Exploring Failure Evolution of Anti-dip Slate Slope Using Centrifuge Test and Discrete Element Method

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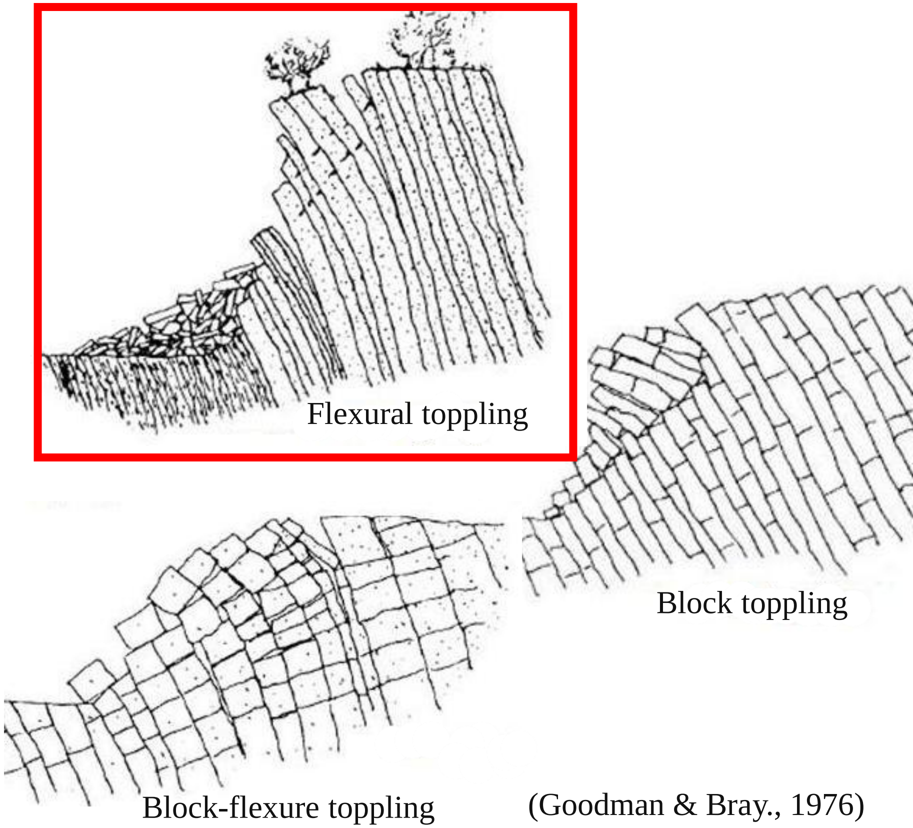
Introduction

What is Toppling Failure?

Toppling failure is a type of slope instability mechanism that typically occurs in rock layers with anti-dip.

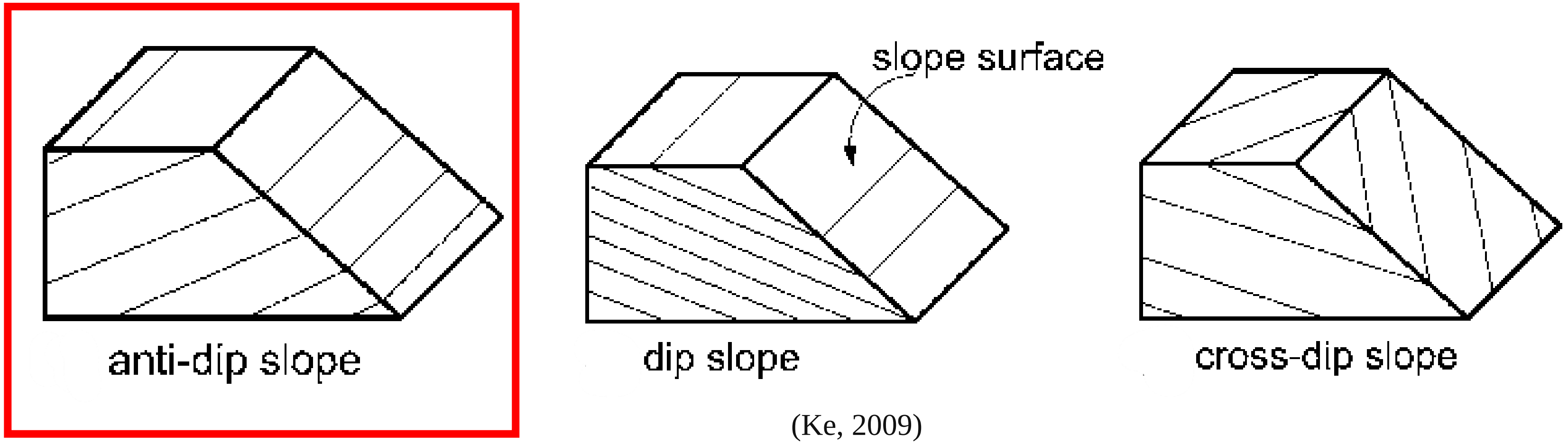
- The type of toppling failure in this report belongs to **flexural toppling**.
- It primarily occurs in layered rocks, such as slate and shale.



(Goodman & Bray., 1976)

What is Anti-dip Slope?

The dip direction of the rock layers is opposite to the slope direction.

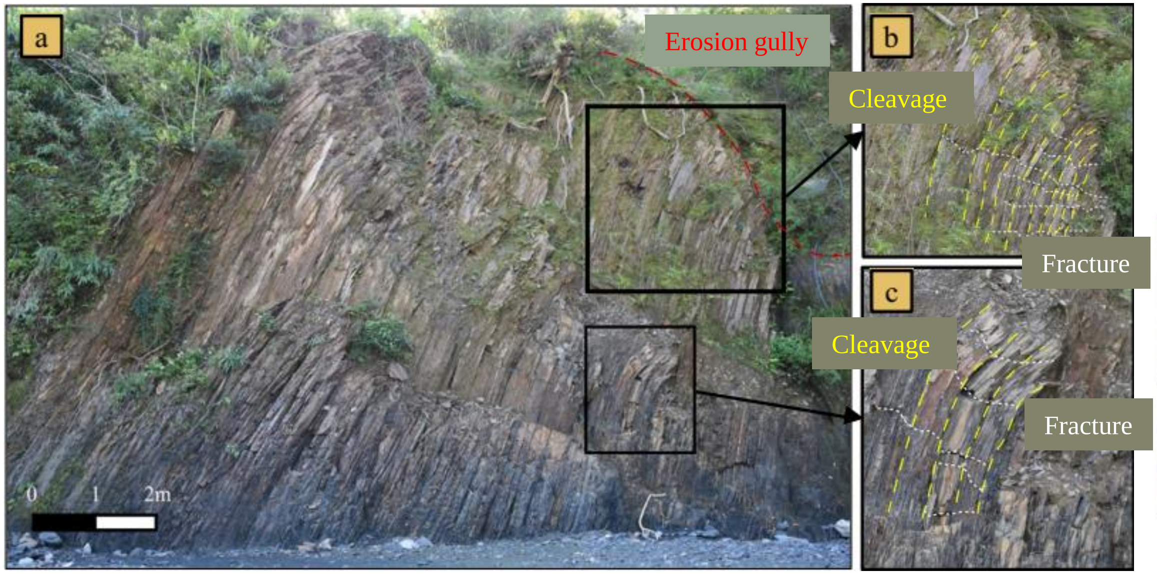


(Ke, 2009)

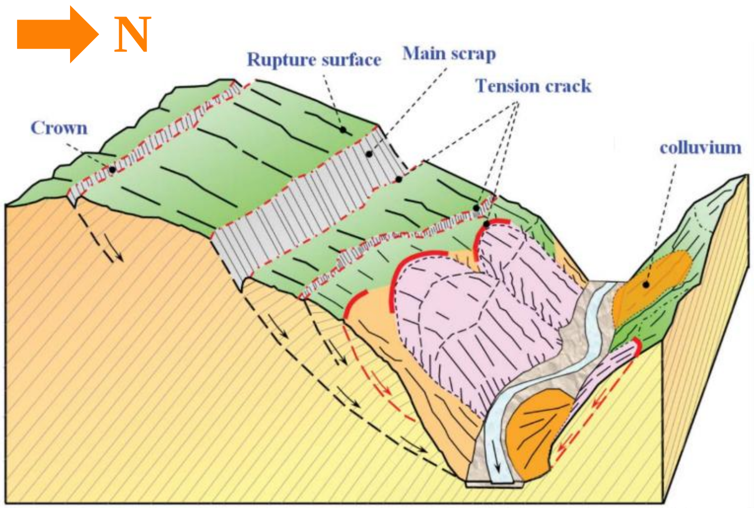
Introduction

1. Lo (2017) studied the deep-seated landslides in the Putanpunas stream and found that **toppling failure occur in the anti-dip slopes**.
2. Weng et al. (2024) investigated **the toppling failure mechanism of the anti-dip slate slopes** through centrifuge tests and discrete element method (DEM) simulations.

Toppling failure in the right bank of the study area (Lo, 2017)



Flexural toppling of anti-dip slate slopes in Ilan, Taiwan (Weng et al., 2024)



Profile map of the study area (Lo, 2017)

Objective

- Analyze the influence of existing fractures and cleavage on toppling failure in an anti-dip slope.

Collected samples

- **Have** existing fractures
- **No** existing fractures

Effects of existing fractures

Location
- Upper part
- Lower part

Spacing
- Wide
- Narrow

Length
- Long
- Short

Methods

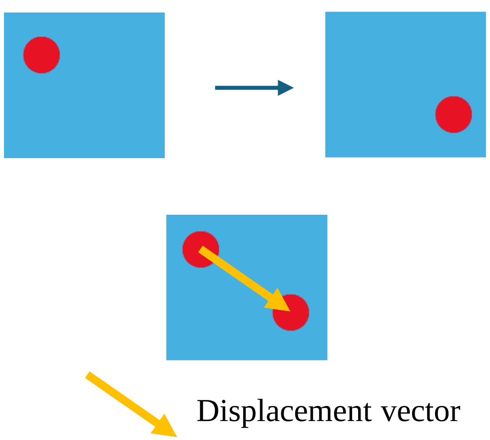
Why choose centrifuge test?

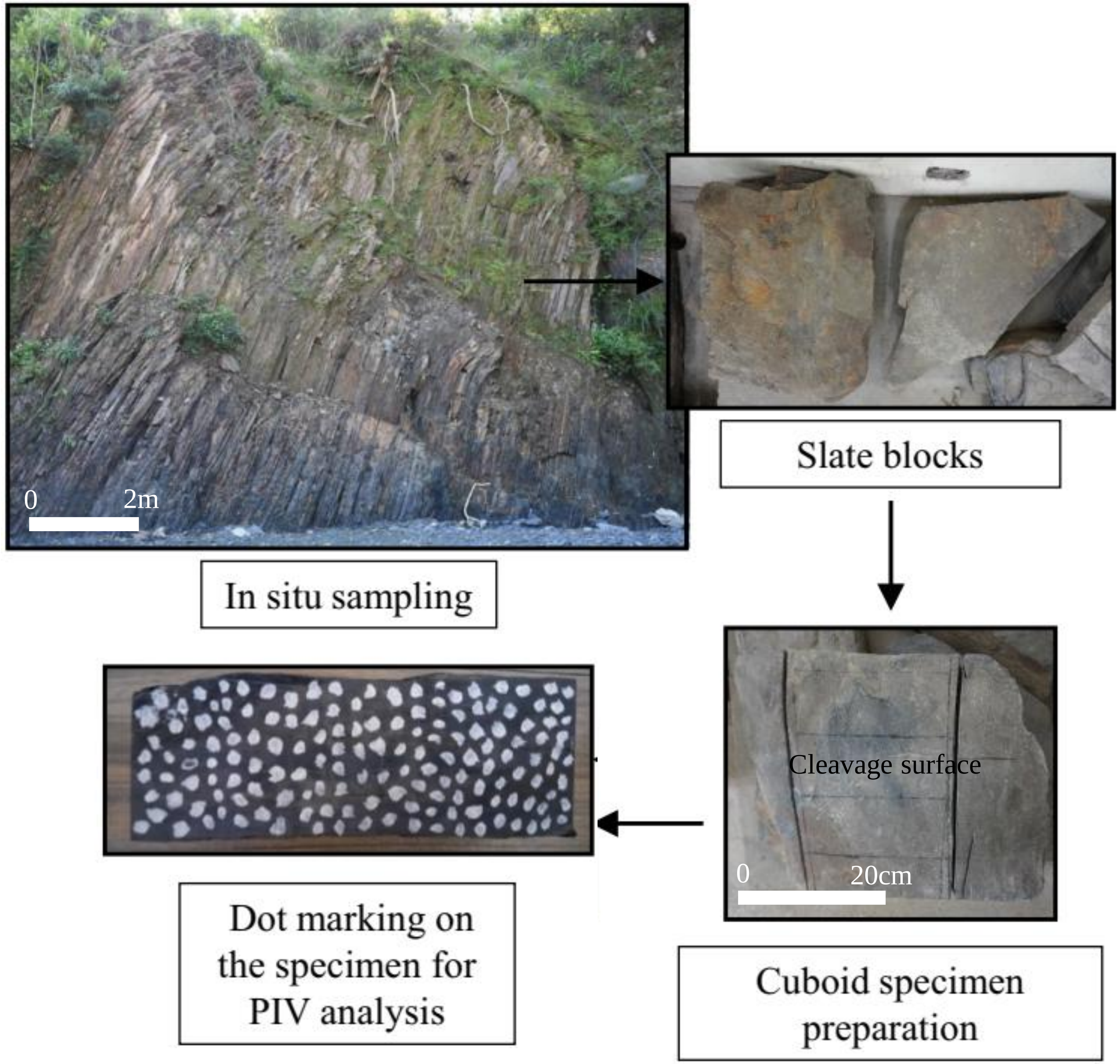
Outcrop of Centrifuge test Sample

Slope high: ~15m

Comprises slate and argillite with mature cleavage. Steep angle of the cleavage of 75° opposite to the slope direction.

What is PIV?





PIV (Particle Image Velocimetry)

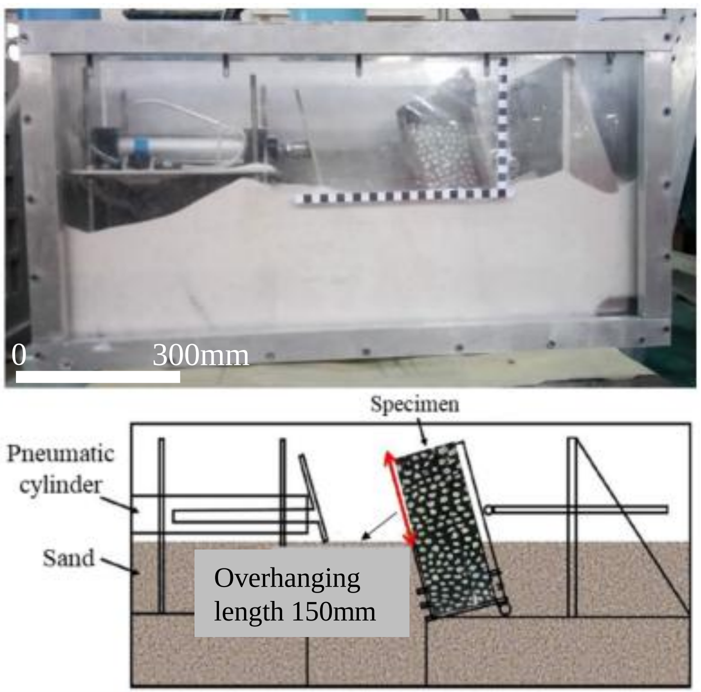
Specimens preparation for the centrifuge test

Methods

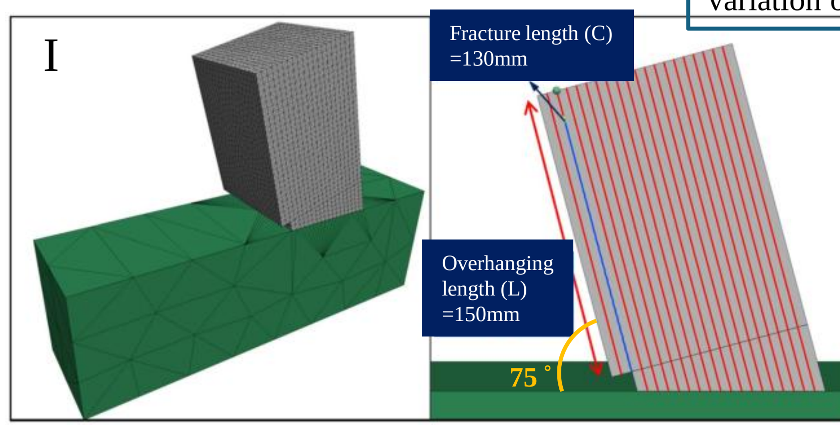
- Centrifuge test: Simulated the deformation and failure process of rock layers under different fracture conditions in **artificial gravity environment**.
- Discrete Element Method (DEM) **simulation**: Developed a **numerical model of anti-dip slate slopes** to analyze the effects of fractures & cleavage on toppling failure.

Implemented a customized **Foliation Failure Criterion (FFC):** $\tau_f = [\alpha T_0(\sigma_n + T_0)]^\beta$

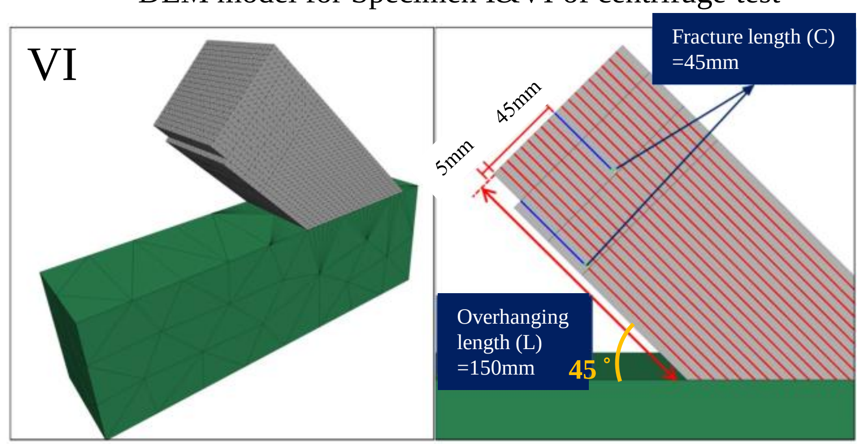
T_0: Tensile strength
α, β: Two parameters related to the nonlinear variation of the criterion



Experimental setup of the centrifuge test



DEM model for Specimen I&VI of centrifuge test



Results – Sample I

Except for Samples I and VI, no significant deformation or failure was observed in other samples, even when the gravity reached 80 g.

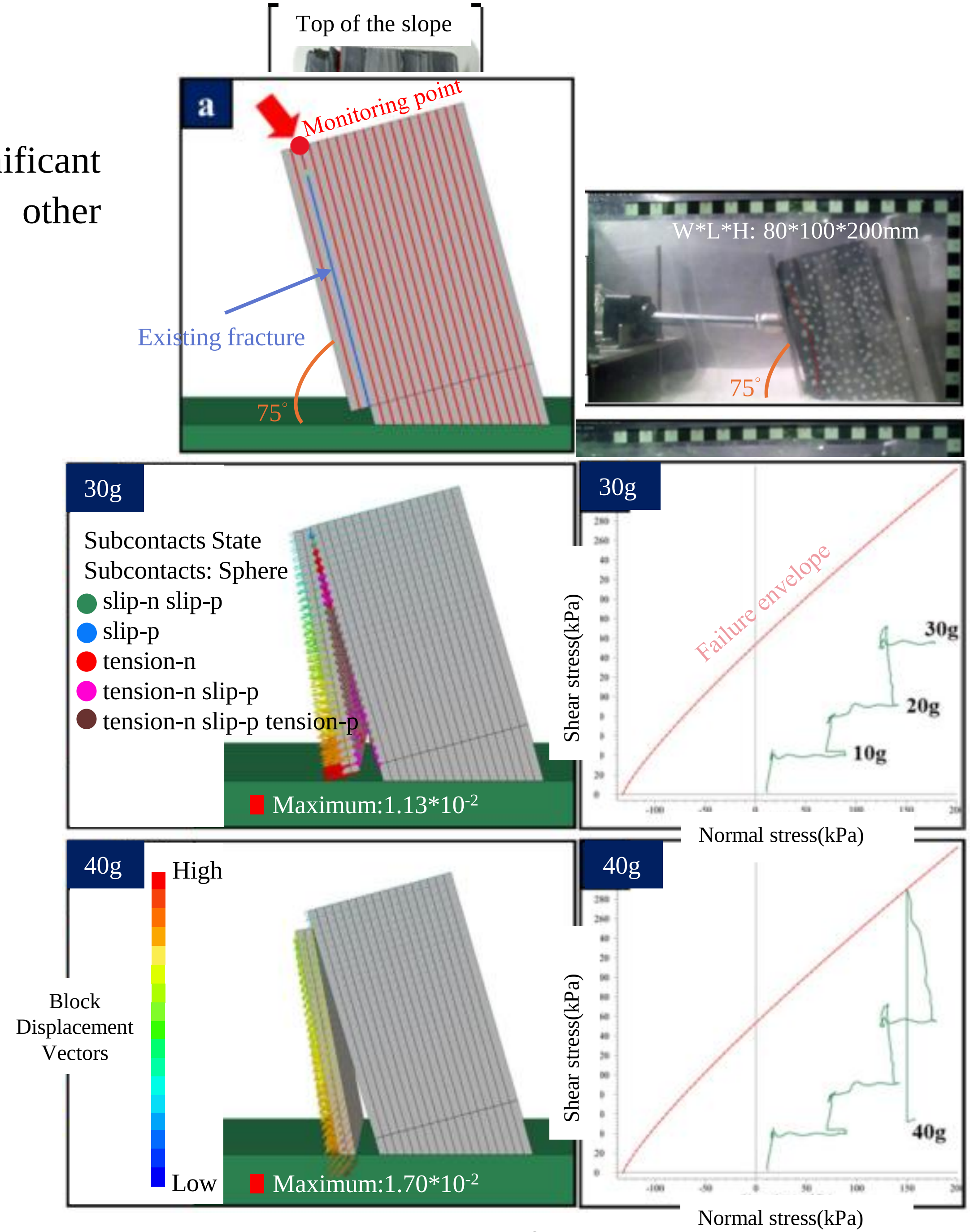
Centrifuge Test:
(Sample I)

- A fractures existed at the bottom of slope.
- When gravity **=40g**, the fracture underwent **forward tipping breakage** along the slope.

Simulation:
(Sample I)

- When gravity **=30g**, the fracture **began to propagate upward.**
- When gravity **=40g**, the fracture completely penetrated the front layer, forming a **free block**.

✓ The results of the **centrifuge tests and DEM simulations** are consistent.



Simulation results of Test I

Results – Sample VI

Centrifuge Test:

(Sample VI)

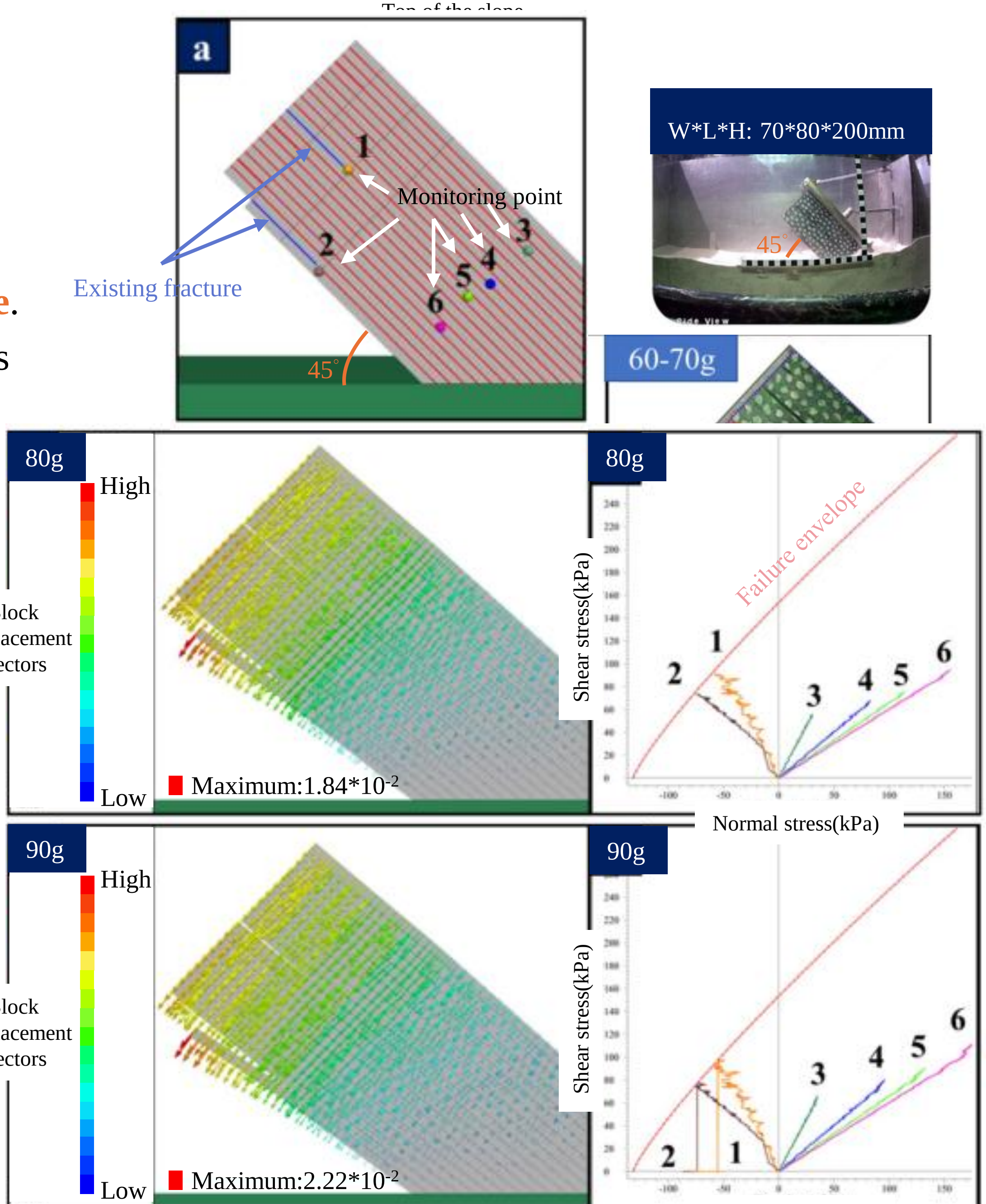
- **Two fractures existed at the top of slope**.
- When gravity **=80g**, no failure was observed in the sample.

Simulation:

(Sample VI)

- When gravity **=80g**, no failure or fracture propagation was observed.
- When gravity **=90g**, the fractures **began to propagate along the cleavage direction**, leading to **toppling failure**.

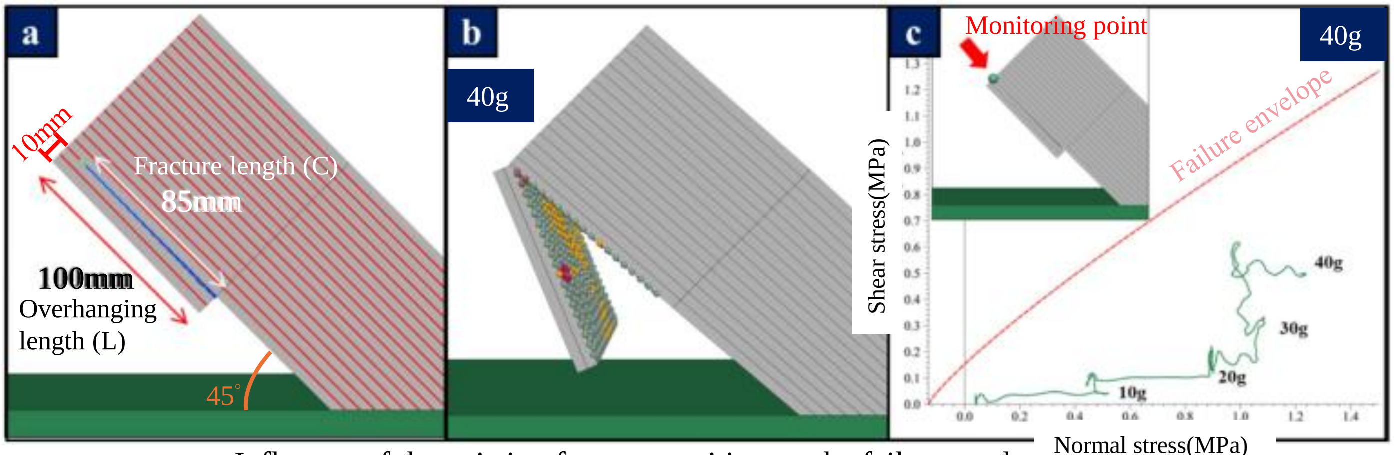
✓ The results of the **centrifuge tests and DEM simulations** are consistent.



Simulation results of Sample VI

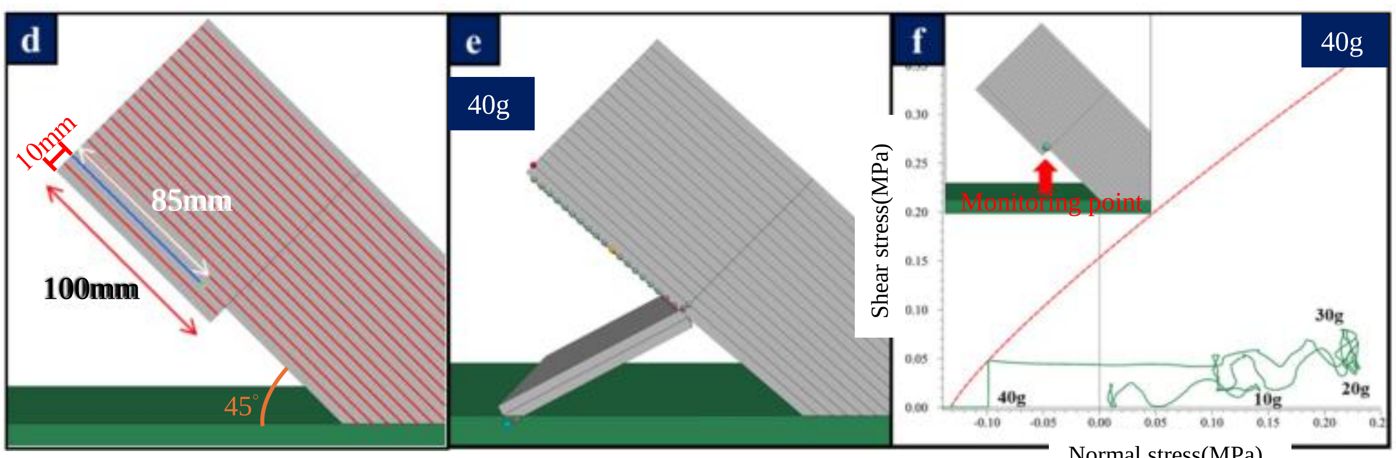
Discussion – Fracture location

- **Lower fractures (a, b, c)** → The fractures propagate upward but **do not penetrate** the rock layer.



Influence of the existing fracture position on the failure mode

- **Upper fractures (d, e, f)** → The fractures propagate downward and **penetrate** the rock layer.



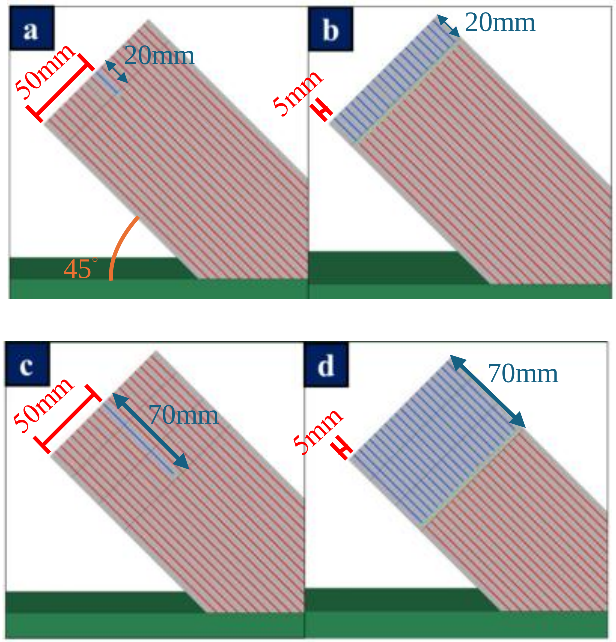
Influence of the existing fracture position on the failure mode

➢ **The fractures on the upper slope propagate more easily** than those on the lower slope due to gravity.

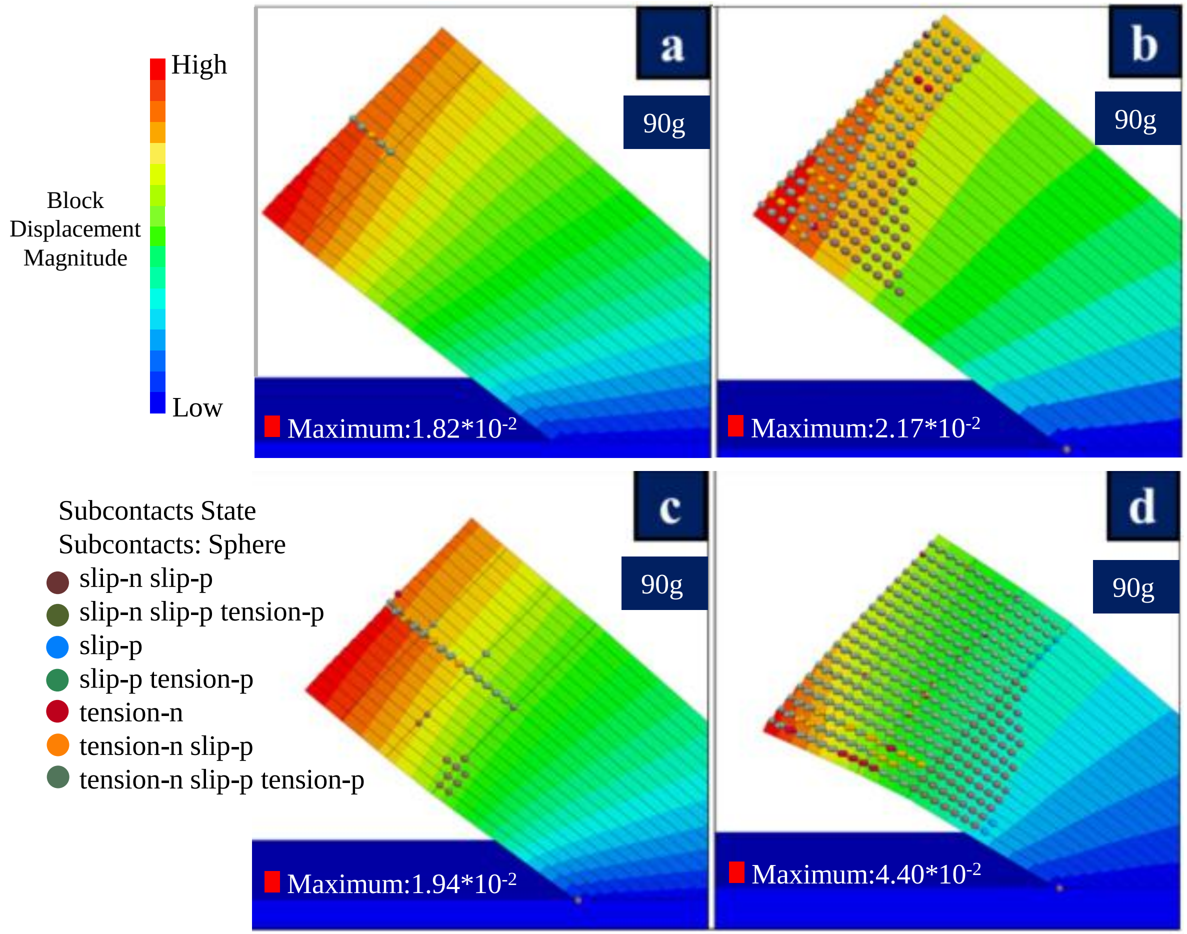
Discussion – Fracture spacing & length

The influence of **fracture spacing and length** on the failure mode

DEM models with different spacing and lengths of existing fractures



Effect of spacing and length of existing fractures on failure modes



- The **longer the fracture** and the **smaller the spacing**, the greater the degree of failure.

- **Cleavage itself does not directly cause failure,** the actual failure is driven by **fracture development**.

Conclusions

1. Toppling failure of the anti-dip slope was **initiated by existing fractures**, rather than the original cleavage.

2. The cleavage is regarded as a kind of weak plane in the rock mass, **it retains a higher strength than the existing fracture** so that the toppling failure is difficult to initiate from the cleavage.

3. The **fractures located on the top propagate easily** rather than those on the bottom.

4. **The smaller the distance** between the fractures and **the longer the initial length** of the fractures, the higher the proportion of failure caused.

Thank you for listening