Effect of Model Scale and Particle Size Distribution on PFC3D Simulation Results

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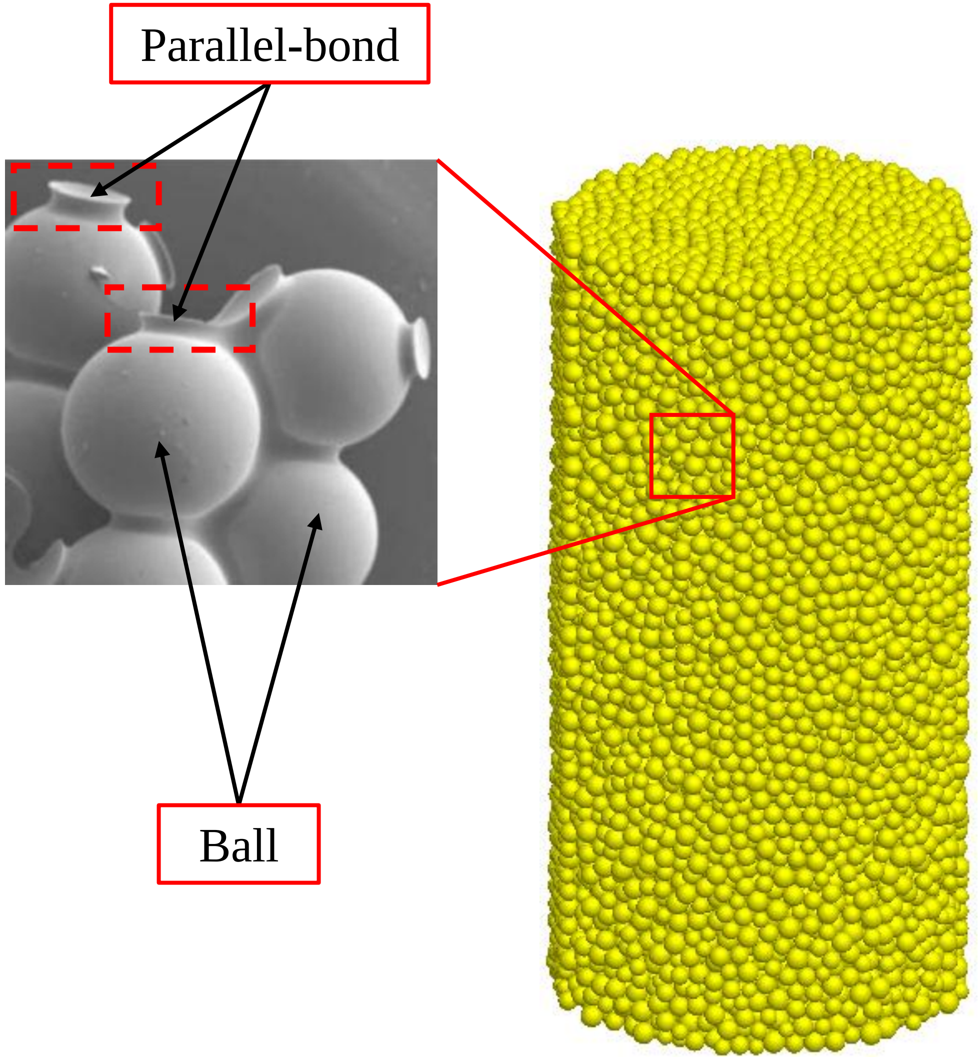
Outline

- Introduction
- Methodology
- Results and Discussion
- Conclusions
- My Study

Rock can be considered a granular material with discontinuous and heterogeneous behavior at the microscale. Discontinuous numerical methods are especially capable of capturing this type of behavior.

Particle Flow Code(PFC) simulates rock as an assembly of bonded particles, capturing its mechanical behavior through interactions and bond breakage.

The effects of model size and particle size distribution factors that strongly influence simulation results are often overlooked in existing studies.

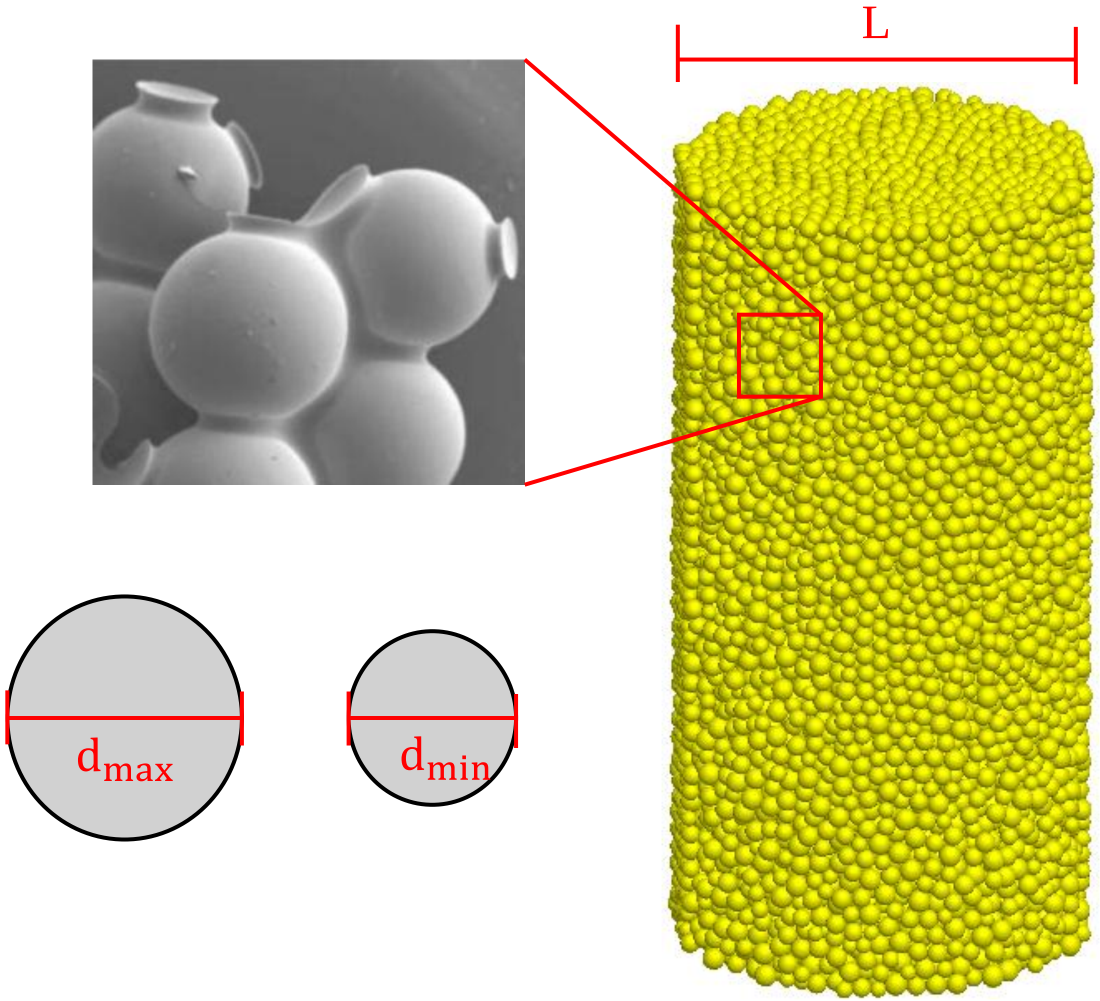


Objective

This study investigates how model size(L/d) and particle size distribution(d_{max}/d_{min}) affect the mechanical behavior of Discrete Element Method (DEM)specimens.

Numerical studies underscore the importance of well-justified parameter selection for accurate simulation of intact rock behavior.

Calibration parameters



L is the smallest model length

d is the average particle diameter, $d = \frac{d_{max}+d_{min}}{2}$

d_{max}/d_{min} is maxium/minmum particle diameter

Particle Flow Code (PFC^{3D})

Based on the Discrete Element Method (DEM) — Cundall, 1971

What is Discrete Element Method (DEM)?

Each particle acts as an independent moving unit. The interactions between particles, such as collisions, friction, and bonding, are described using contact models.

DEM allows simulation of both microscopic and macroscopic mechanical behaviors in granular materials and can represent random particle arrangements and failure phenomena observed in nature.

Application in geotechnical engineering fields：

Slope stability, tunnel excavation, hydraulic fracturing, debris flows, and the behavior of composite materials.

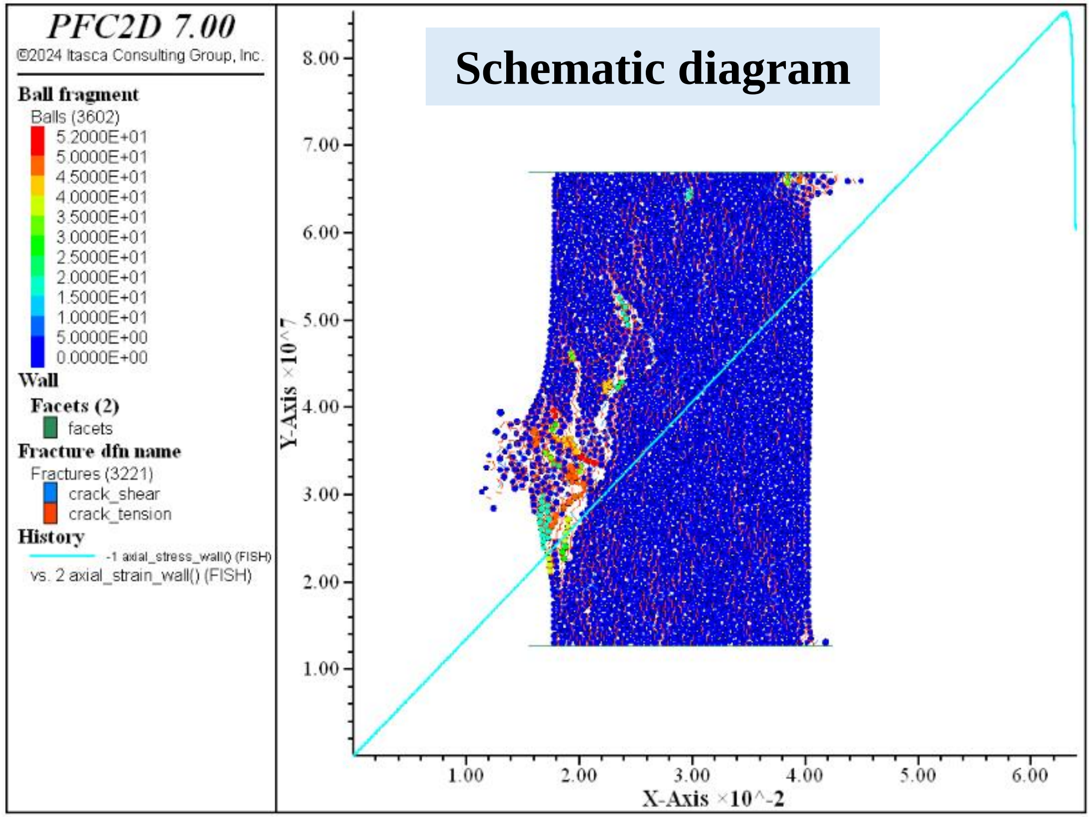


Figure 5: Results of the UCS test on the flat-jointed model.

(Itasca, 2019)

This study is based on microscopic parameters calibrated using the experimental data of Lac du Bonnet (LDB) granite.

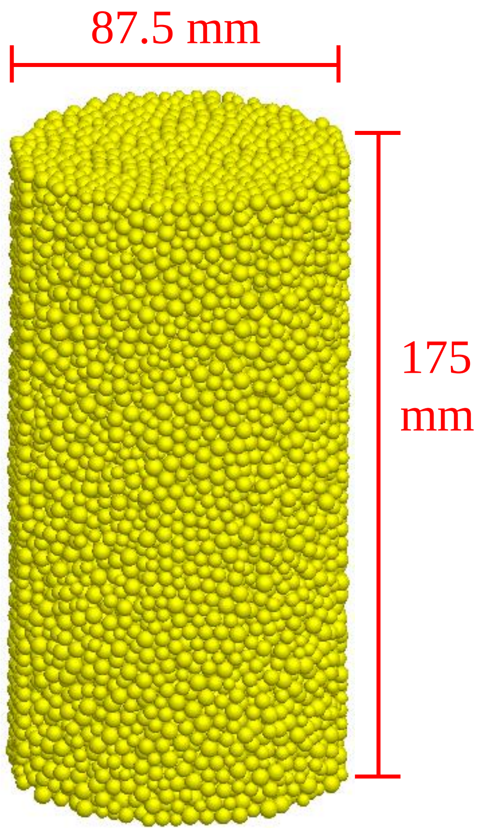
Steps

1. **Data collection:**
   Collect the basic physical and mechanical properties of the LDB granite from the published literature.
2. **Model generation in PFC3D:**
   Create a numerical model in PFC3D that mimics the particle size distribution of the LDB granite.
3. **Microscopic Parameter Calibration:**
   Adjust microscopic parameters so that the simulation results match experimental mechanical properties.
4. **Systematic Parameters Study:**
   Use the calibrated parameters to analyze the influence of model size and particle size distribution.

Experimental test data and calibration results

The micro-parameters were calibrated following the methodology of Potyondy and Cundall (2004) to reproduce the Unconfined Compressive Strength(UCS), Young's modulus, and Poisson's ratio.

Property (mean ± SD with *n* specimens)	Lab experiment	Potyondy and Cundall (2004)	This study
UCS, σ_c (MPa)	200 ± 22 (*n* = 81)	198.8 ± 7.2 (*n* = 10)	202.9 ± 3.9 (*n* = 20)
Young's modulus, *E* (GPa)	69 ± 5.8 (*n* = 81)	69.2 ± 0.8 (*n* = 10)	68.1 ± 0.59 (*n* = 20)
Poisson's ratio, *v*	0.26 ± 0.04 (*n* = 81)	0.256 ± 0.014 (*n* = 10)	0.289 ± 0.0015 (*n* = 20)
Specimen size (diameter/height) (mm)	63/157.5	31.7/63.4	87.5/175
L/*d* ratio	18	44.1	25



1. The simulation results shows smaller standard deviations (SD) compared to lab tests, meaning the material in the model is more consistent.
2. To reduce edge and particle size effects, we used larger samples with an L/d ratio of 25.
3. The calibrated model reliably replicates the macroscopic mechanical behavior observed in experimental tests.

L is the smallest model length

d is the average particle diameter

Model size and particle size distribution

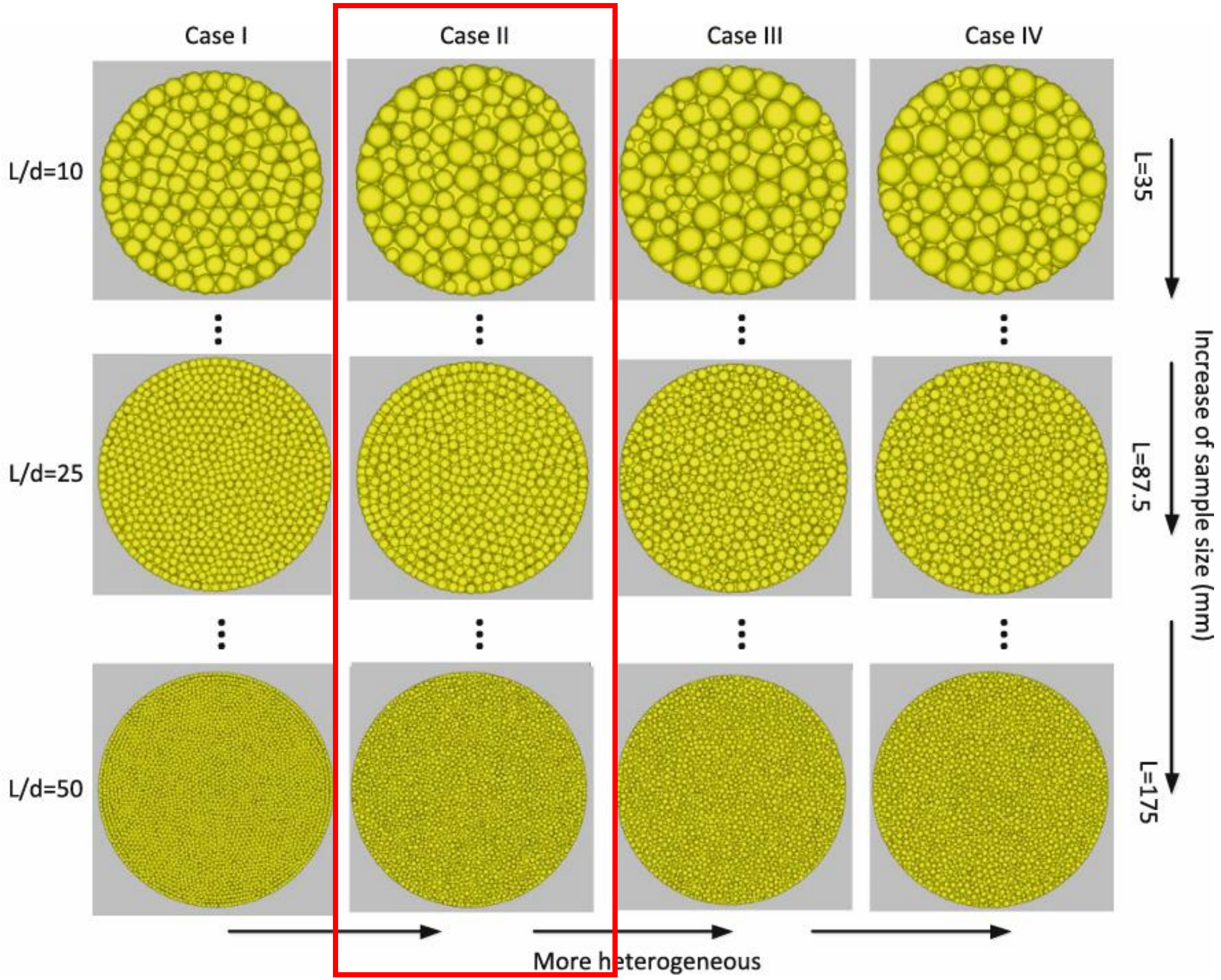
- Four particle size ratios:
  d_{max}/d_{min} $(maxium/minmum\ particle\ diameter)$ $= 1, 2, 4, 6$
- Seven model size ratios :
  L/d $(sample\ length\ /average\ particle\ diameter)$ $= 10, 15, 20, 25, 30, 35, 50$

Particle Size Ratio d_{max}/d_{min} :

- This ratio defines how varied the particle sizes are.
- A higher ratio means greater size variation, resulting in a more heterogeneous structure.
- A lower ratio means uniform particle sizes, forming a more homogeneous model.

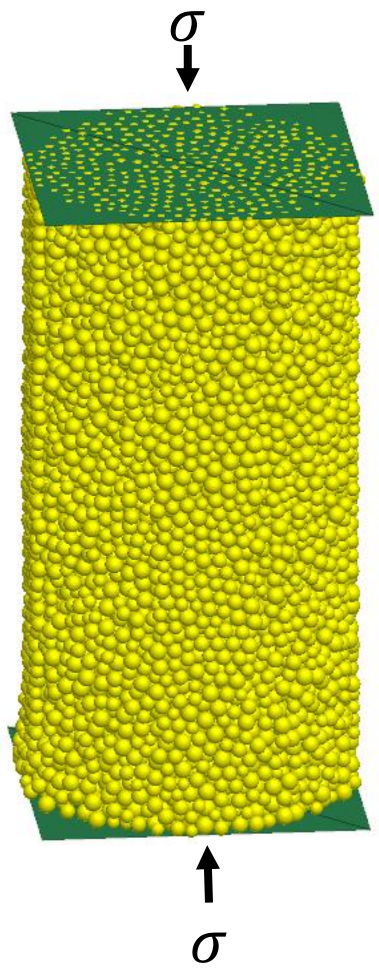
Model Size Ratio L/d:

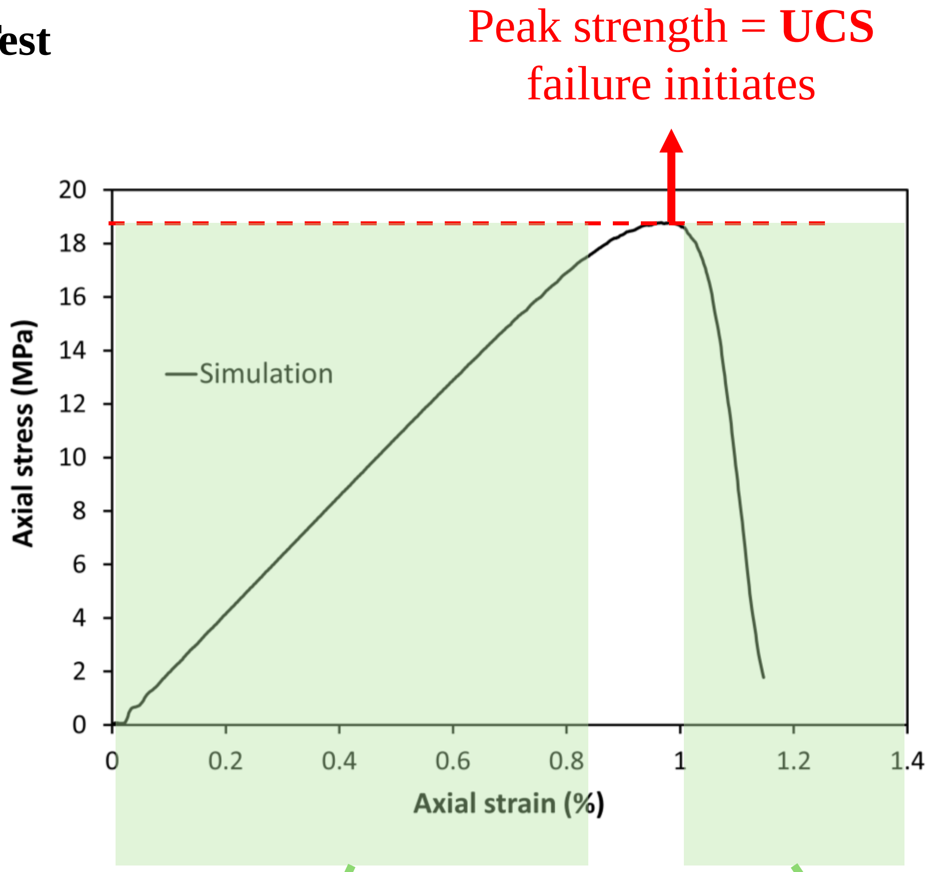
- A larger L/d means more particles in the sample
- The maximum L/d is limited by computer capacity.
- $L/d < 10$ may lead to unreliable results
  (based on past studies)



Effect of Model Scale - UCS (Unconfined Compressive Strength)

Uniaxial Compression Test

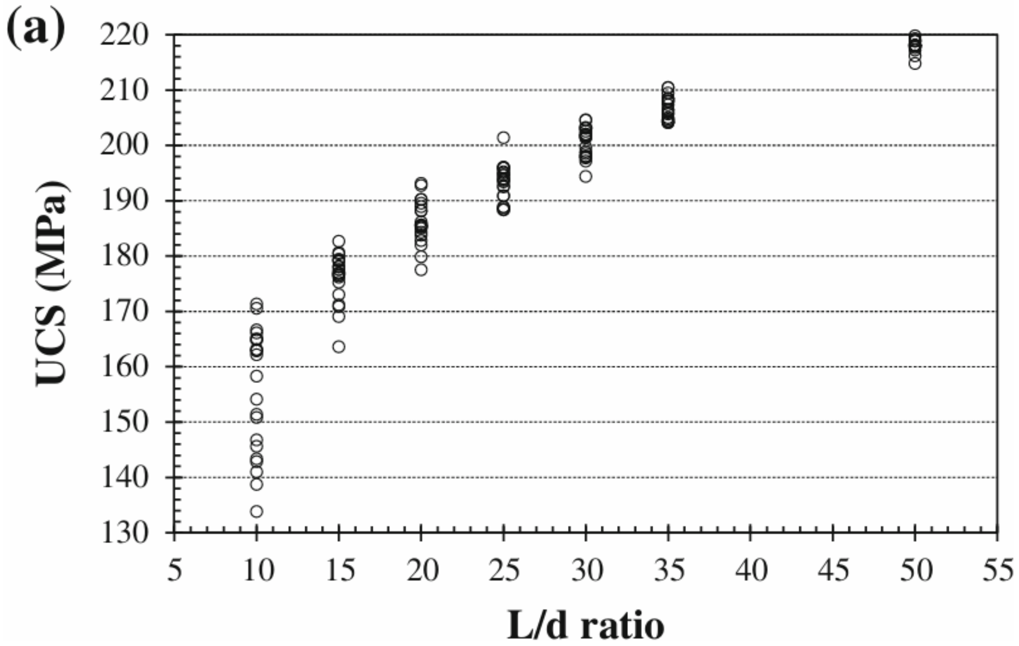




Elastic Region
Stress increases linearly with strain

Post-Peak
Bonds break and strength rapidly decreases

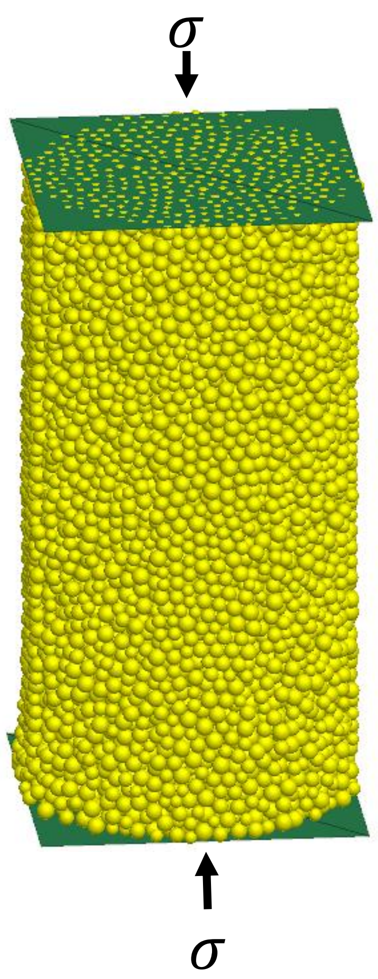
For each model size, 20 random particle arrangements were generated using the same particle size distribution ($d_{max}/d_{min} = 2$).



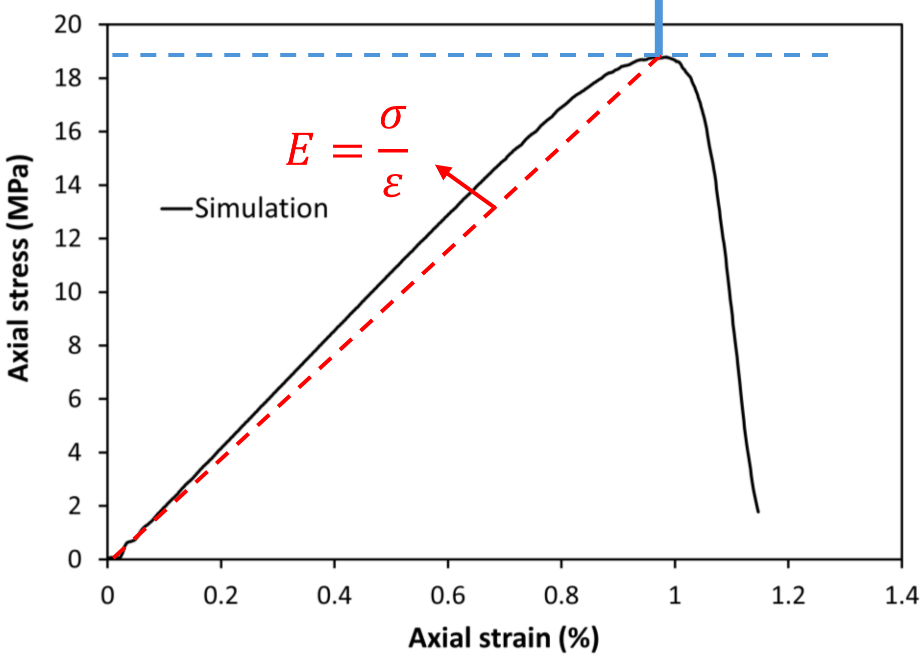
UCS increases :
Larger models contain more particles and contacts
→ Larger model size exhibit higher strength

Effect of Model Scale - Young's Modulus, *E*

Uniaxial Compression Test



Peak strength = **UCS**
failure initiates



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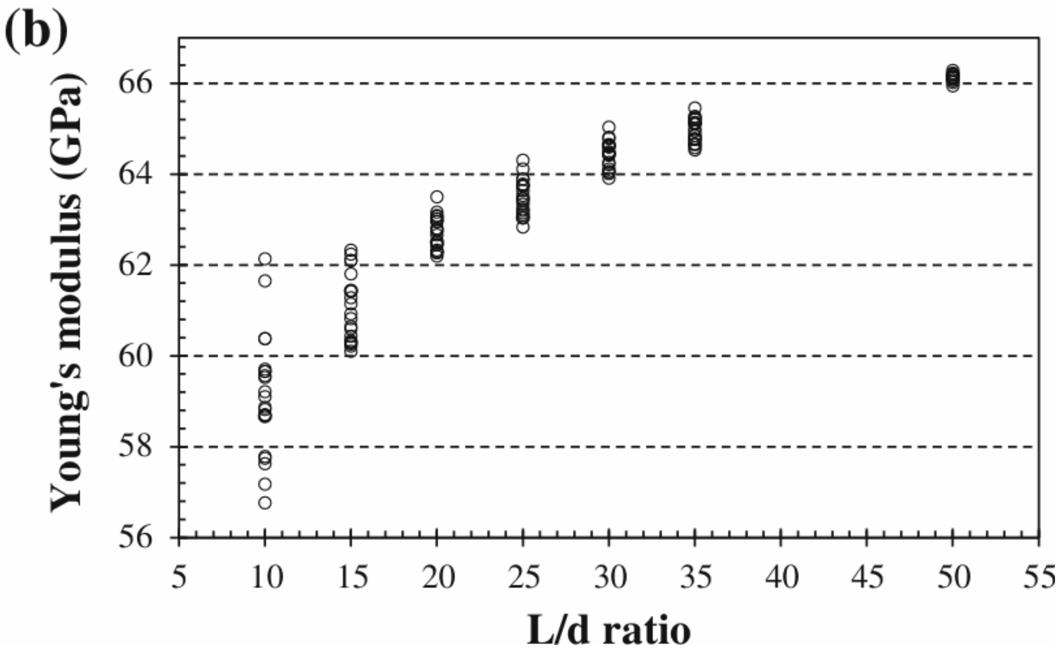


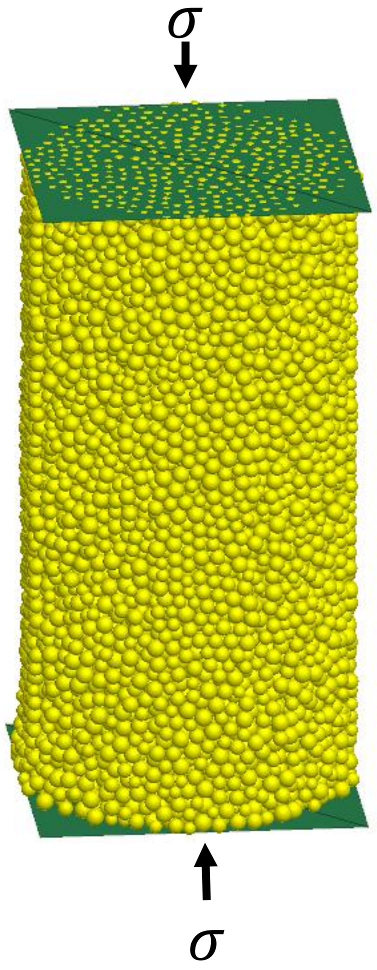
For each uniaxial compression simulation, ***E*** was estimated as the slope of the stress–strain curve from the initial point up to the peak stress (UCS).

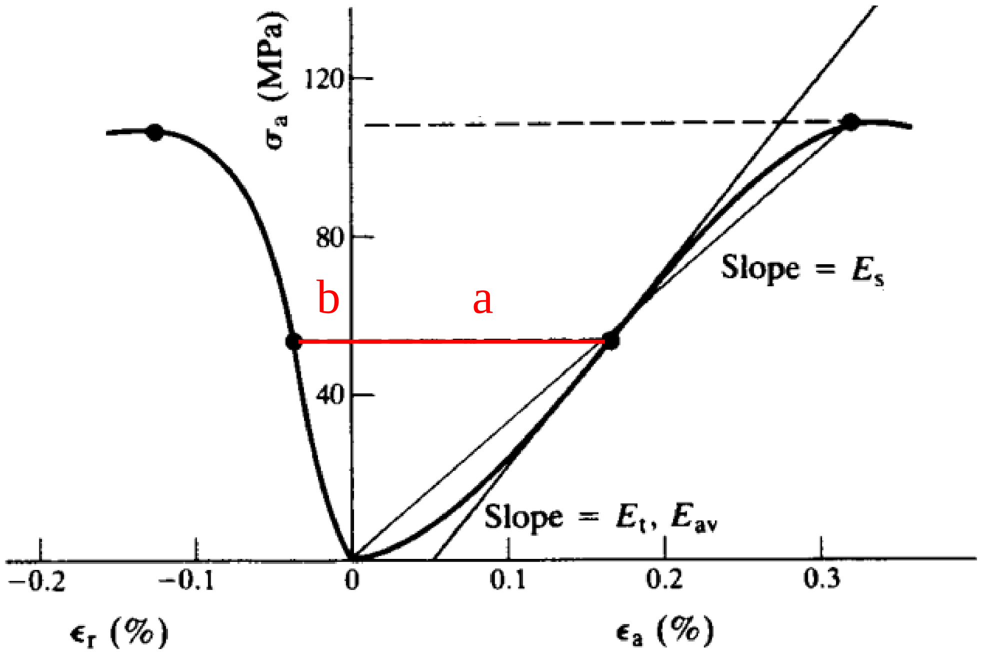
Young's Modulus increases

As model size increases, the number of particle contacts grows, reducing local structural variability and enhancing overall stiffness.

Effect of Model Scale - Poisson's ratio, ν

Uniaxial Compression Test

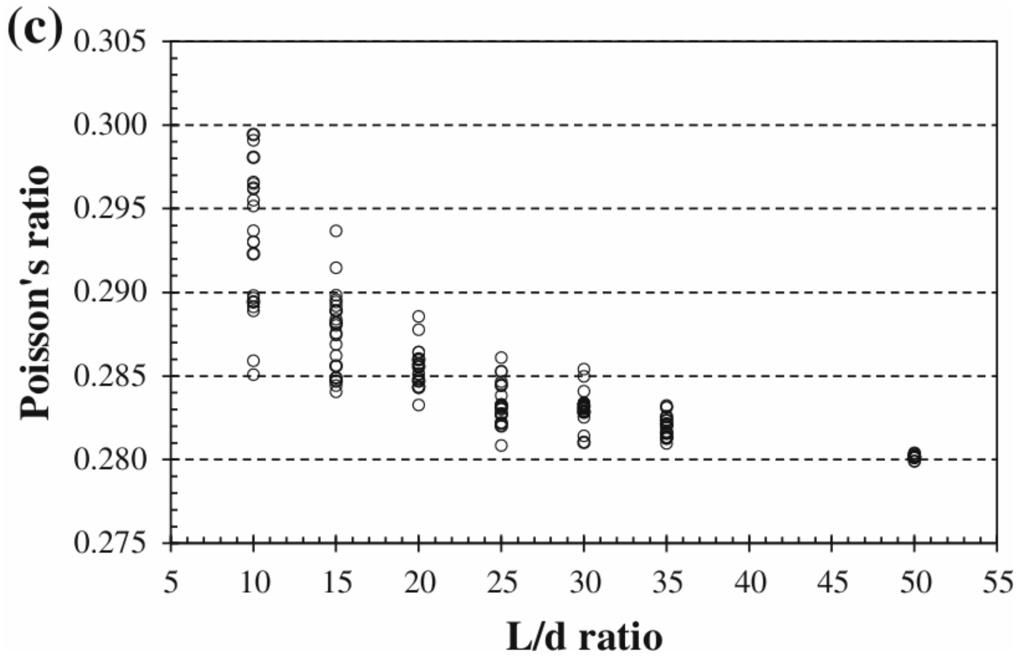




$$\nu = \frac{\varepsilon_{lateral}}{\varepsilon_{axial}} = -\frac{b}{a}$$

Poisson's ratio = lateral strain (b) / axial strain (a).

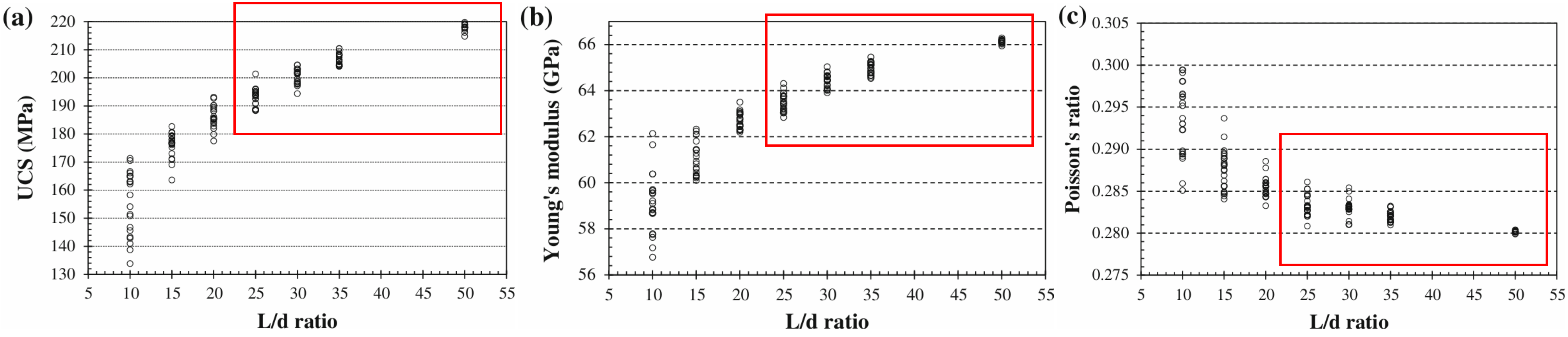
For each model size, 20 random particle arrangements were generated using the same particle size distribution ($d_{max}/d_{min} = 2$).



Poisson's ratio decreases:

As the model size increases, local deformation effects such as particle rotation and strain localization diminish, leading to reduced lateral expansion.

Effect of Model Scale (L/d)



The scatter in the macroscopic properties decreases.

- Increasing the model size minimizes the effect of random microstructural variability
- For all three simulated macroscopic properties, the COVs keep decreasing with higher model size (L/d).
- $L/d \geq 25 \rightarrow$ COVs $< 2\%$

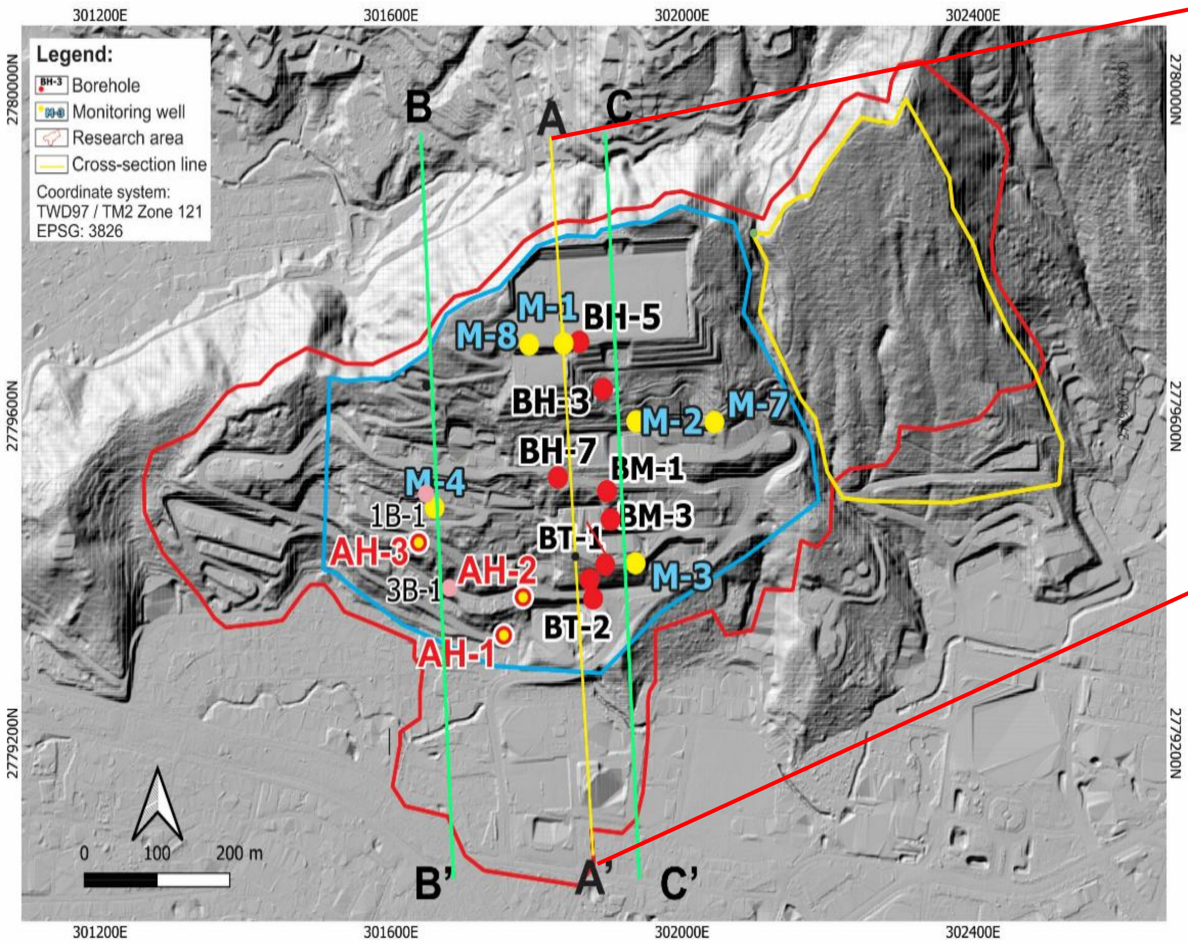
  Stable and reliable simulation results

Note:

1. COVs (Coefficient of Variation) = Standard Deviation / Mean
   - Describes how scattered the simulation results are
   - Lower COVs → more consistent & reliable results
2. International Society for Rock Mechanics(ISRM) ：
   - COVs below 2%, indicating reliable and consistent results

1. Increasing the model size (L/d) leads to a significant reduction in the coefficient of variation (COVs), indicating enhanced statistical reliability.
2. Unconfined Compressive Strength(UCS) and Young's modulus increase with model size due to reduced porosity, which enhances inter-particle contact density and force chain continuity.
3. Poisson's ratio shows a slight decreasing trend in both procedures, attributed to improved force chain stability and more uniform stress distribution, which reduce lateral deformation relative to axial strain.

Study area and Study motivation



The Yangming Campus of NYCU from Alivian

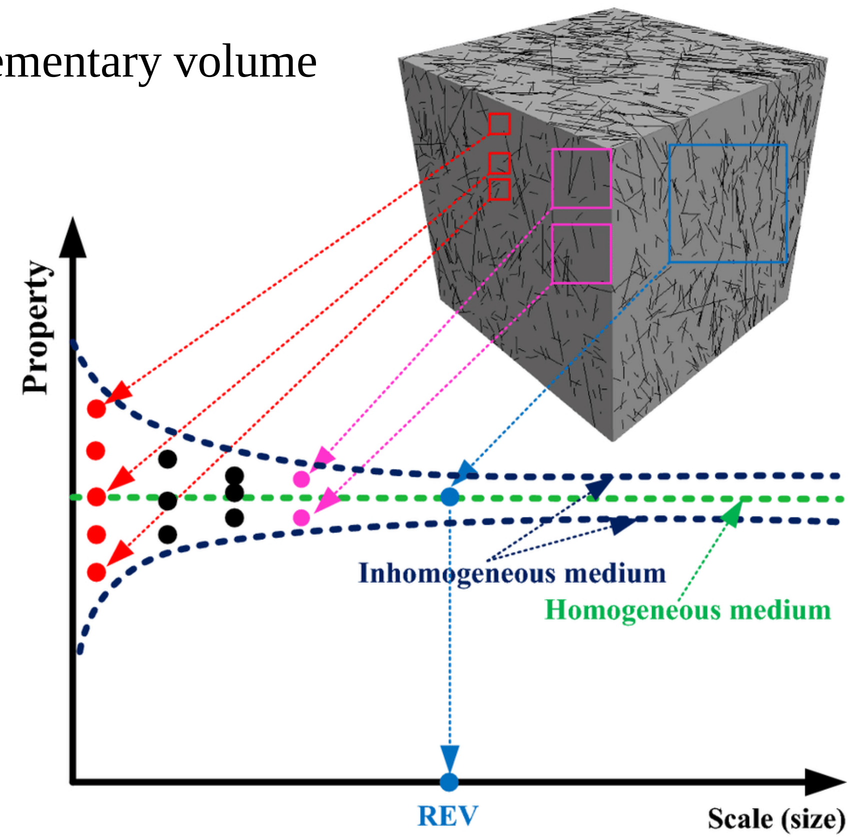
圖 2-8 地質剖面圖(陽明大學山坡地總體檢期末報告，2020)

It is located on a dip slope and has experienced slope failures in the past.

Due to the large number of fractures within the layers, it is difficult to measure and analyze each one individually.

My study uses borehole and core data to perform a Representative Elementary Volume (REV) analysis via the Discrete Element Method (DEM) to obtain **the strength parameters of weak planes** and further investigates **how mechanical parameters and fracture orientation affect slope stability.**

Represent elementary volume (REV)



- If the volume is **too small**, the measurement may vary wildly due to local heterogeneity.
- If the volume is **large enough**, the properties measured become **stable and representative** of the whole.

REV is a key step before converting a discrete system into a continuum model, ensuring the parameters represent the overall behavior.

Simple flow chart

Literature review

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Represent elementary volume (REV)

1. Search for previous physical test results
2. Adjust the micro-parameters to match the numerical simulation results with the physical test results.
   - Particle
   - Parallel-bond model
3. Conduct uniaxial compression simulations to verify the existence of scale effects in the rock mass without the introduction of joints.
4. Introduce joints and perform uniaxial compression tests, adjusting the smooth joint parameters.
5. Simulate the scale effects of joints at different angles.

↓

Mechanical properties analysis

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Simulation of an equivalent continuum model for slope stability analysis

Thank you for your attention.