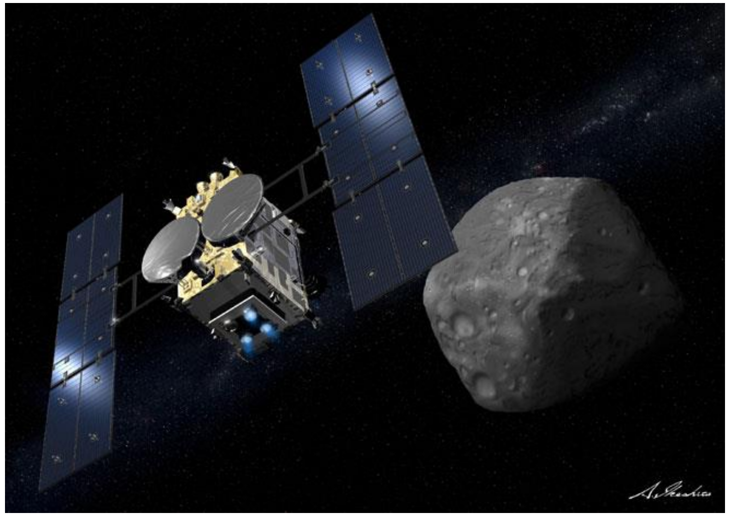
Hayabusa



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Hayabusa 2

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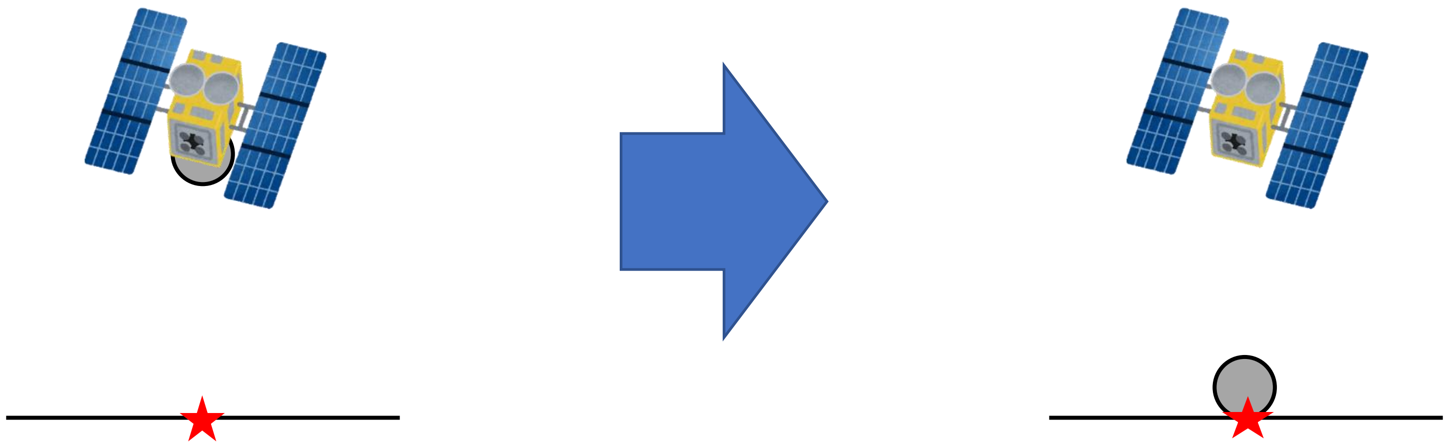
Target Marker

How to Use Target Marker



(1) Dropping

(2) Landing

Target point

Target point

Target Marker must be accurately placed at target point

- No bounce
- Do not move horizontally

Structure of Target Marker

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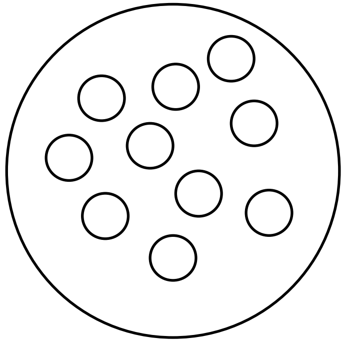
Target Marker

① Contain multiple beads (like a beanbag)

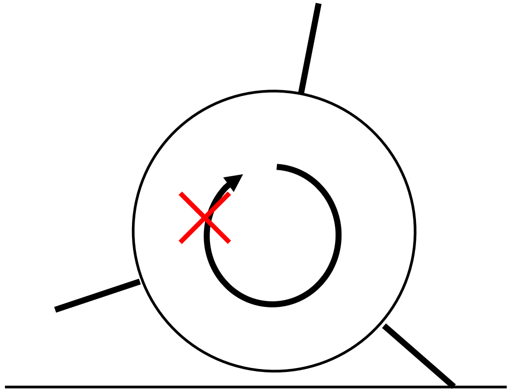


Hard shell

+

Multiple beads

② Have spikes to prevent rolling

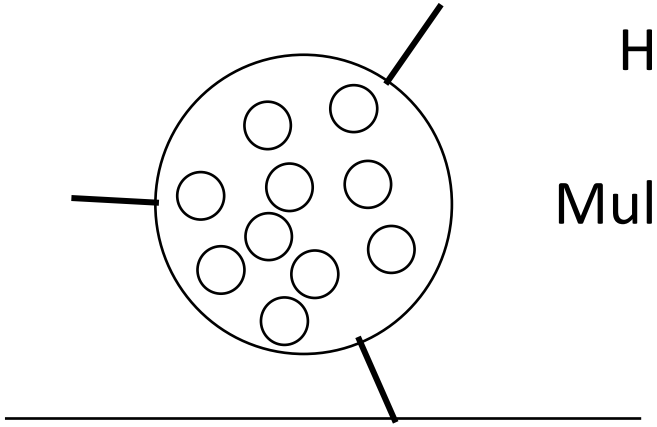


Purpose

Problems

- Shock absorption mechanism is not clear
- No studies have been conducted on the effects of spikes
- The combined model has not been discussed

Combined model (①&②)



Hard shell
+
Multiple beads
+
Spikes

Purpose

Analyze the behavior of spherical Target Marker with spikes

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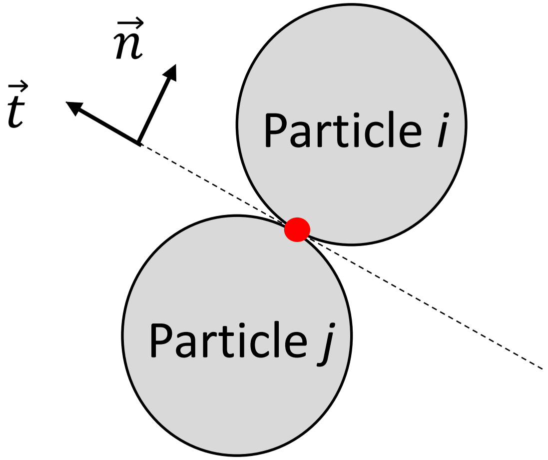
Non-smooth DEM: Contact Determination

- Treat particles individually
- Contact forces between particles are a function of relative velocity



Objects are modeled as **circles**

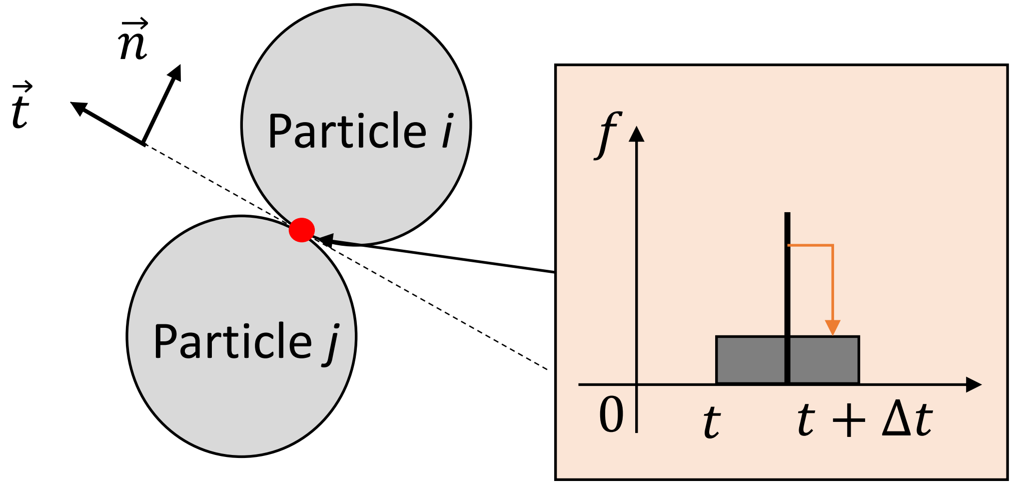
Contact determination

$$\begin{cases} d \leq r_j + r_i & \Rightarrow \text{Contact} \\ d > r_j + r_i & \Rightarrow \text{No contact} \end{cases}$$

d: Particle distance
r: Particle radius

Non-smooth DEM: Transfer Equation

- Treat particles individually
- Contact forces between particles are a function of relative velocity



Convert impact force into impulse

Transfer equation

$$\boldsymbol{\mathcal{W}}_{nn}^{\alpha\alpha} \boldsymbol{f}_n^{\alpha} + \boldsymbol{\mathcal{W}}_{nt}^{\alpha\alpha} \boldsymbol{f}_t^{\alpha} = (1 + \boldsymbol{e}_n) \frac{1}{\delta t} \boldsymbol{u}_n^{\alpha} + \boldsymbol{a}_n^{\alpha}$$

$$\boldsymbol{\mathcal{W}}_{tt}^{\alpha\alpha} \boldsymbol{f}_t^{\alpha} + \boldsymbol{\mathcal{W}}_{tn}^{\alpha\alpha} \boldsymbol{f}_n^{\alpha} = (1 + \boldsymbol{e}_t) \frac{1}{\delta t} \boldsymbol{u}_t^{\alpha} + \boldsymbol{a}_t^{\alpha}$$

α :Contact point
u :Relative velocity
t :Time
$\mathcal{W}$:Jacobian

e:Coefficient of Restitution
$\vec{f}$:Contact force
$\vec{n}$:Normal vector
$\vec{t}$:Tangent vector

Non-smooth DEM: Complementarity Condition

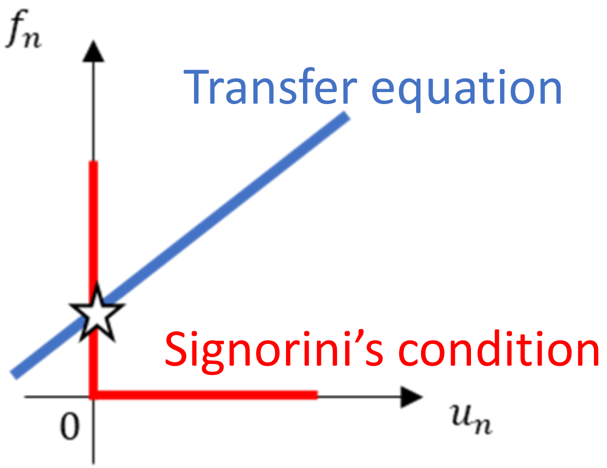
Signorini’s condition

$$\begin{cases} \boldsymbol{\delta_n} > \mathbf{0} \Longrightarrow \boldsymbol{f_n} = \mathbf{0} \\ \boldsymbol{\delta_n} = \mathbf{0} \wedge \begin{cases} \boldsymbol{u_n} > \mathbf{0} \Longrightarrow \boldsymbol{f_n} = \mathbf{0} \\ \boldsymbol{u_n} = \mathbf{0} \Longrightarrow \boldsymbol{f_n} \succcurlyeq \mathbf{0} \end{cases} \end{cases}$$

δ_n: Normal relative distance

u_n: Normal relative velocity

f_n: Normal contact force



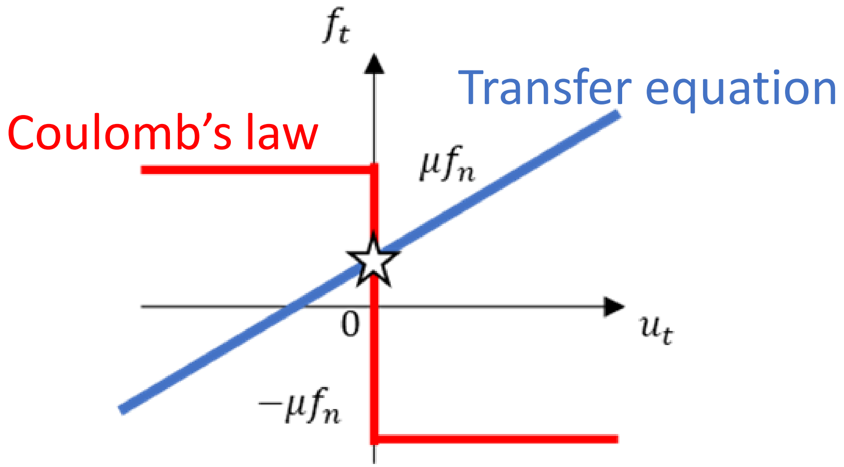
Coulomb’s law

$$\begin{cases} \boldsymbol{u_t} > 0 \Rightarrow \boldsymbol{f_t} = -\mu \boldsymbol{f_n} \\ \boldsymbol{u_t} = 0 \Rightarrow -\boldsymbol{\mu f_n} \leq \boldsymbol{f_t} \leq \mu \boldsymbol{f_n} \\ \boldsymbol{u_t} < 0 \Rightarrow \boldsymbol{f_t} = \mu \boldsymbol{f_n} \end{cases}$$

u_t: Tangential relative distance

f_t: Tangential relative velocity

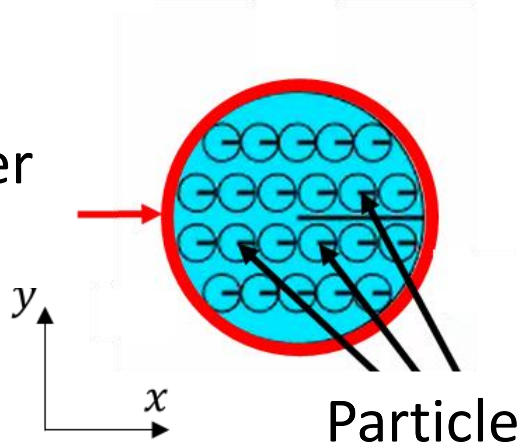
μ : Coefficient of friction



Outline

Behavior Analysis: Model without Spikes

Model



Analysis condition

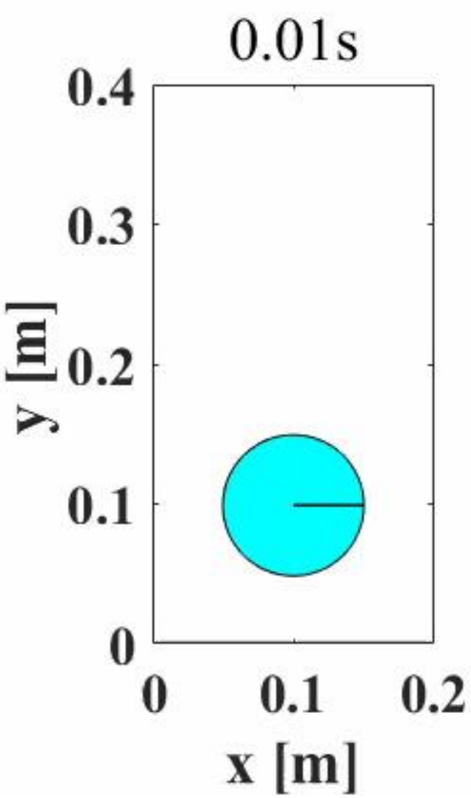
Time step [s]	0.0001
Simulation time [s]	3
Gravity acceleration [m/s²]	0
Outer shell	
Mass [kg]	55×10^{-3}
Diameter [m]	100.8×10^{-3}
Horizontal initial position [m]	0.1
Vertical initial position [m]	0.1
Inner ball	
Mass [kg]	3.0×10^{-3}
Diameter [m]	14.8×10^{-3}
Particle number	22
Mass ratio	1.2
Coefficient of restitution and friction	
Horizontal coefficient of restitution	0.7
Vertical coefficient of restitution	0.7
Coefficient of friction	0.5

Actual size

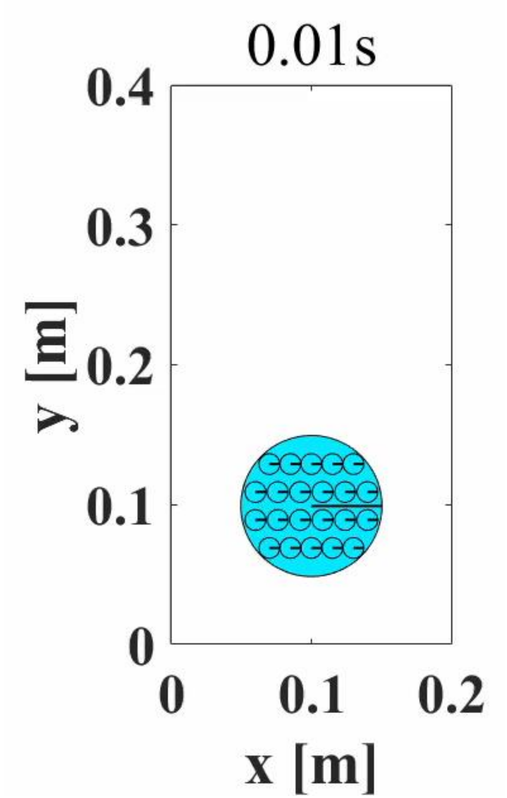
= Actual fill rate

= Whole particle/Outer shell

Vertical Drop (0.1 m/s)

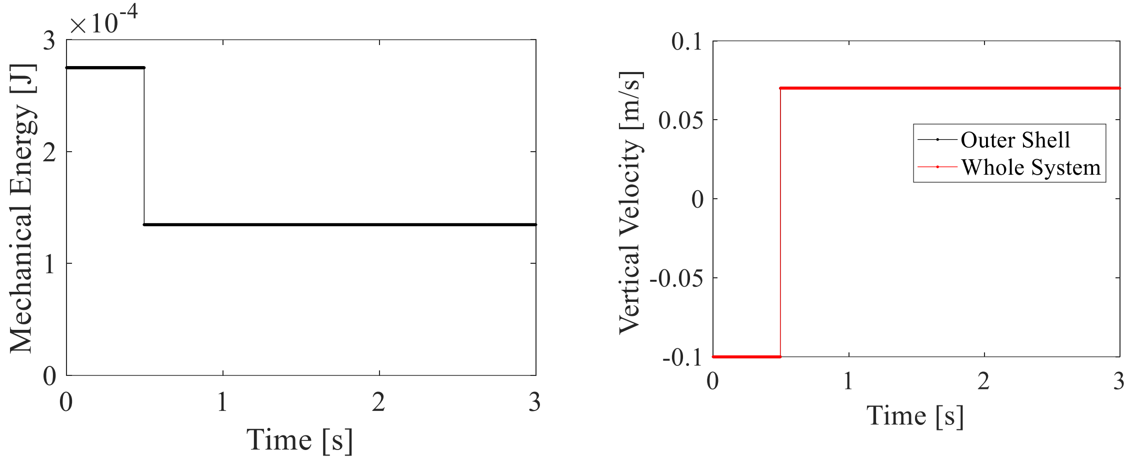


No particle



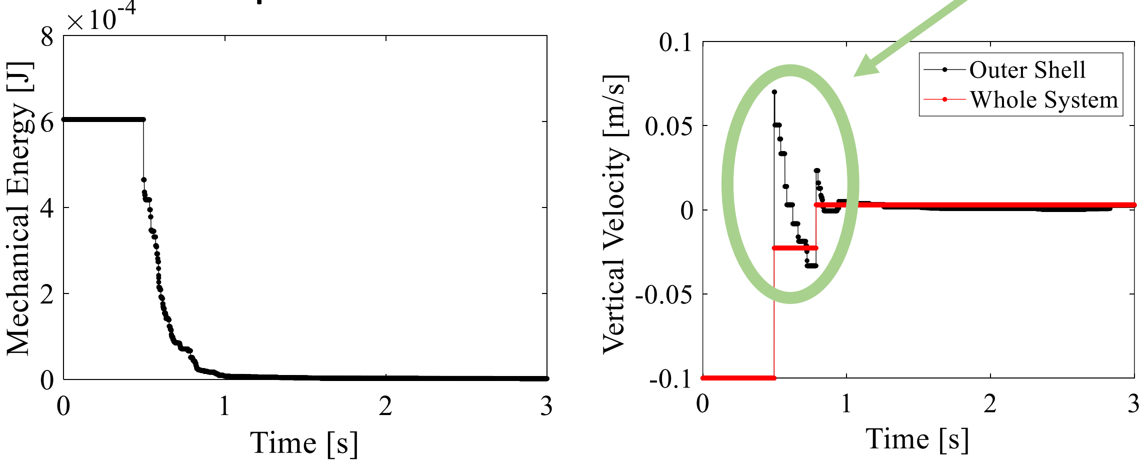
Contain particles

No particle

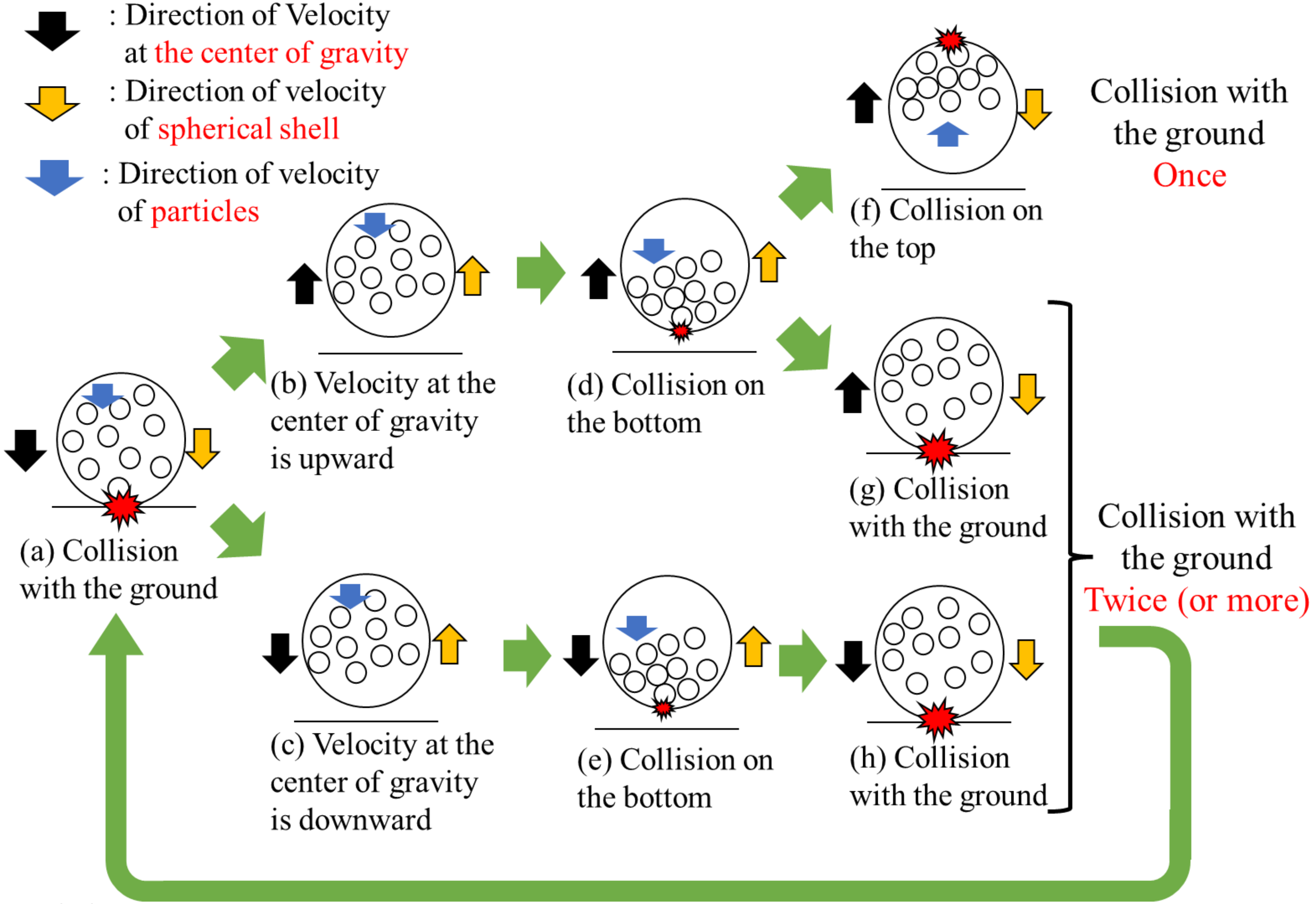


Two collisions with the ground

Contain particles



Mechanism of Collision with the Ground



⬇ : Direction of Velocity at the center of gravity

⬇ : Direction of velocity of spherical shell

⬇ : Direction of velocity of particles

(a) Collision with the ground

(b) Velocity at the center of gravity is upward

(c) Velocity at the center of gravity is downward

(d) Collision on the bottom

(e) Collision on the bottom

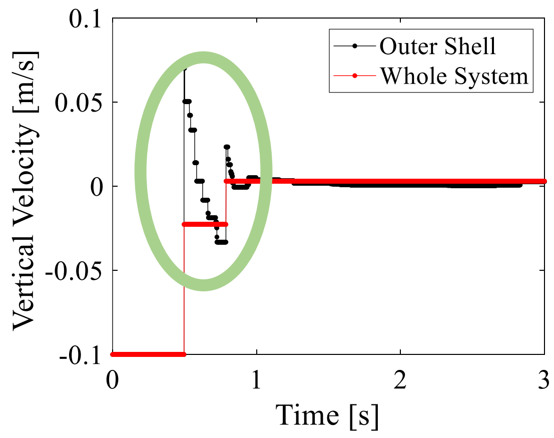
(f) Collision on the top

(g) Collision with the ground

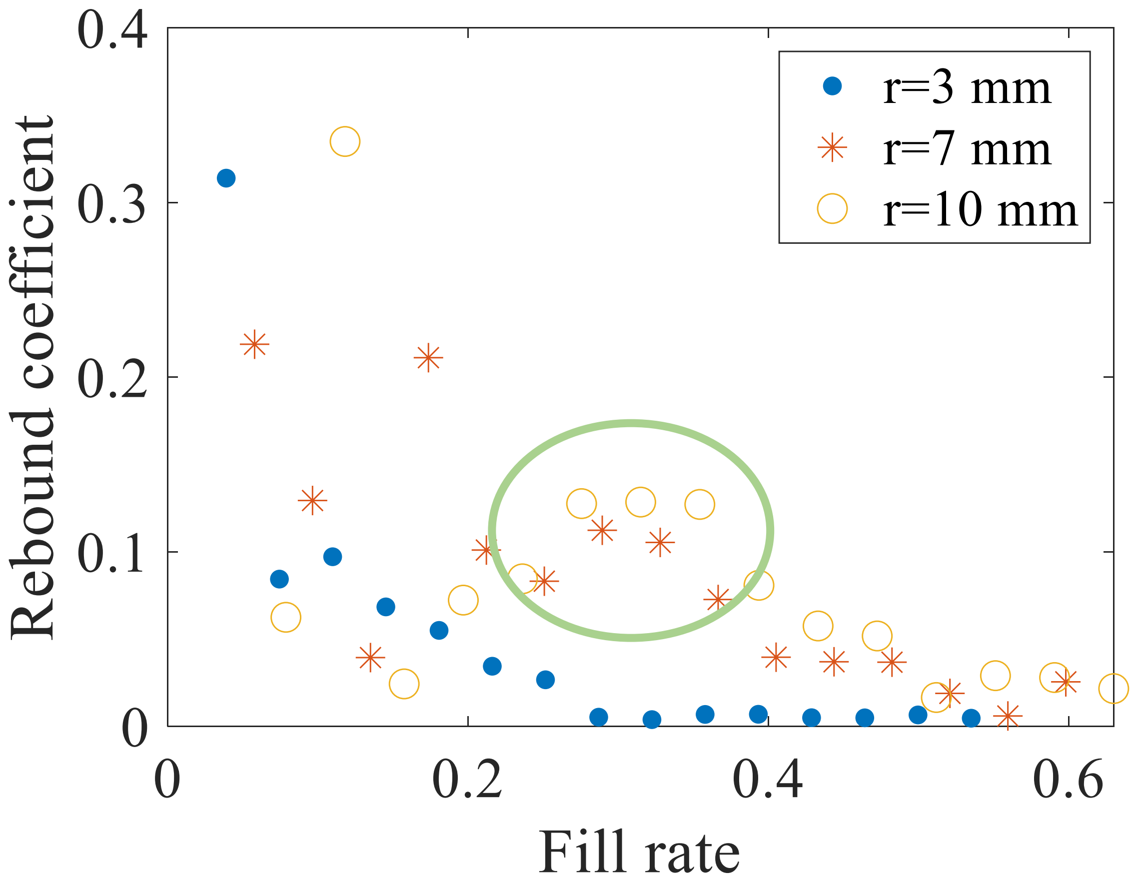
(h) Collision with the ground

Collision with the ground Once

Collision with the ground Twice (or more)



Change the Number of Particles & Particle Size



$$\text{Rebound coefficient} = -\frac{\text{Velocity after bounce}}{\text{Velocity before bounce}}$$

- The higher the fill rate, the better the shock absorption
- Smaller particle size is better
- When the number of particles is small, results are inconsistent
- Shock absorption performance is worse when fill rate is 0.3 (r=3 mm, 7 mm)

Effect of particle placement on ground impact

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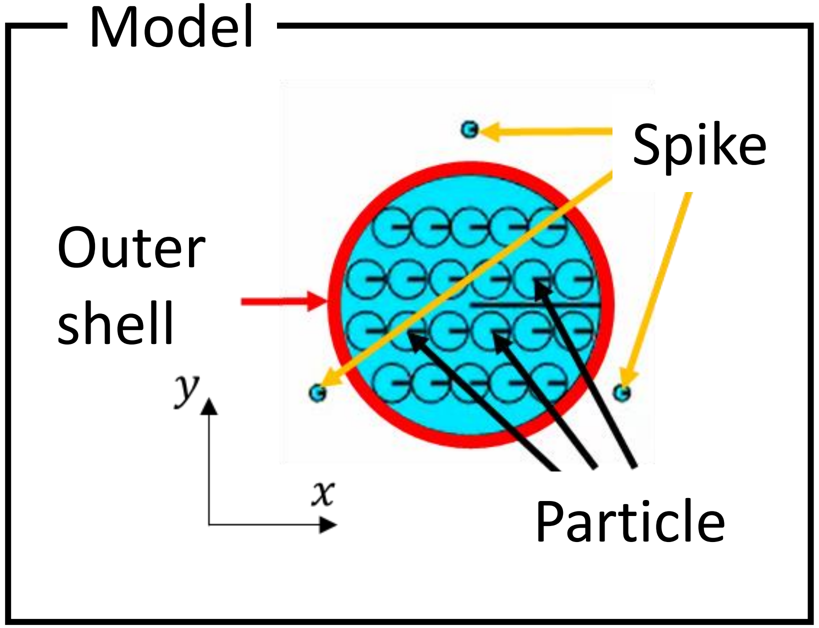
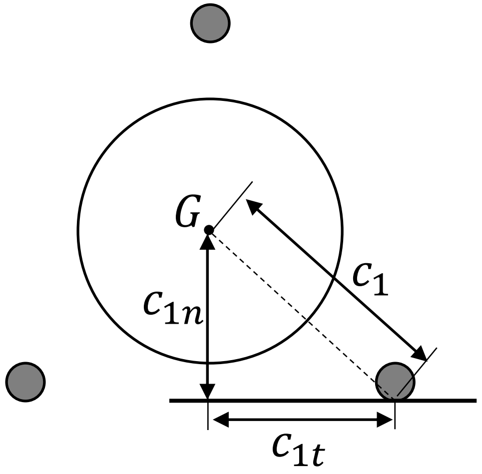
Behavior Analysis: Model with Spikes

Modeled by placing particles at the tips of spikes



Spike length: 35 mm, 100 mm

Spike mass: 5 g



$$\mathcal{W}_{nn}^{\alpha\alpha} = \frac{1}{m_1} + \frac{1}{m_2} + \frac{(c_{1t})^2}{I_1} + \frac{R^2}{I_2}$$

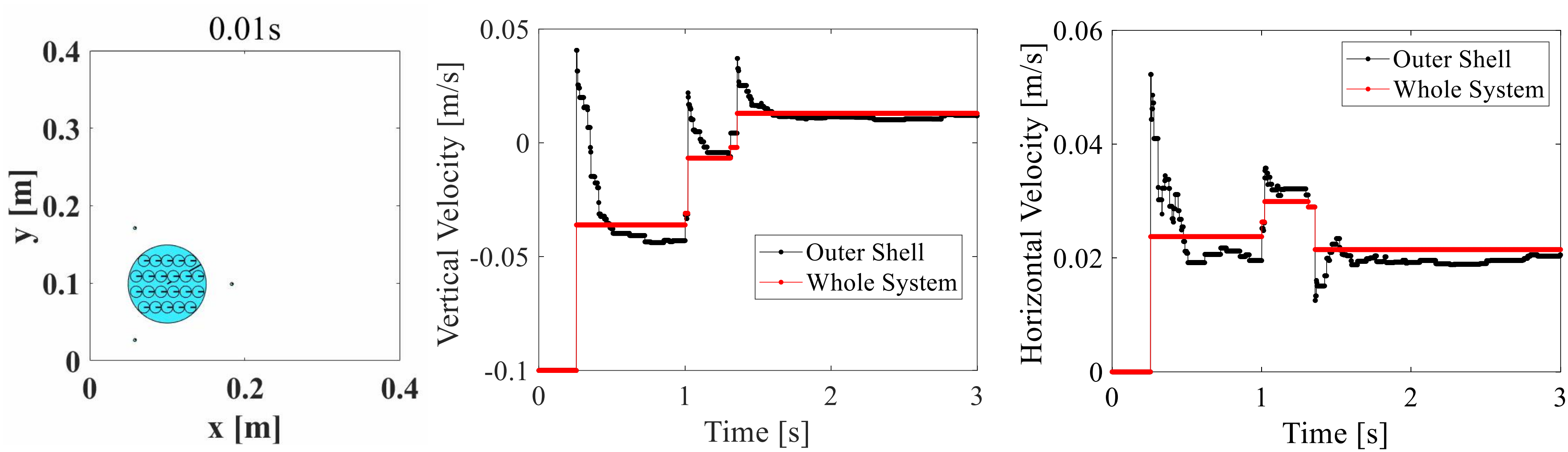
$$\mathcal{W}_{tt}^{\alpha\alpha} = \frac{1}{m_1} + \frac{1}{m_2} + \frac{(c_{1n})^2}{I_1}$$

$$\mathcal{W}_{nt}^{\alpha\alpha} = \frac{c_{1n}c_{1t}}{I_1}$$

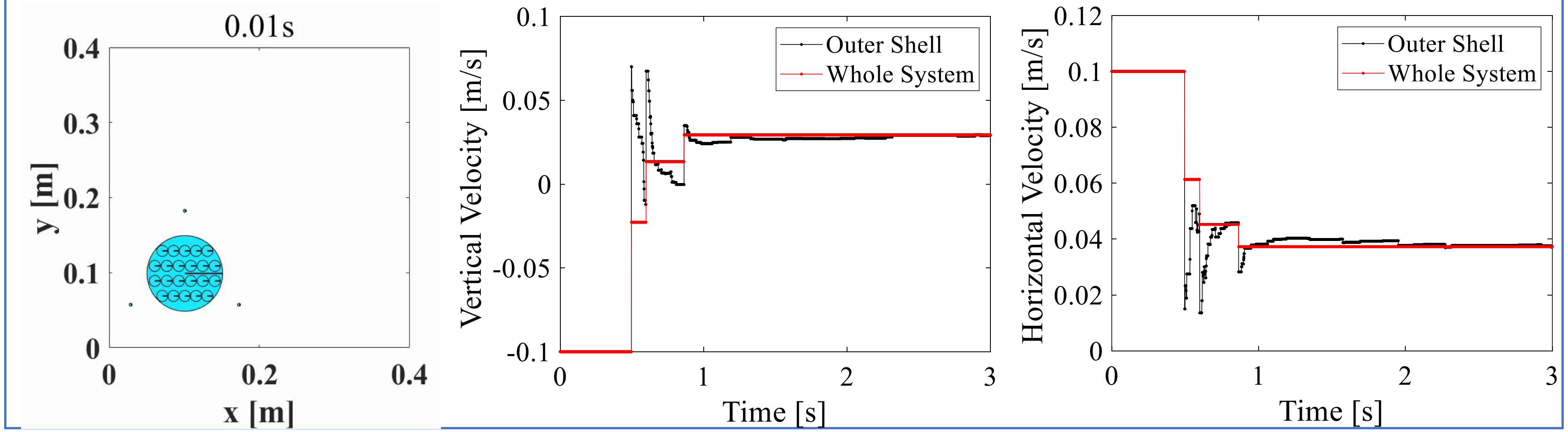
R : Ground particle radius

Basic Bounce Behavior

① Initial angle: π/6 rad, Vertical drop

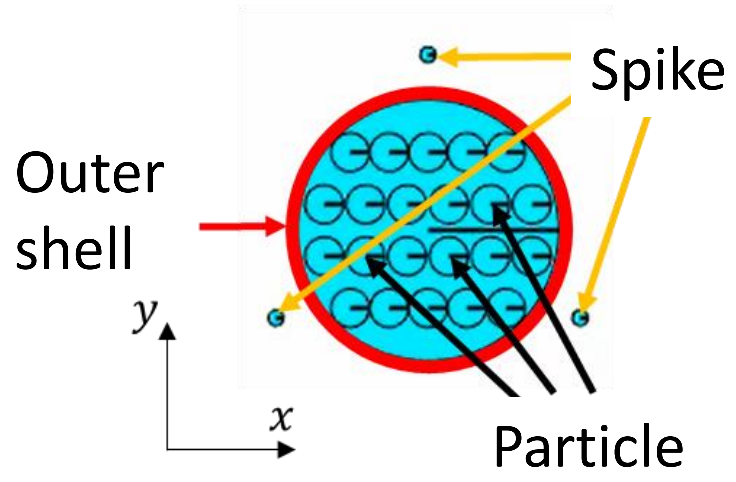


② Initial angle: 0 rad, Vertical and horizontal drop



Monte Carlo Simulation

Model



Spike length: 35 mm, 100 mm
Spike mass: 5 g

Initial velocity

$$V_{x0} = N(0, \sigma_x^2)$$

$$V_{y0} = N\left(-0.1, \sigma_y^2\right)$$

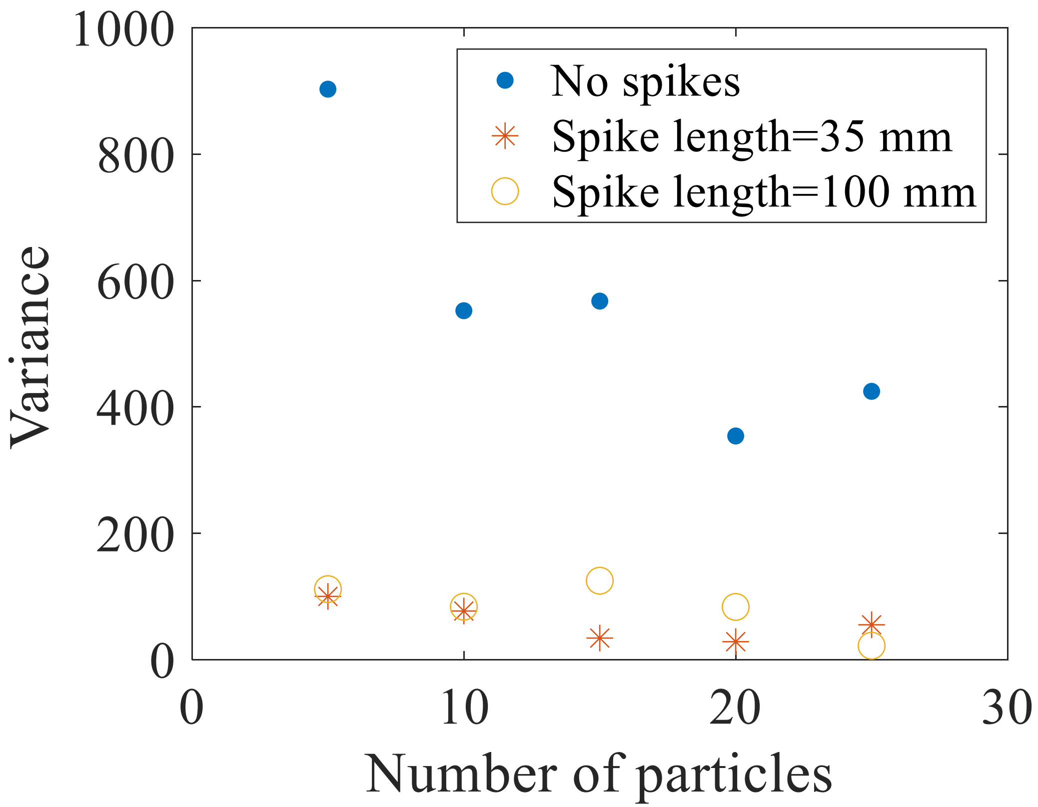
$$\dot{\theta}_{G0} = N(0, \sigma_\omega^2)$$

σ: Standard deviation
σ^2: Variance

Trial bins	100
Time step [s]	0.01
Gravity acceleration [m/s²]	0.0001
Horizontal initial position [m]	0
Vertical initial position [m]	0.3
Initial angle ($3\sigma_\theta$) [rad]	0
Horizontal standard deviation ($3\sigma_x$) [m/s]	6×10^{-2}
Vertical standard deviation ($3\sigma_y$) [m/s]	1×10^{-2}
Standard deviation of angular velocity ($3\sigma_\omega$) [rad/s]	1

Effect of Spikes

Final resting horizontal position



$$\text{Variance} = \frac{1}{100}\sum(x_l - 0)^2$$

Trial bins

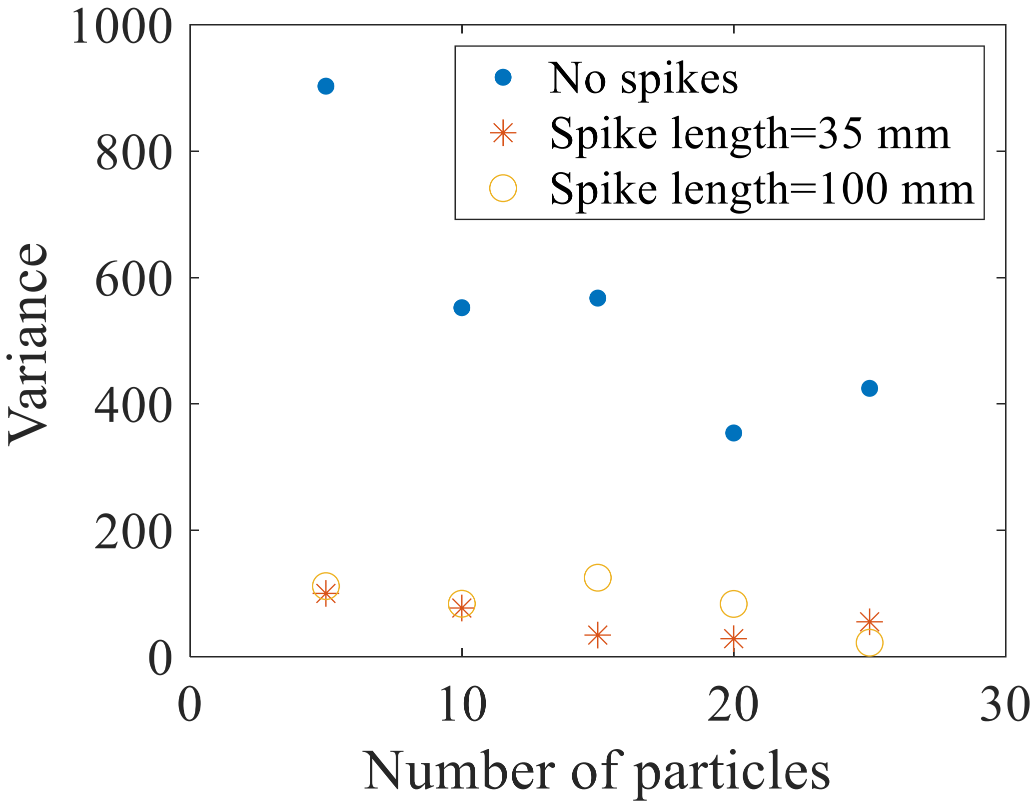
Target point

Variance is small → Static performance is high

- Spikes restrain horizontal movement

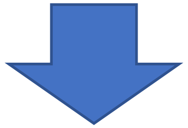
Length of Spikes: Final Resting Position

Final resting horizontal position



Result of changing the length of the spikes

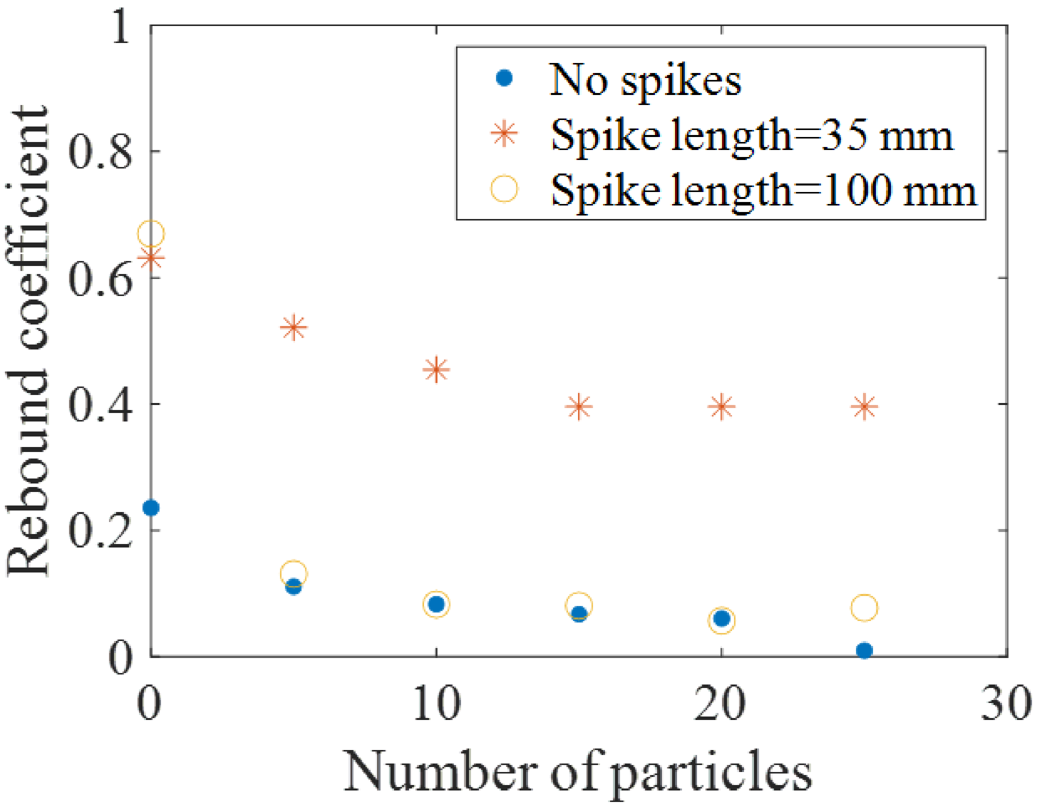
- 35 mm : About the same as actually used
- 100 mm: Extremely long



- Results for extremely long cases are dependent on the number of particles
- Results for the spike length of 35 mm are stable and not affected by the number of particles

Length of Spikes: Rebound Coefficient

Rebound coefficient



$$\text{Rebound coefficient} = -\frac{\text{Max. velocity after bounce}}{\text{Velocity before bounce}}$$

- At 35mm the bounce is significant and at 100mm there is no difference between the case without the projection

- 35mm is still not long enough
  - ➢ Expected to be bounded by the length of the spike

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Summary

- Analyzed the behavior of Target Markers with spikes used Non-smooth DEM
- Shock absorption performance is better with
  - A) smaller particle size
  - B) higher fill rate
- Spikes are effective in controlling horizontal movement
- Optimal length for spikes may exist, considering shock absorption performance