農村水保署技術研究發展平台分享

三維物質點法分析光華崩塌行為與地形約束效應

Three-Dimensional Material Point Analysis of the Guanghua Landslide Constrained by the Topographic Constraints

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- Technical Committee, Reinforced Fill Structures (TC218), ISSMGE
- Technical Committee, Soil Reinforcement, IGS
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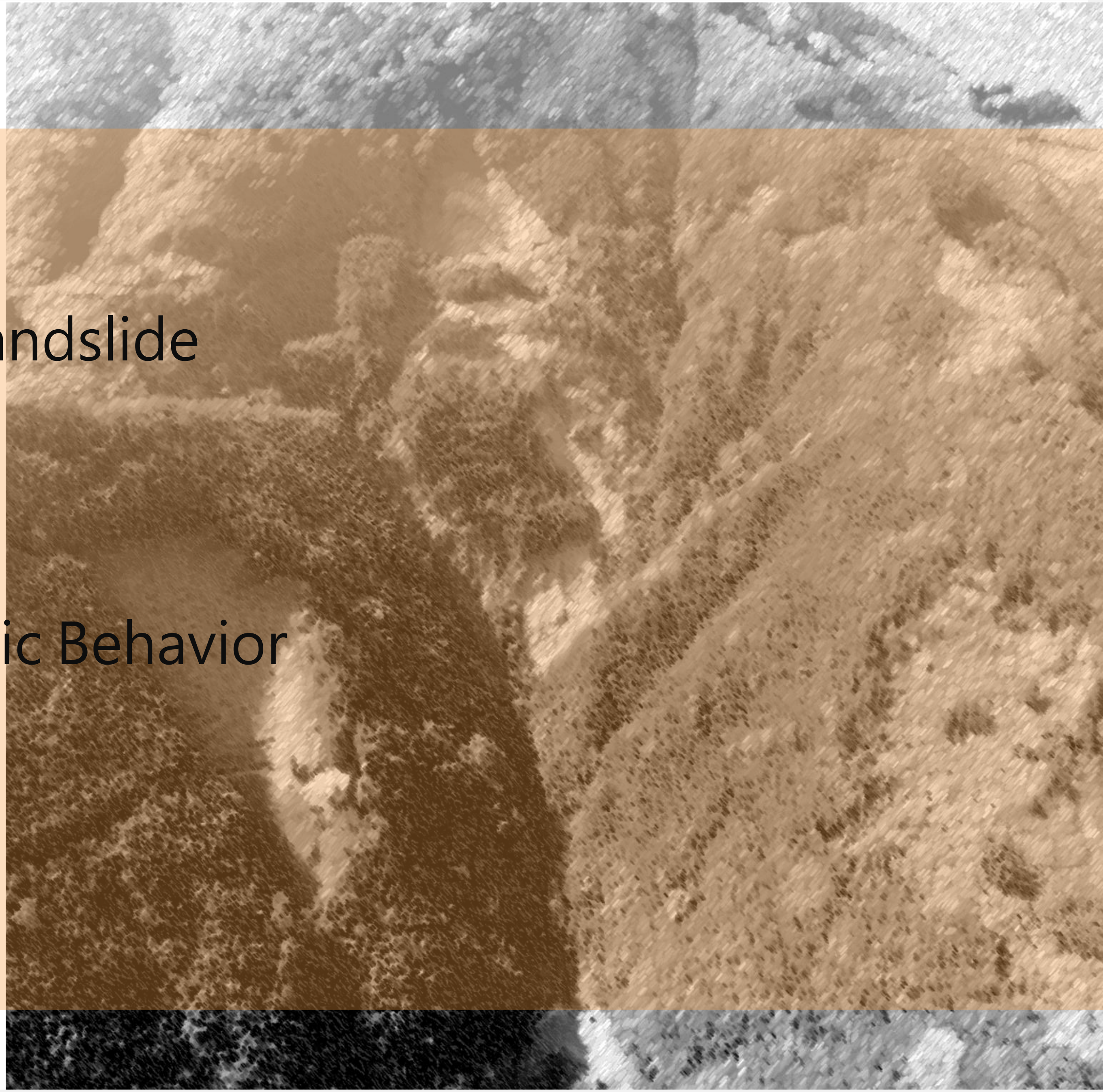
Outlines



1. Introduction of MPM
2. Background of the Guanghua Landslide
3. Objectives of the 3D Analysis
4. 3D Model and Validation
5. Failure Mechanism and Kinematic Behavior
6. The Topographic Constraints
7. Conclusions

1. Introduction of MPM

Large Deformation Problem in Geotechnical Engineering

Natural disaster
- Heavy rainfall
- Earthquake

→

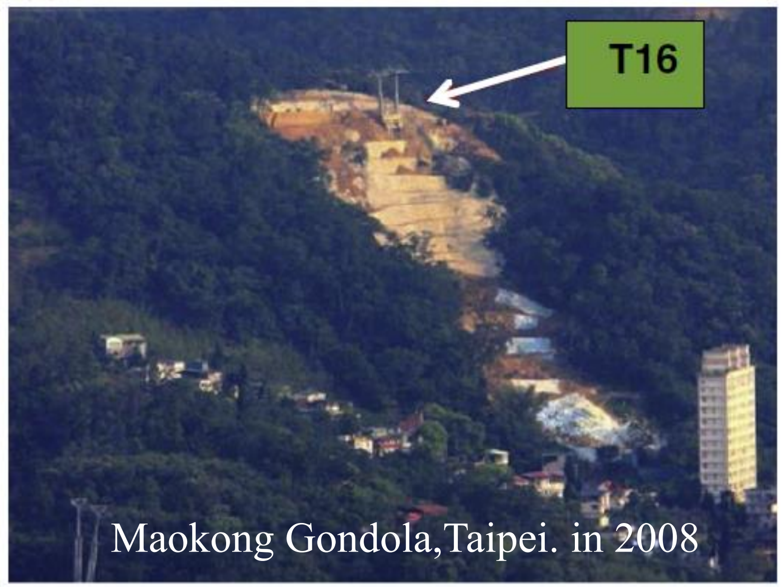
- Failure mechanisms
- Failure process
- Large deformation behavior

Disaster mitigation and prevention plan

→

- Influence area

People ?
House ?
Road ?
Infrastructures?

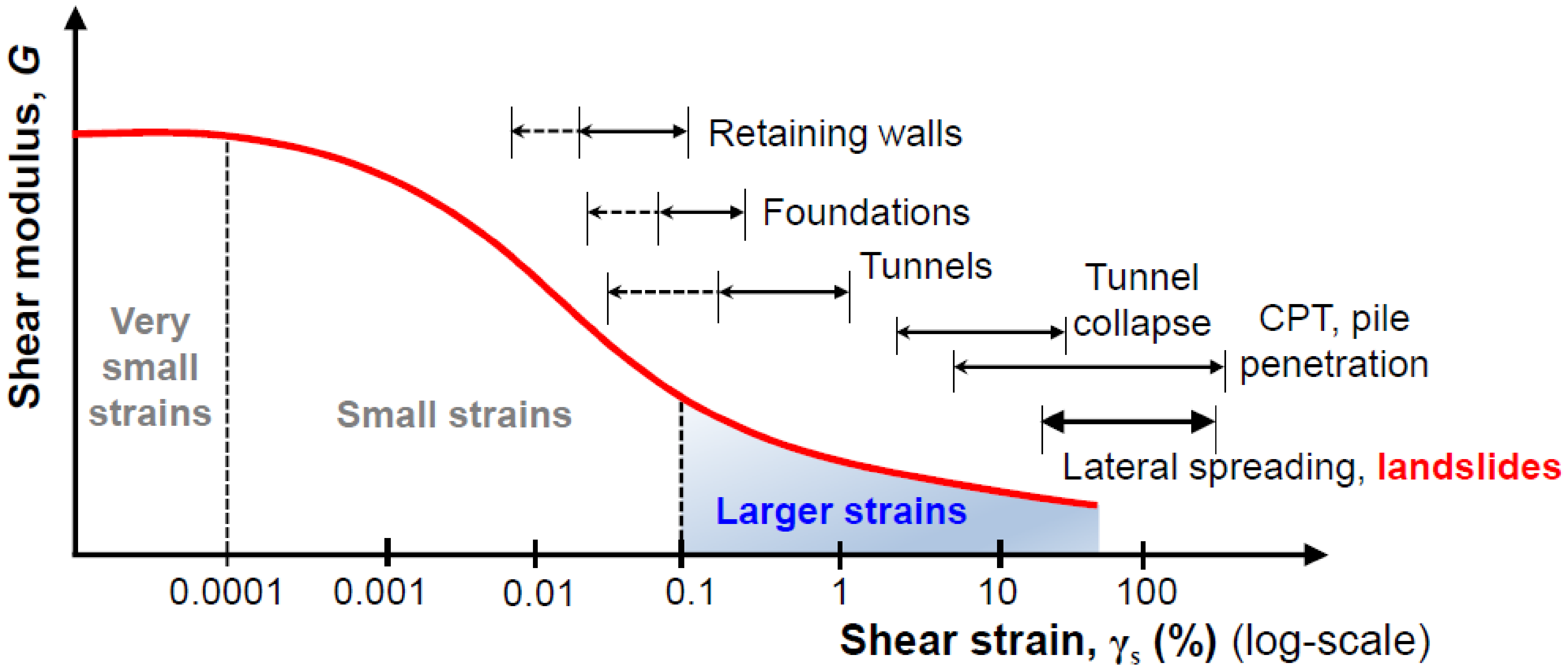


Maokong Gondola,Taipei. in 2008


Wulai, New Taipei, in 2015

1. Introduction of MPM

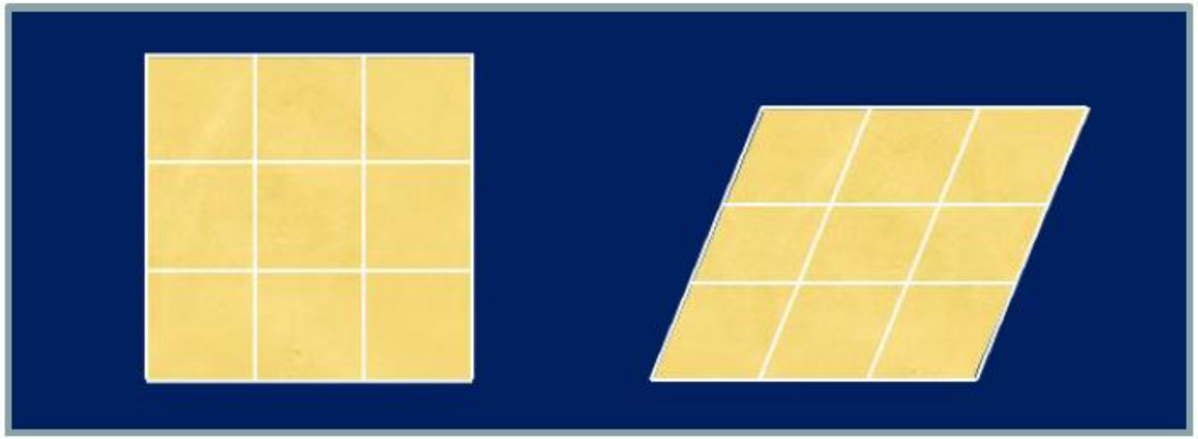
Large Soil Deformation



1. Introduction of MPM

Basic FEM Approaches

Lagrangian : mesh deforms as the body deforms → SOIL MECHANICS



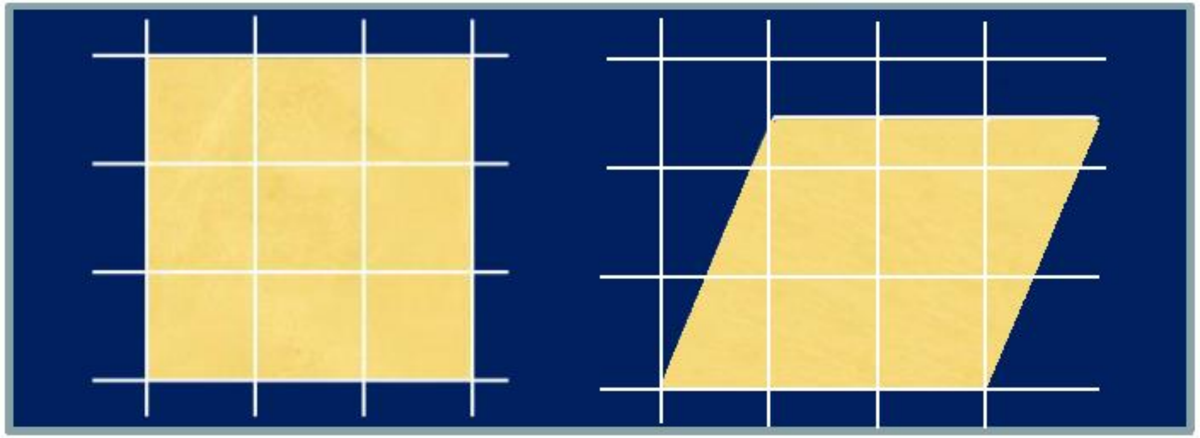
-Mesh deforms as the body deforms

-material does not cross elements

- nodes remain on boundary

- Difficulties with **mesh distortion**

Eulerian : material flows through a fixed mesh → FLUID MECHANICS



-material flows through a fixed mesh

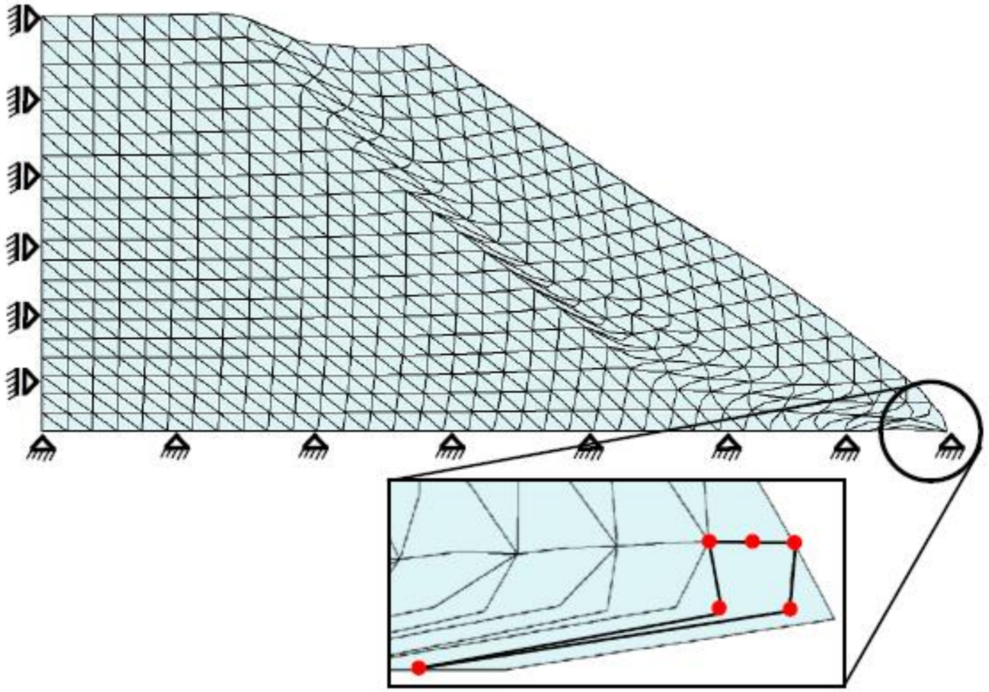
- no mesh distortion

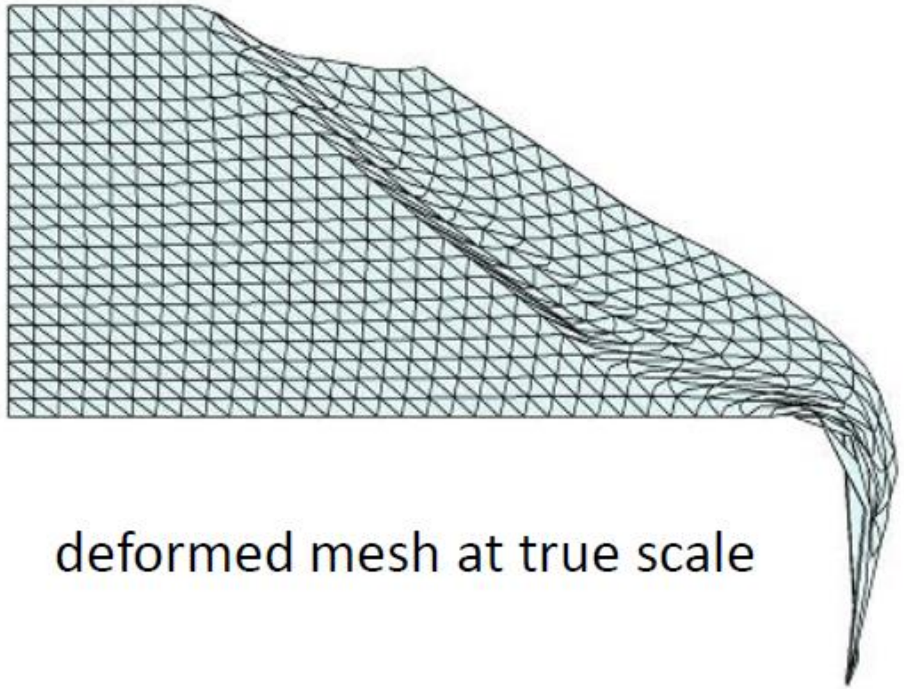
- Difficulties with **history dependent material**

1. Introduction of MPM

Mesh Distortion in Classical FEM

elements become inaccurate / unstable if distorted too much





deformed mesh at true scale

→ remeshing needed

1. Introduction of MPM

Advantages of MPM

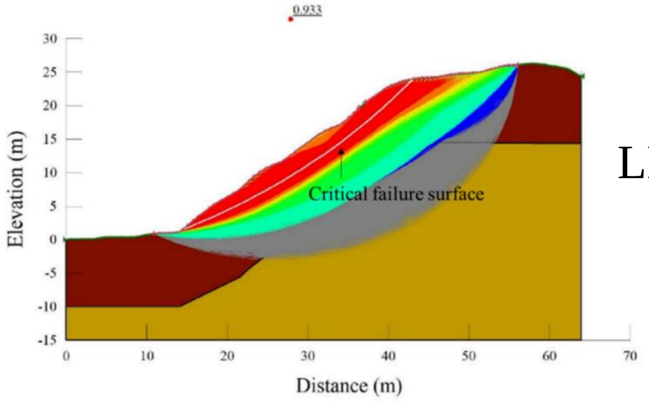
1. Large-scale failure analysis based on continuum description of material flow using an Eulerian–Lagrangian approach
2. Capable of simulating from the beginning of the process (small displacement regime) to the very end, after extremely large deformation
3. The implementation is intuitive for users of FEM
4. The application of boundary conditions is more straightforward than other mesh-free methods
5. Equipped with history-dependent soil constitutive models (stress history)
6. Capable of simulating dynamic coupled hydro-mechanical process of soil and water interaction

Soga, K., et al. (2016). "Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method." *Géotechnique* 66(3): 248-273.

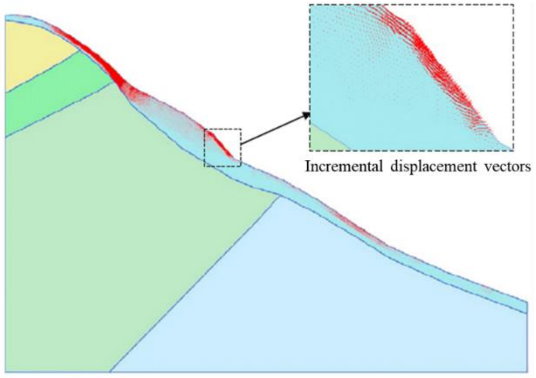
1. Introduction of MPM

Comparison with Other Numerical Methods

	LEM	FEM	DEM	MPM
Failure mechanisms	O	O	O	O
Failure process	X	O	O	O
Post-failure behavior	X	X	O	O
Large deformation	X	X	O	O
Factor of safety	O	O	X	X
Constitutive model	X	O	X	O
Coupled hydro-mechanical	X	O	X	O
Software	SLIDE	PLAXIS	PFC^{3D}	Anura3D



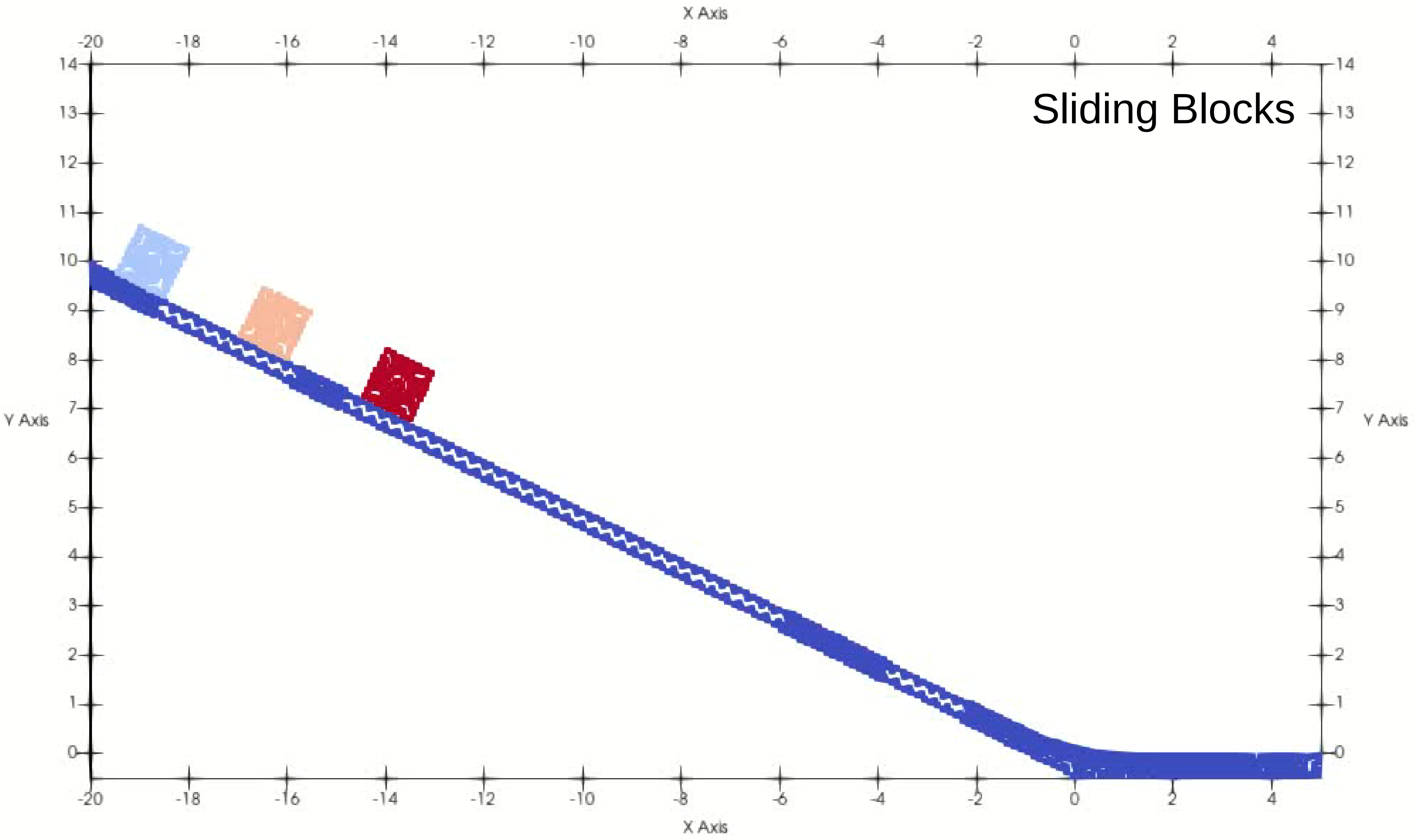
LEM



FEM

1. Introduction of MPM

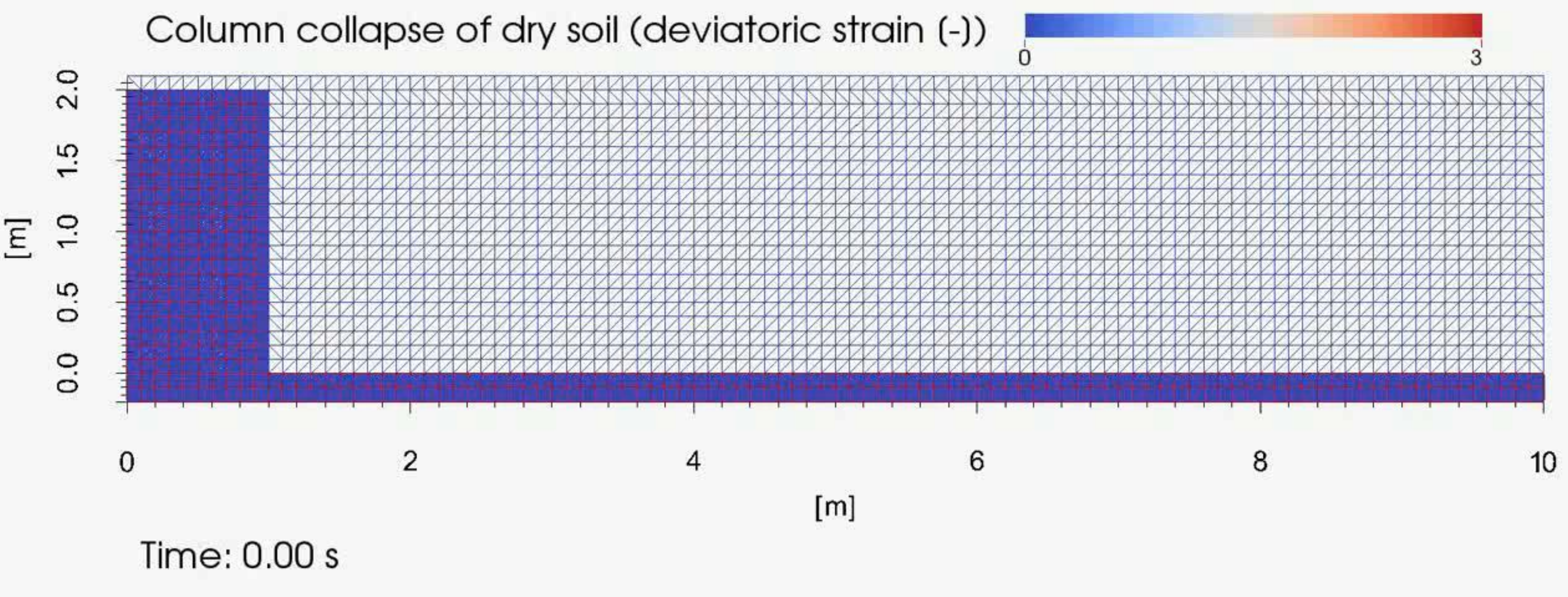
MPM Examples



1. Introduction of MPM

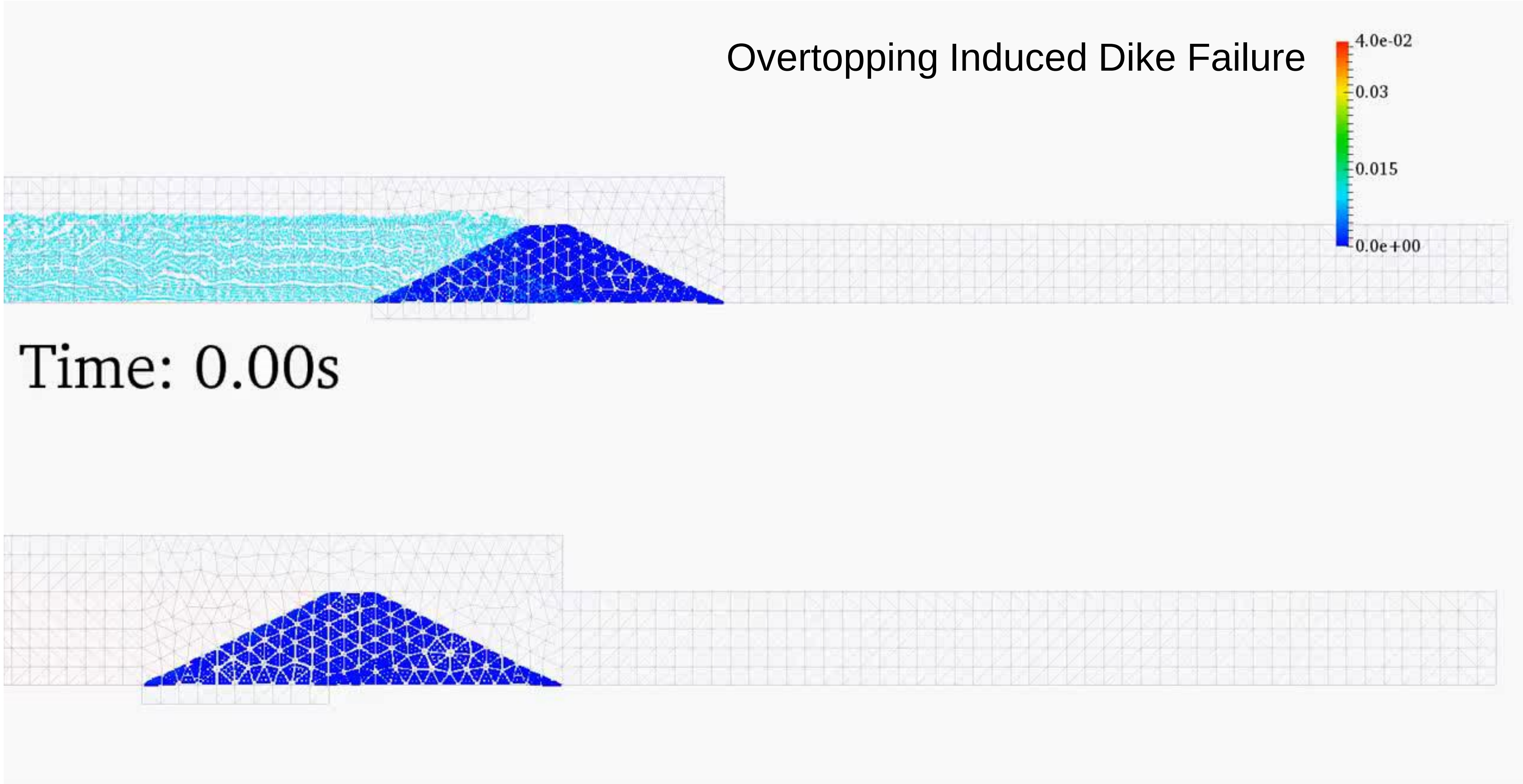
MPM Examples

Column Collapse



1. Introduction of MPM

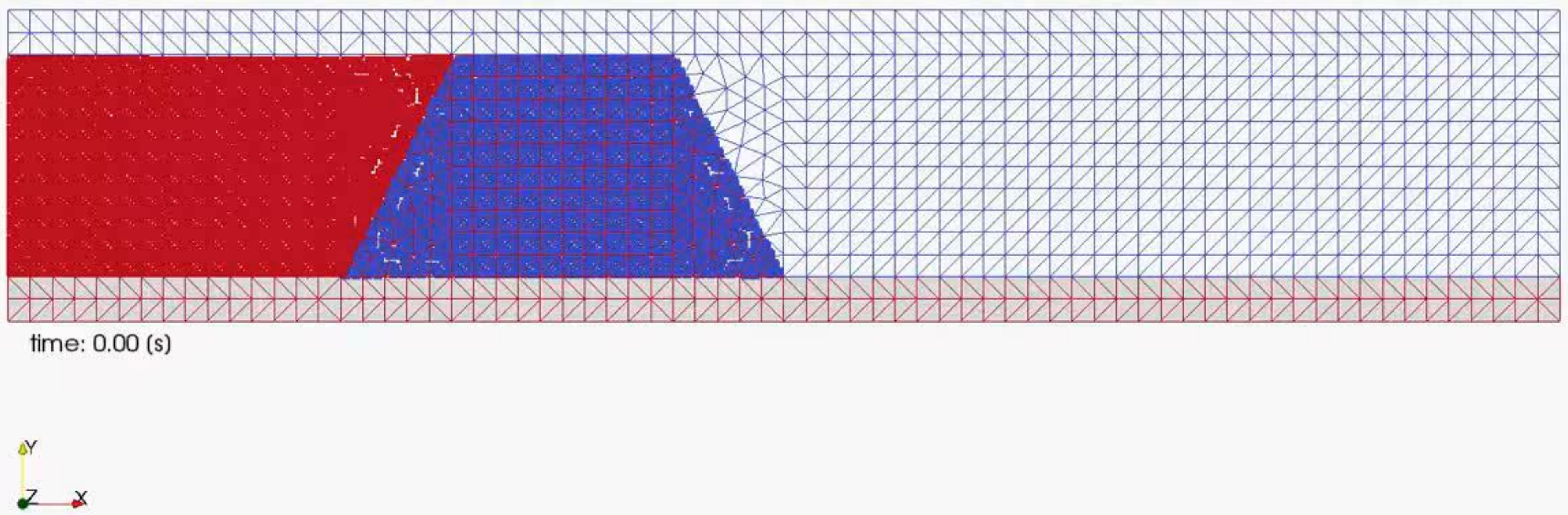
MPM Examples



1. Introduction of MPM

MPM Examples

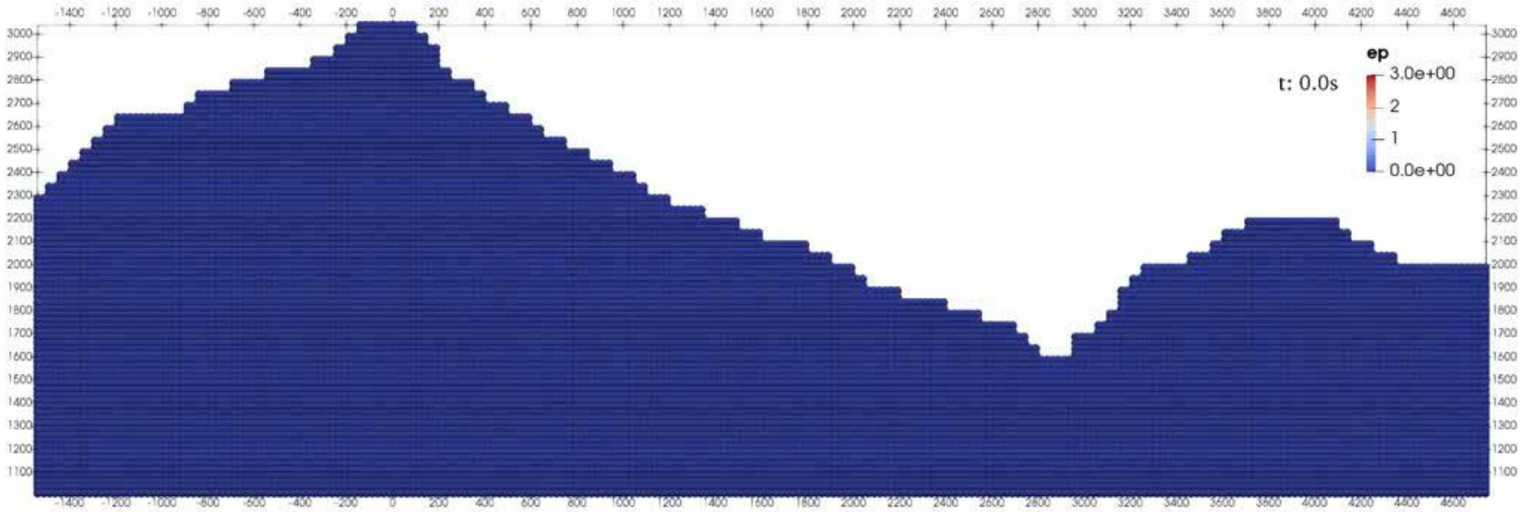
Debris Flow acting on Dam

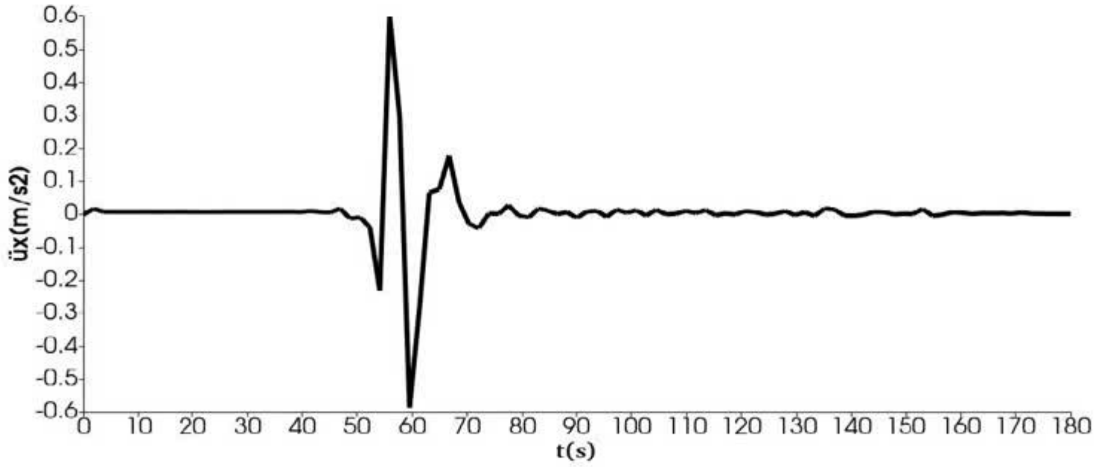


1. Introduction of MPM

MPM Examples

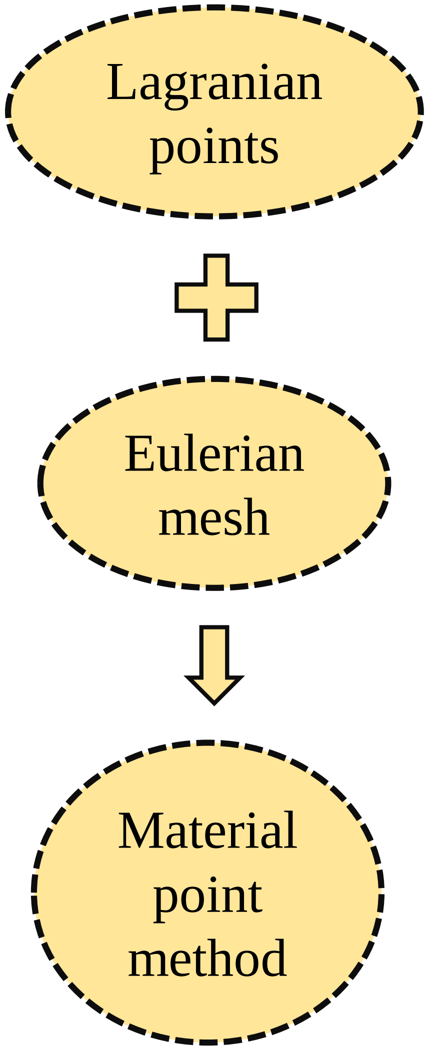
Earthquake induced Landslide

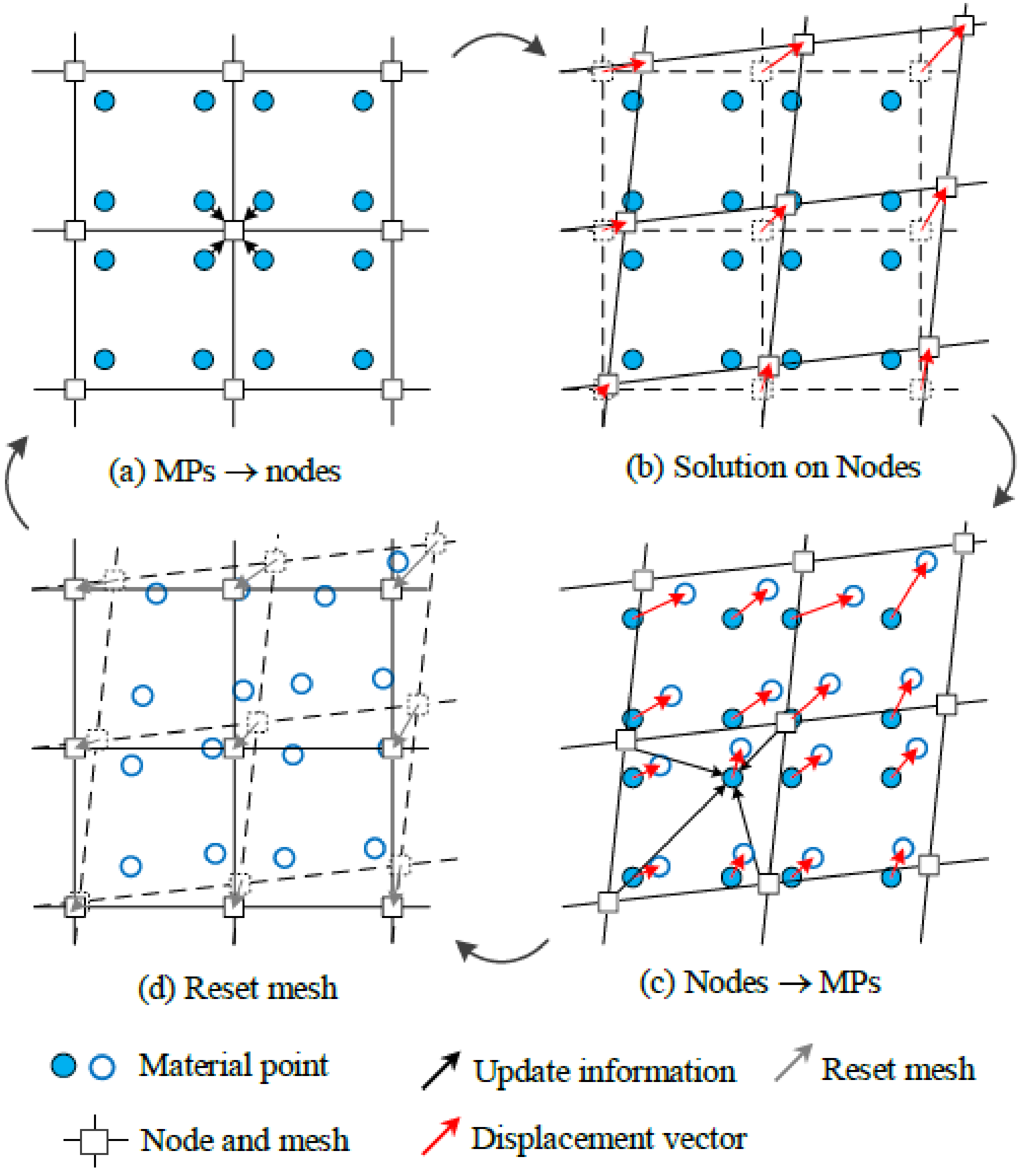




1. Introduction of MPM

Computational Procedure

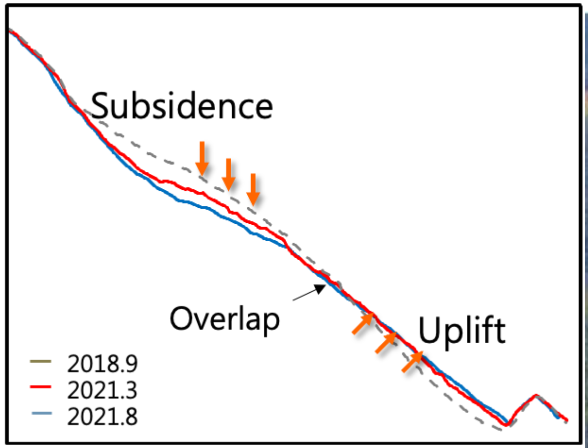


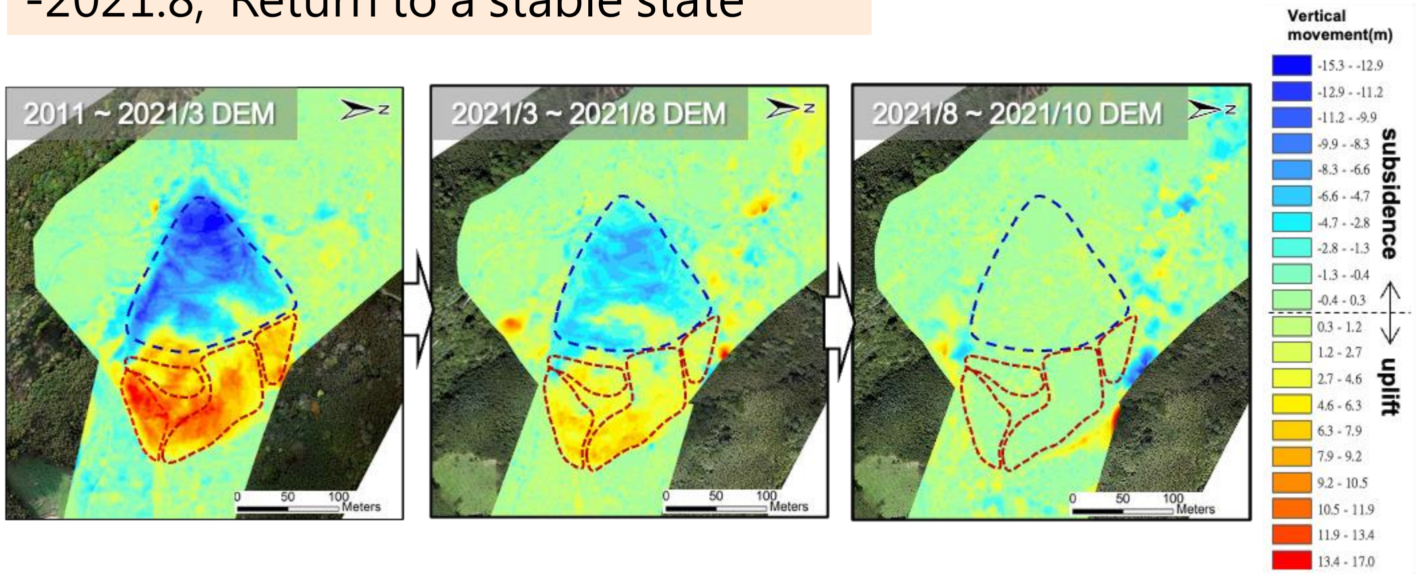


2. Background of the Guanghua Landslide

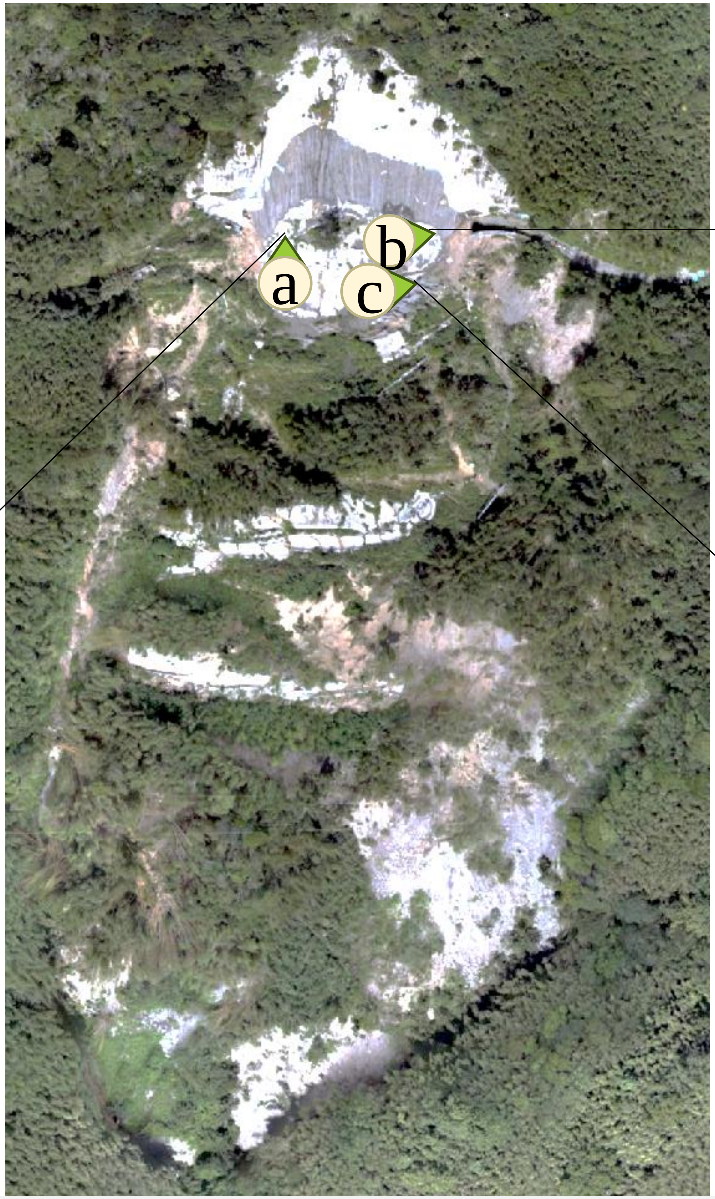
History of Sliding Activity

- -Since 2002, slowly sliding
- -2018, investigation and monitoring
- -2021.1, sliding accelerated (100~200 mm/day)
- -2021.5, movement slowdown
- -2021.8, Return to a stable state

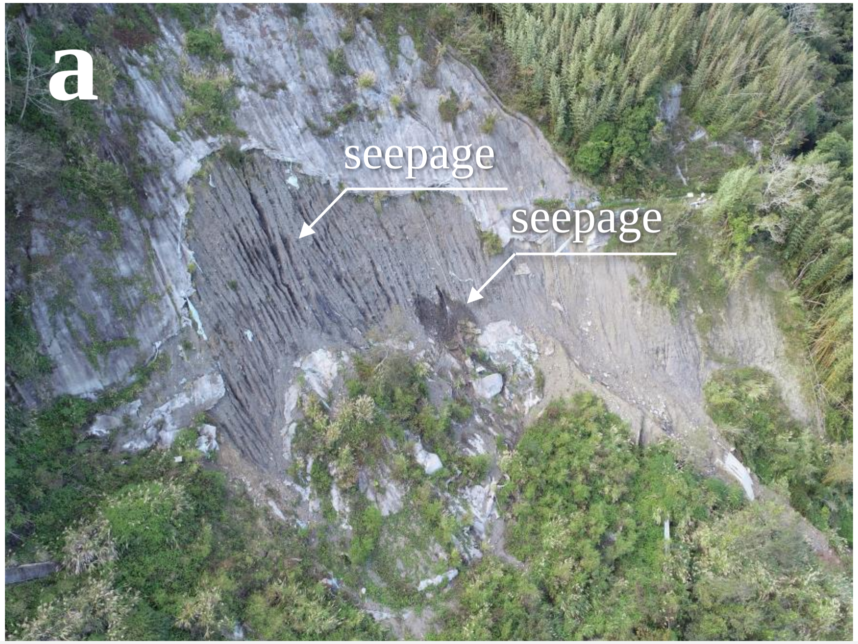




2. Background of the Guanghua Landslide



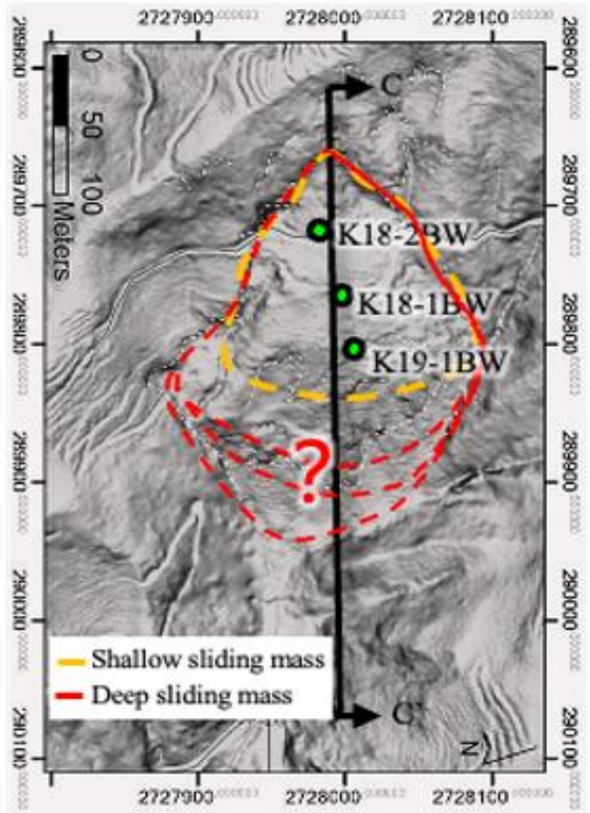
2021/4/26

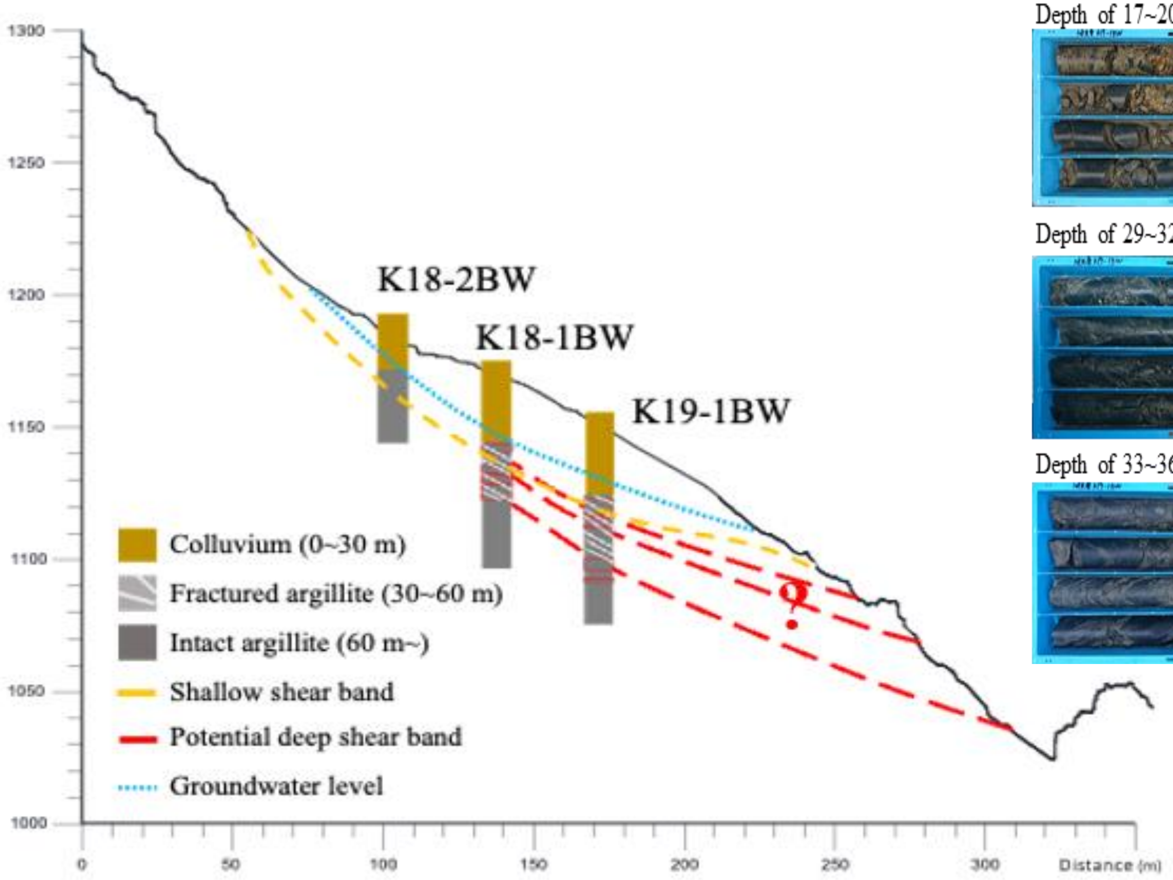


2. Background of the Guanghua Landslide

2. Background of the Guanghua Landslide

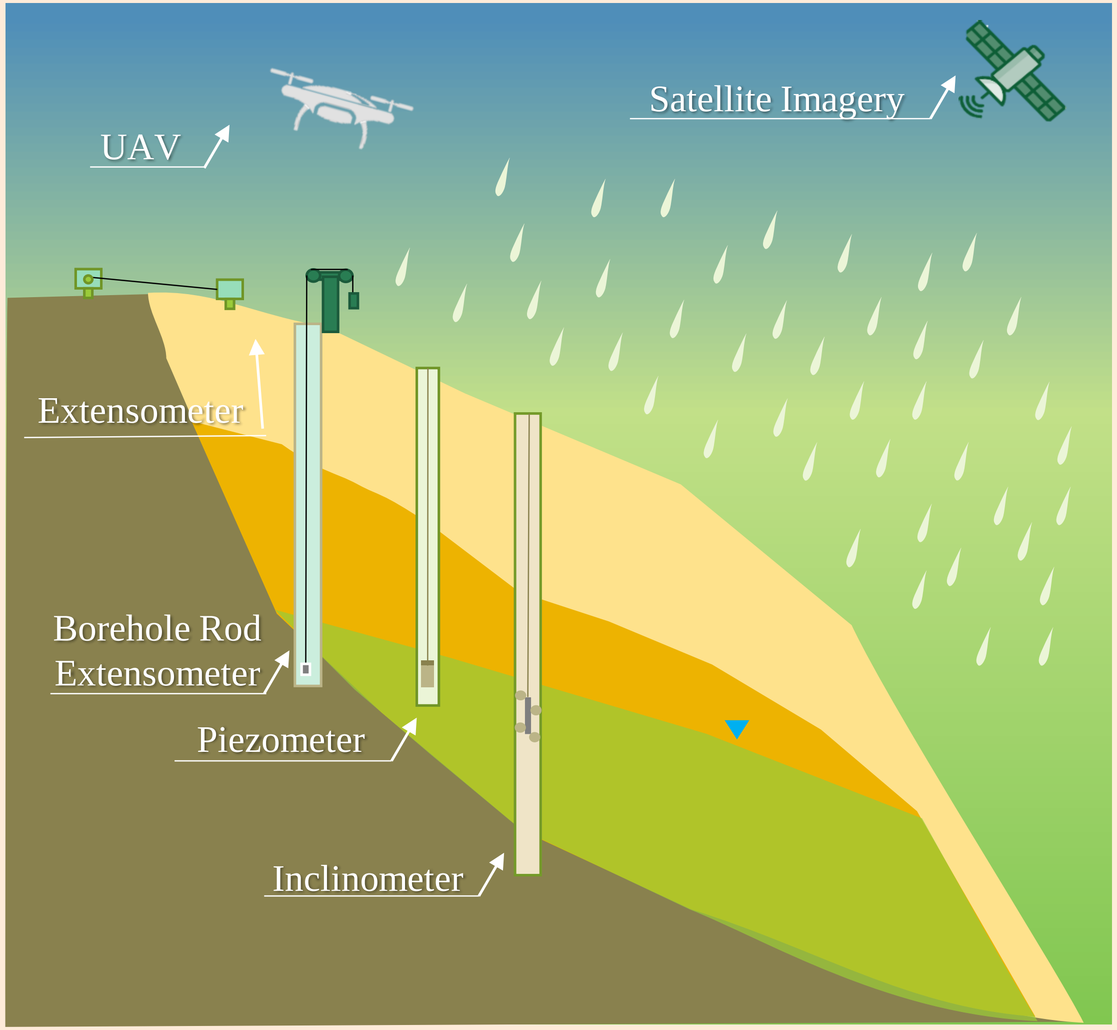
Slope Profile and Subsurface layers





2. Background of the Guanghua Landslide

Field Investigation



Ground surface:

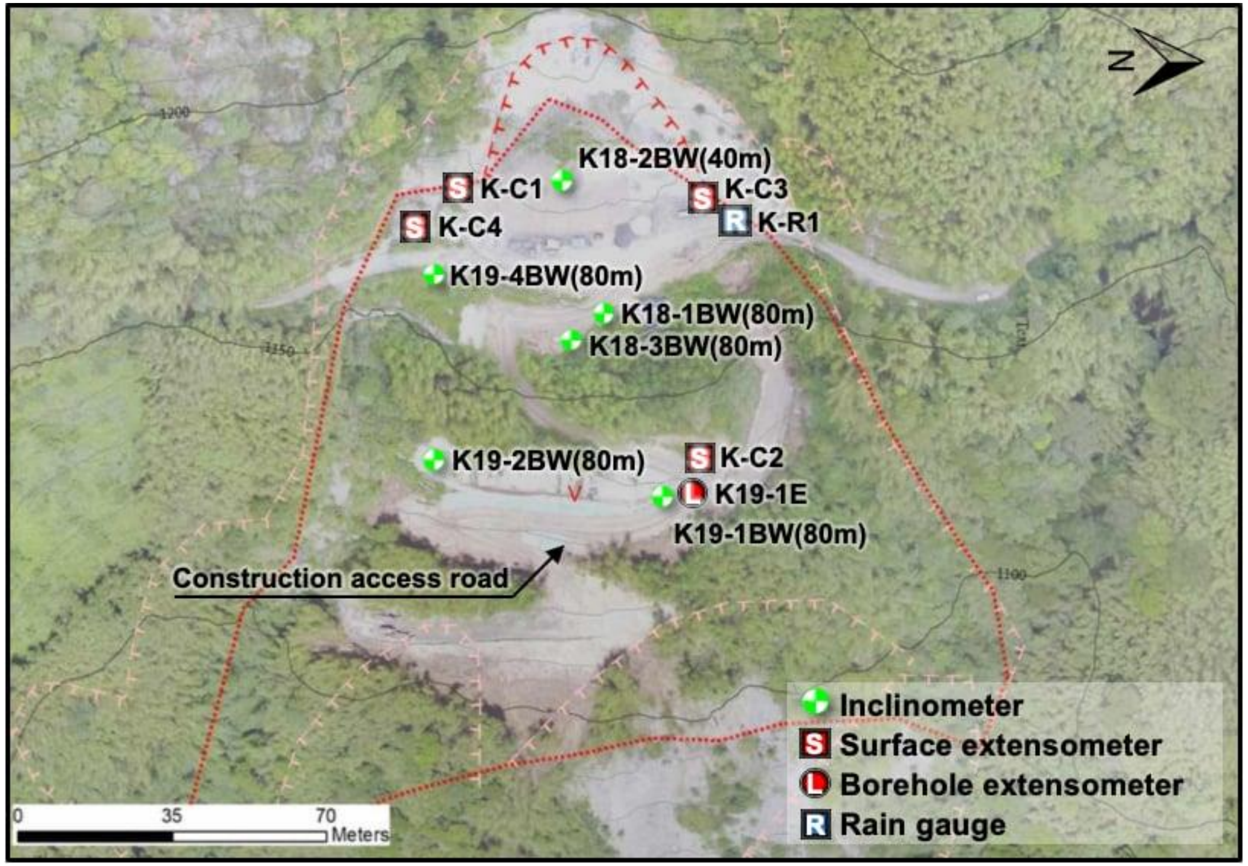
1. Lidar -> Digital elevation model DEM (1 m)
2. Historical Satellite imagery
3. UAV imagery
4. Global Navigation Satellite Systems (GNSS)
5. Extensometer

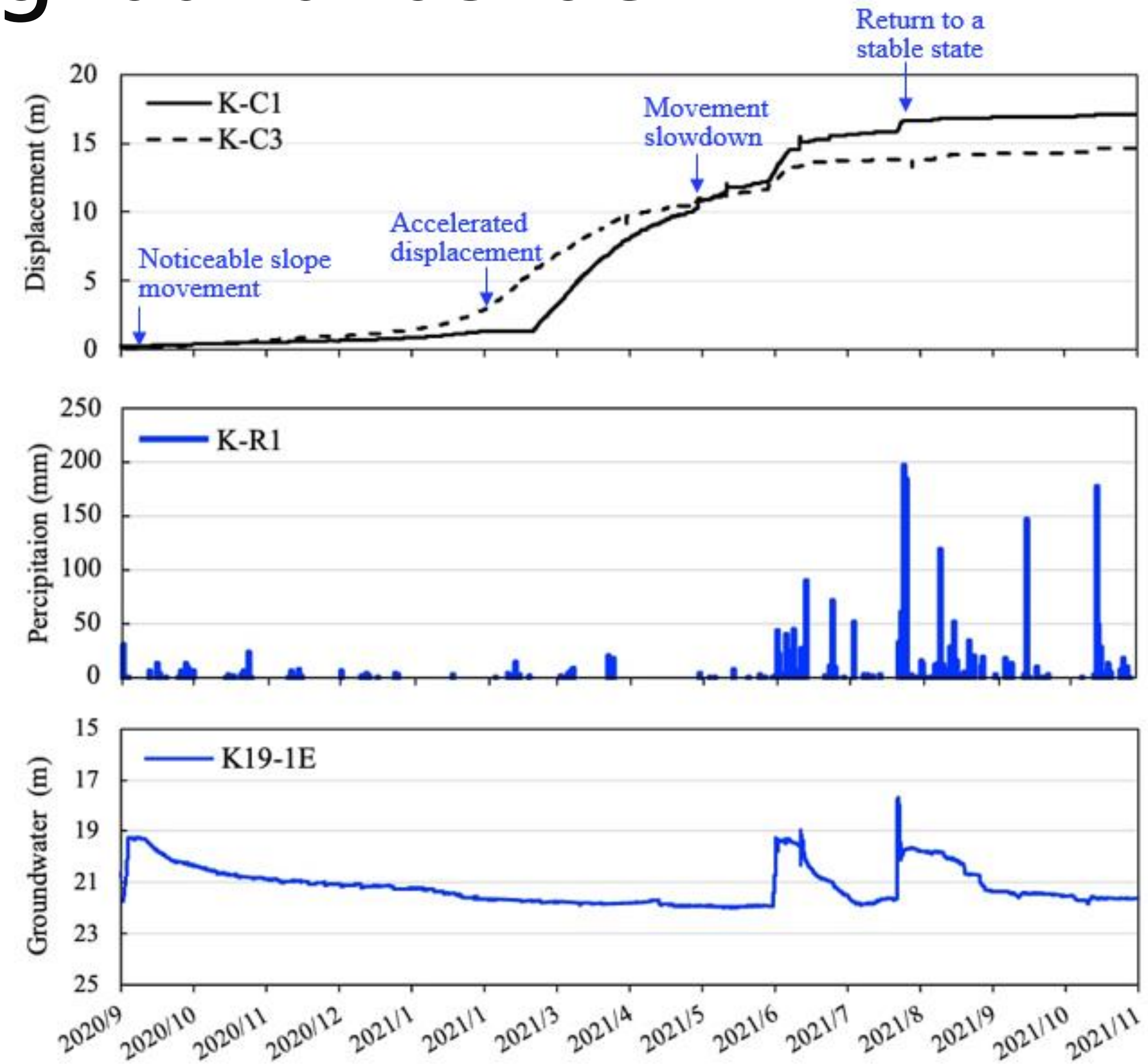
Subsurface (upper slope):

1. Inclinometer
2. Borehole soil sampling
3. Borehole rod extensometer
4. Piezometer
5. Ground resistance

2. Background of the Guanghua Landslide

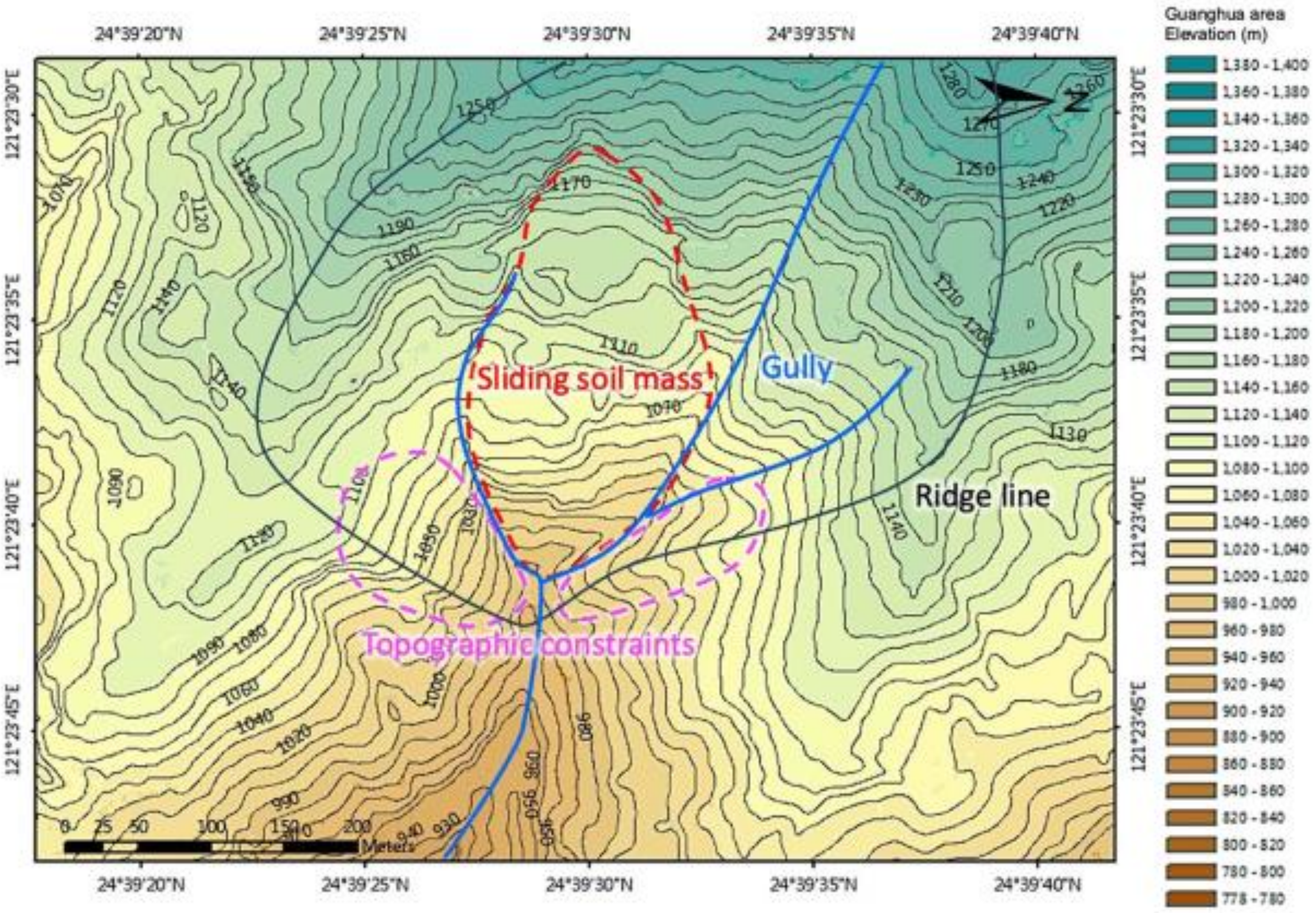
Instrumentations and Monitoring





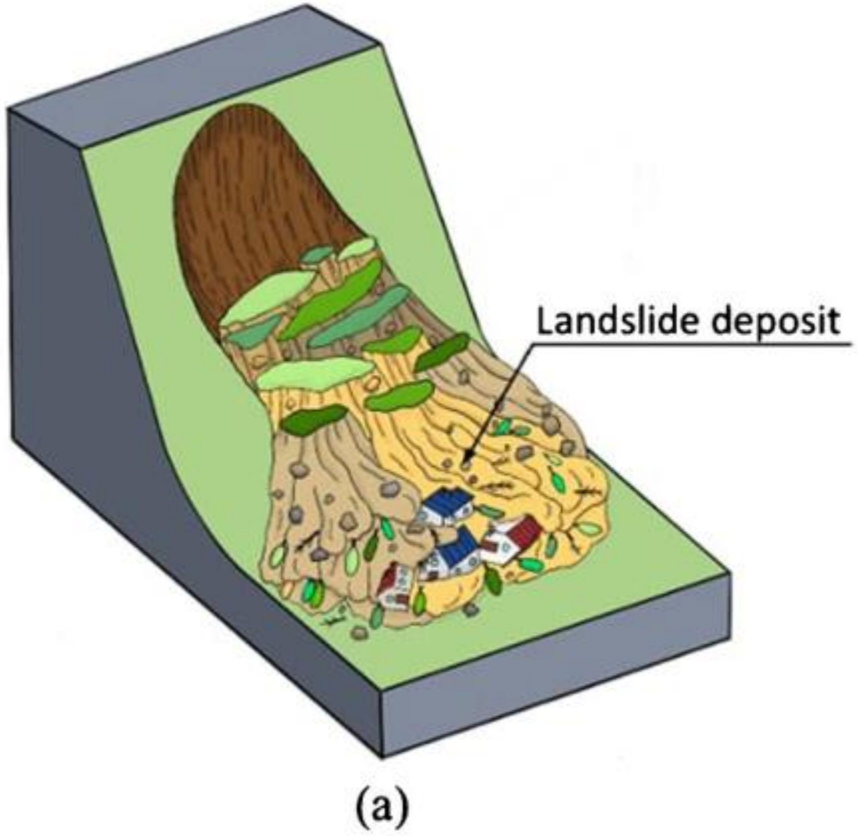
2. Background of the Guanghua Landslide

Topographic Constraints

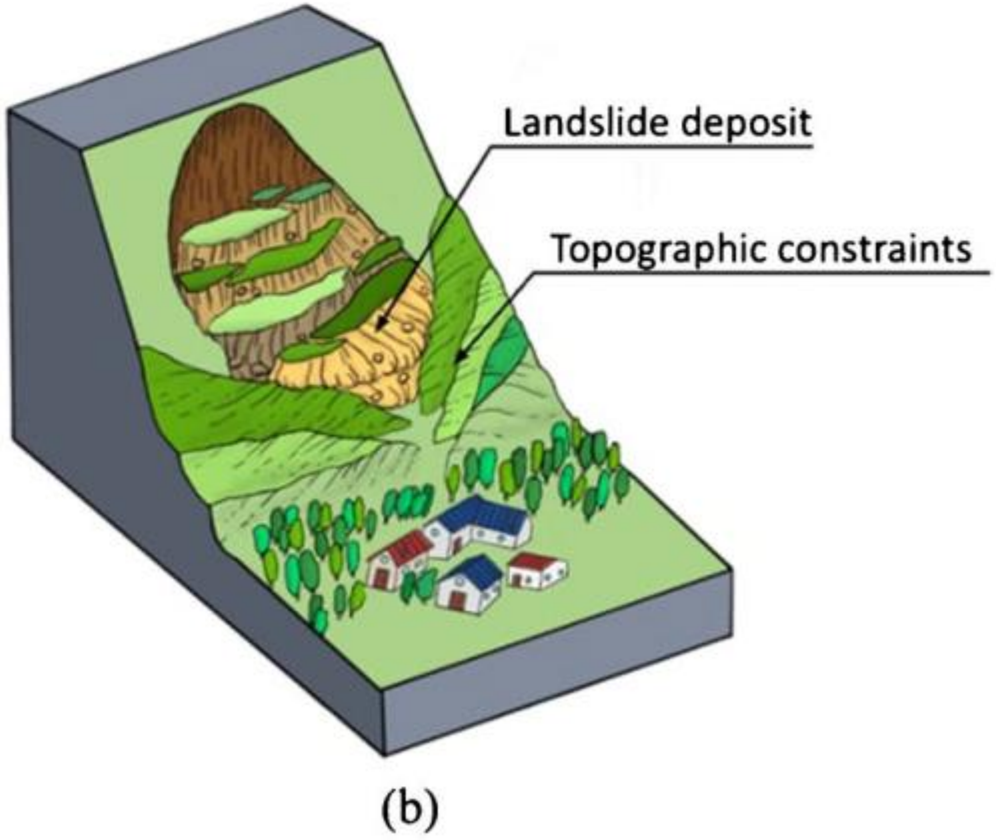


2. Background of the Guanghua Landslide

Topographic Constraints



without Topographic constraints

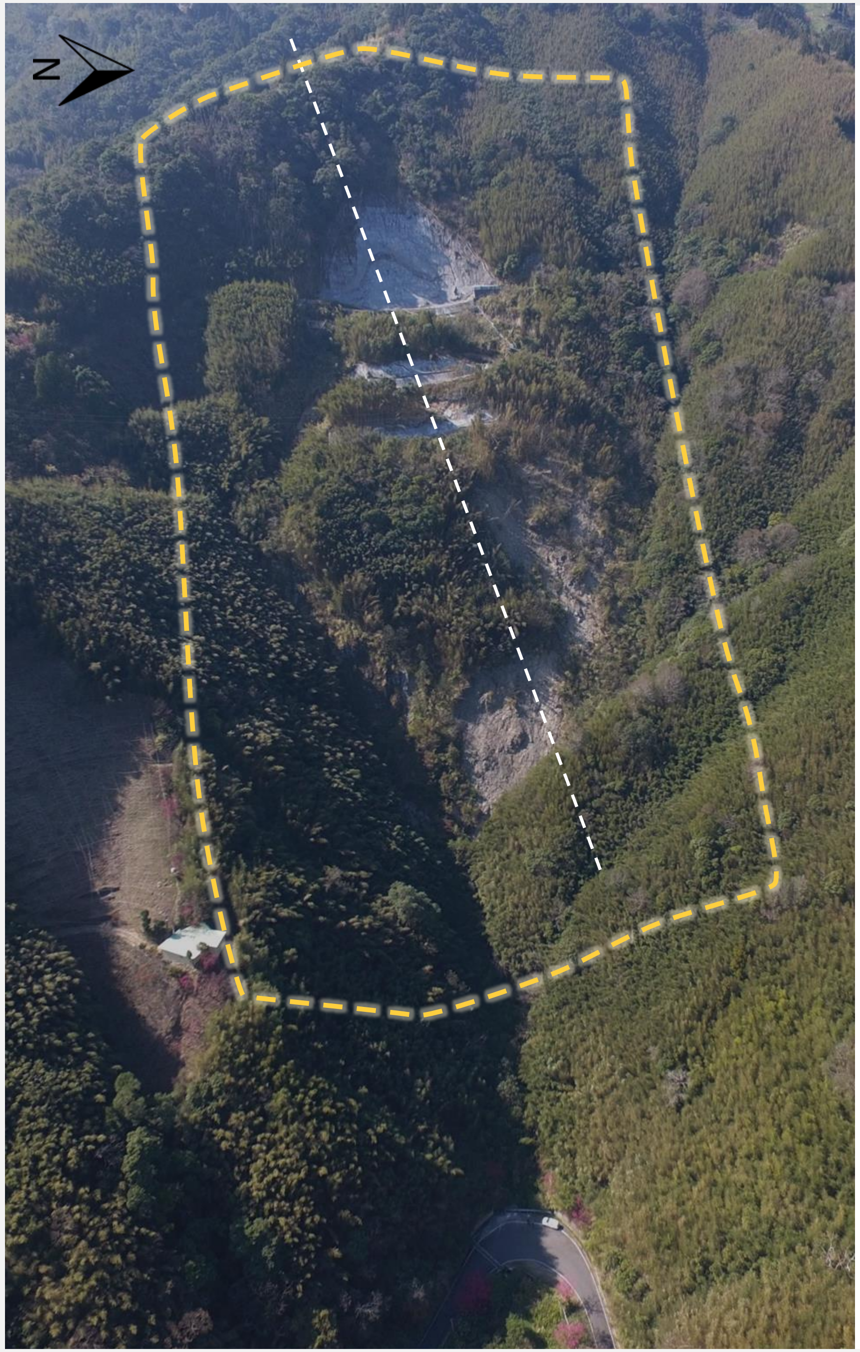


with Topographic constraints

2. Background of the Guanghua Landslide

Challenges

1. Subsurface investigations for the lower slope is not feasible because the lower slope is very steep.
2. The lack of subsurface data can lead to a less comprehensive understanding of landslide potential, ultimately affecting the accuracy of landslide hazard and risk assessments.
3. The slope displacement unexpectedly began to decelerate in May 2021 and then returned to a stable state; however, the reason was not clear.



3. Objectives of the 3D Analysis

Limitations of 2D Analysis

1. A single profile cannot represent the Guanghua landslide behavior.
2. The landslide area has clear boundaries and a constricted lower slope.

Objectives

3D MPM analyses are conducted to:

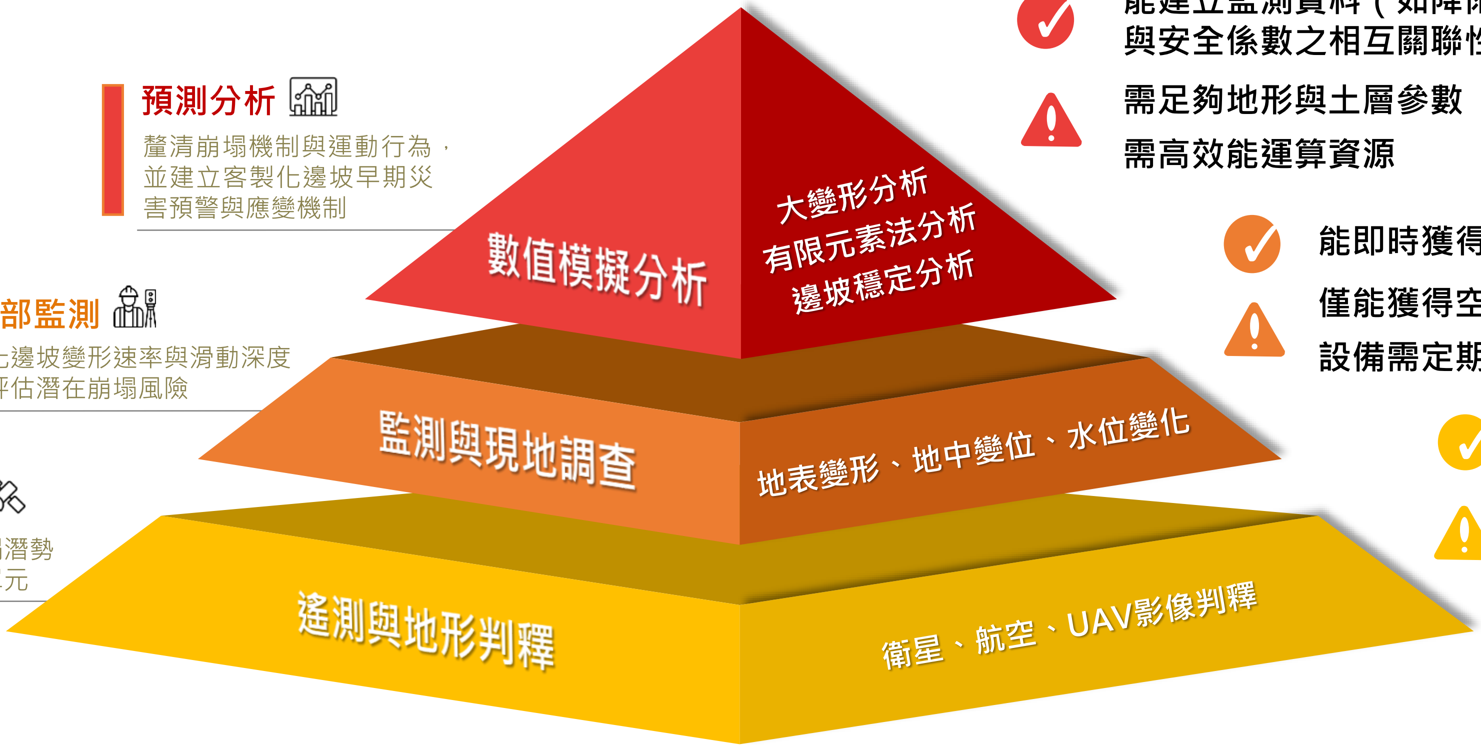
1. Investigate the post-failure process and kinematic behavior of the landslide (the depth of failure surface, the volume of sliding mass, and the extent of landslide's influence).
2. Evaluate the 3D effects of the topographic constraint on the landslide kinematics.

3. Objectives of the 3D Analysis

預測分析
釐清崩塌機制與運動行為，並建立客製化邊坡早期災害預警與應變機制

細部監測
量化邊坡變形速率與滑動深度以評估潛在崩塌風險

廣域篩選
初步辨識具崩塌潛勢之斜坡區域或單元



- ✓ 能建立監測資料（如降雨、水位、位移）與安全係數之相互關聯性
- ⚠ 需足夠地形與土層參數
  需高效能運算資源

- ✓ 能即時獲得真實性資訊
- ⚠ 僅能獲得空間上有限資訊
  設備需定期維護

- ✓ 覆蓋範圍廣、監測效率高
- ⚠ 無法掌握地層內部資訊
  易受氣候與植被干擾

<u>邊坡崩塌災害多尺度作業與判釋流程圖</u>

Peng, Y.P., Yang, K-H, Lee, W.L., Rus, T.Y., Cheng, S-H., Wang, J-Y., and Kuo, C-P. (2025) “Three-Dimensional Material Point Analyses of Guanghua Landslide influenced by Topographical Constraints”, *Landslides*.

Technical Note

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Three-dimensional material point analysis of the Guanghua landslide influenced by topographic constraints

Abstract This paper presents a case study and numerical investigation of the Guanghua landslide in Taiwan, which developed a significant slope displacement and then was restabilized due to topographic constraints. Due to the steep topography and high slope activity in the landslide area, people and machines cannot access the lower part of the slope, leading to an inability to collect adequate subsurface information and monitoring data. To compensate for this limitation, three-dimensional (3D) material point method (MPM) analyses were conducted in this study. The MPM analyses were first validated by comparing measured and predicted surface and subsurface displacement data of the slope. After validation, the MPM results were used to investigate the post-failure process and kinematic behavior of the landslide. The numerical results indicated that the Guanghua landslide featured two distinct shear bands. The first shear band developed at the soil–rock interface at a depth of 25–30 m. Subsequently, the second/deep shear band formed within the fractured argillite layer at approximately 40–50 m, extending from the lower to the upper slope. This deep-seated sliding resulted in subsidence at the upper section of the slope and uplift at the lower section. When the sliding mass reached a downhill valley, it decelerated and then fully ceased because of the topographic constraints. The numerical results are consistent with the current state of the landslide. Moreover, the stress and strain in the soils at the front edge of the sliding mass that was directly affected by the topographic constraints were examined. The 3D effects of topographic constraints on landslide kinematics are also highlighted and discussed in this paper.

Keywords Material point method (MPM) · Large deformation · Shear band · Kinematic feature · Topographic constraint

Introduction

Landslides are significant geotechnical events that occur globally. Understanding the kinematic features of landslides is complex but is essential for effective disaster prevention and mitigation (Varnes 1958). Key indicators of these kinematic features of landslides include the depth of the sliding surface, the volume of the sliding mass, and the extent of the landslide's influence. Obtaining accurate information on these kinematic features not only facilitates the assessment of the potential scale of a landslide disaster but also guides the development of effective mitigation strategies (Sun et al. 2008; Klar et al. 2011; Qiu et al. 2017). Although empirical formulas are often used to estimate the kinematic features of landslides (Jaboyedoff et al. 2020), these formulas are only applicable to slopes with consistent slope gradients and uniform subsurface layers. They are not suitable for more complex subsurface layers or geometrical conditions. In addition, detailed field investigations and sustained monitoring efforts are typically required to obtain adequate subsurface information for evaluating slope stability and estimating the kinematic features of potential landslides. However, limitations such as project budget constraints or challenging in situ topographic features—like steep slopes or restricted accessibility—can significantly hinder the collection of subsurface data. This reduction in data collection can lead to a less comprehensive understanding of landslide potential, ultimately affecting the accuracy of landslide hazard and risk assessments.

Besides the issues above, the numerical methods used for slope stability analyses can also influence the outcomes of landslide assessments. The two-dimensional (2D) limit equilibrium method (LEM) is often employed in the current engineering practice to assess slope stability by calculating the critical failure surface and factor of safety of a slope. Additionally, advanced numerical methods like the finite element method (FEM) are also used to predict slope deformation patterns. These methods are crucial for understanding slope stability and displacement characteristics. However, their effectiveness is often limited by inherent constraints in foundational theories and numerical techniques, as noted in the literature (Soga et al. 2016; Nguyen et al. 2021; and Qin et al. 2022). These limitations become especially pronounced when modeling and predicting the complex behaviors of slopes with considerable deformation.

Moreover, conventional 2D numerical analyses for slope stability assume that the slope geometry and loading conditions conform to the plane strain idealization. In cases of irregular terrain, non-uniform subsurface layers, or local surcharges applied to the slope—conditions typically common in extensive areas of potential landslides—multiple critical cross-sections often need to be selected (Lee et al. 2011; Wang et al. 2017; Kargar et al. 2021; Kumar et al. 2023). However, even with multiple cross-sections selected for analysis, the true slope failure sometimes could be mispredicted, as the failure may occur locally or in a direction different from the selected cross-sections (Cavounidis et al. 1992; Chen et al. 2006; Chakraborty et al. 2021; Kumar et al. 2023). In addition, 2D numerical analyses often struggle to account for the three-dimensional (3D) terrain effect on landslide kinematics in complex topographic features. Limited studies in the literature discuss the influence of geomorphological factors on the kinematic features of landslides (Agliardi et al. 2001; Brandt 2000; Decaulne et al. 2006; Geertsema et al. 2009; Csiki et al. 2010; Cevasco et al. 2014; Chung et al. 2018; Cucchiaro et al. 2019).

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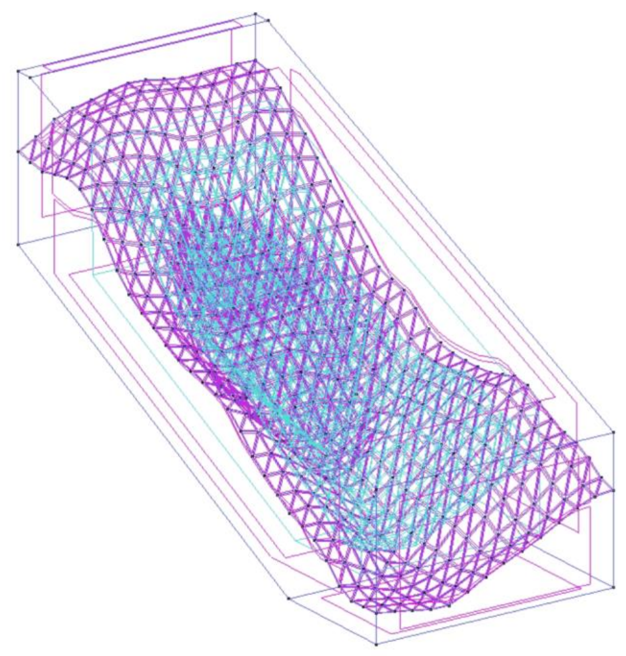
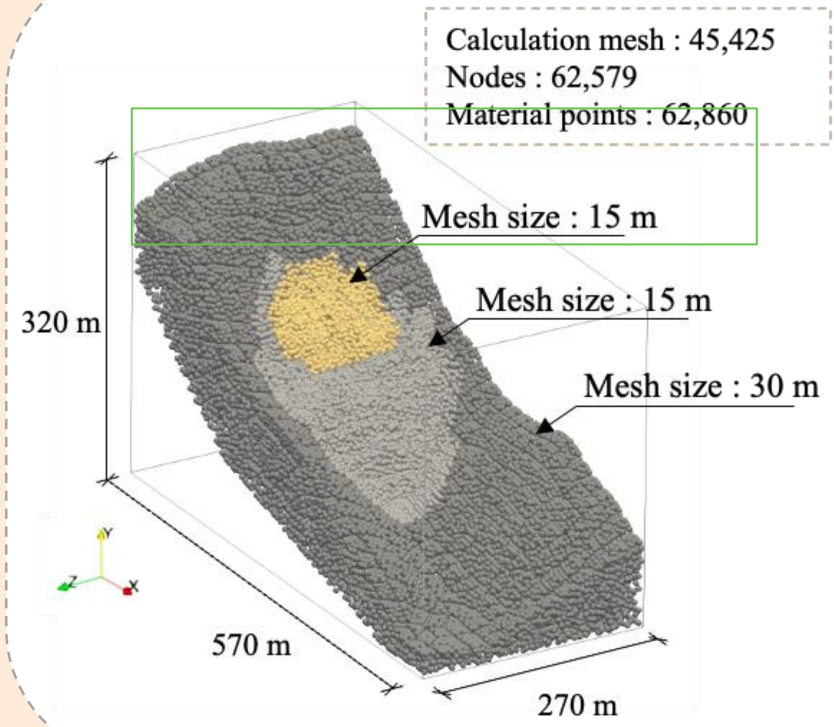
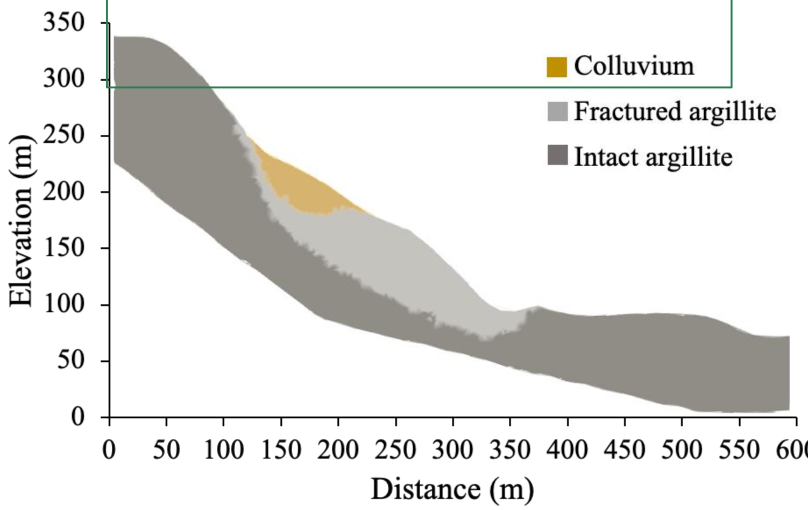
4. 3D Model and Validation







3D Geometric Model

AutoCAD, GiD

Model Setting

Parameters, boundary conditions, MPs

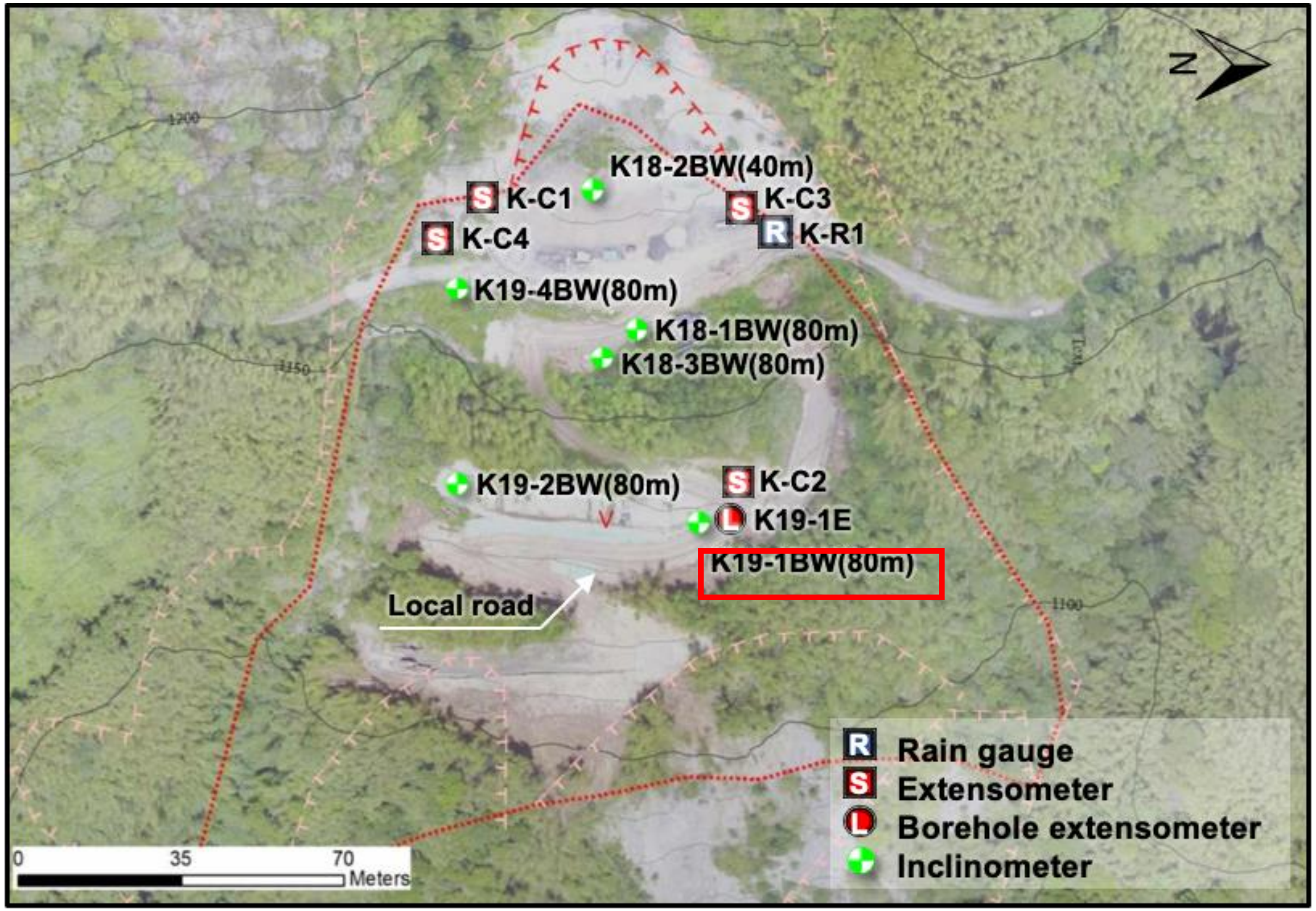
4. 3D Model and Validation

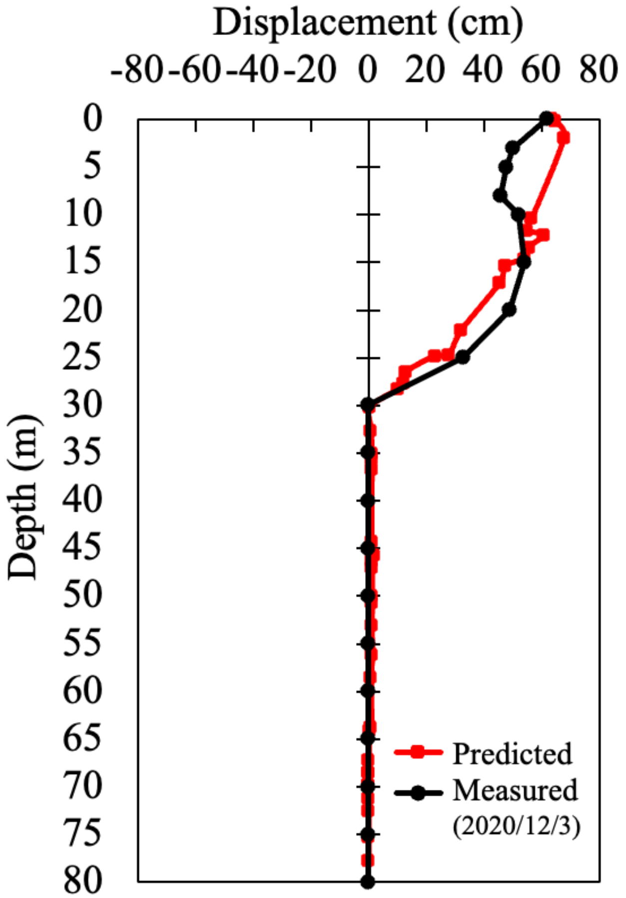
Soil Parameters

Property	Unit	Colluvium	Fractured argillite	Intact argillite
Type of analysis		Saturated Fully Coupled	Saturated Fully Coupled	Dry
Constitutive model		Mohr-Coulomb	Mohr-Coulomb	Linear-Elastic
Unit weight, γ	kN/m^3	20.1	26.5	26.5
Porosity, n	-	0.3	0.3	0.1
Cohesion, c'	kPa	35	60	-
Friction angle, ϕ'	°	25	25	-
Poisson ratio, v	-	0.3	0.3	0.3
Young's modulus, E'	MPa	7	420	6,900
Saturated permeability, k_s	m/s	10^{-3}	10^{-4}	-
Note: the input permeability values of colluvium and fractured argillite were increased 100 times to speed up the computation time of fully coupled analysis				

4. 3D Model and Validation

Initial Sliding Depth

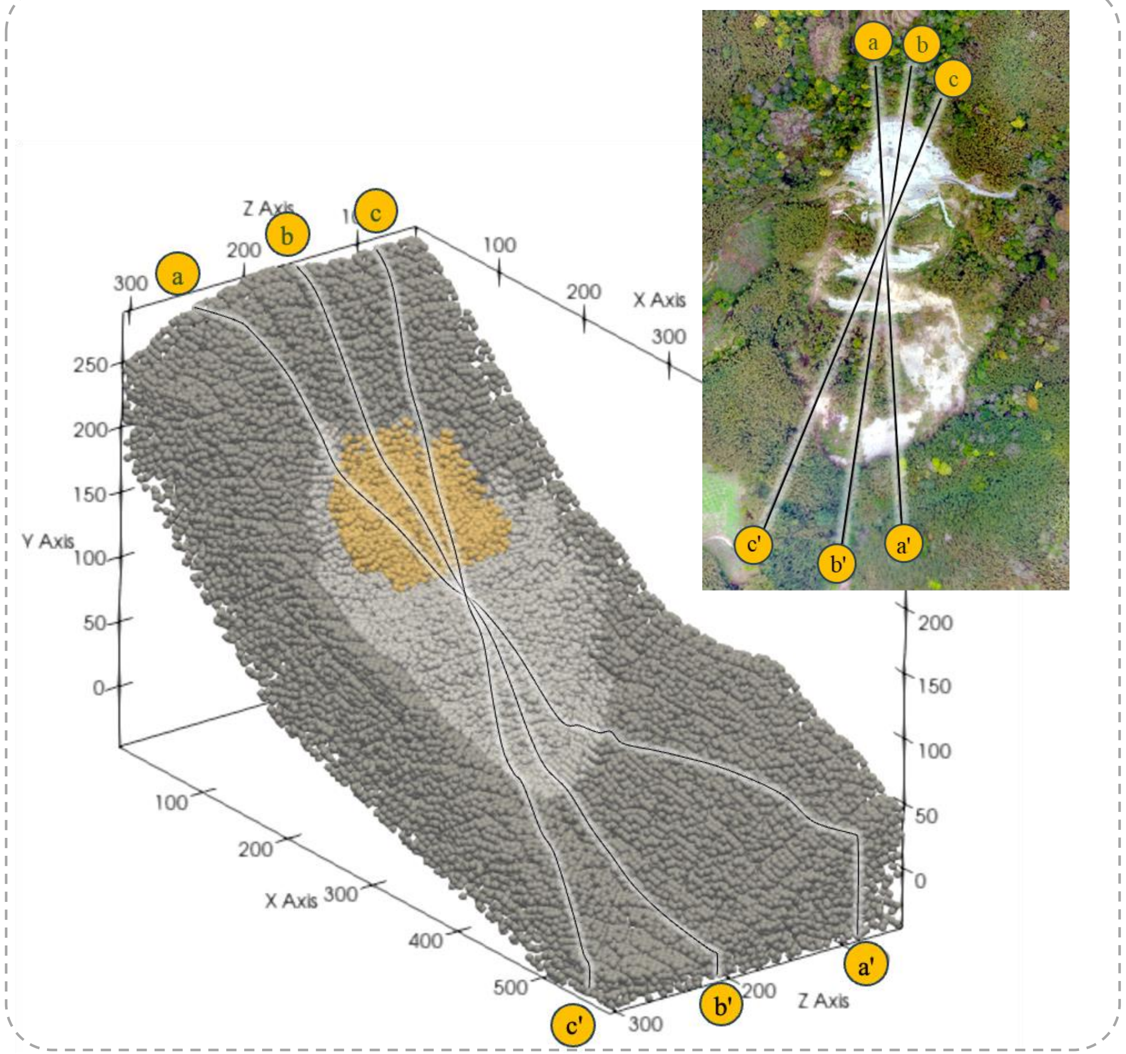




Inclinometer reading

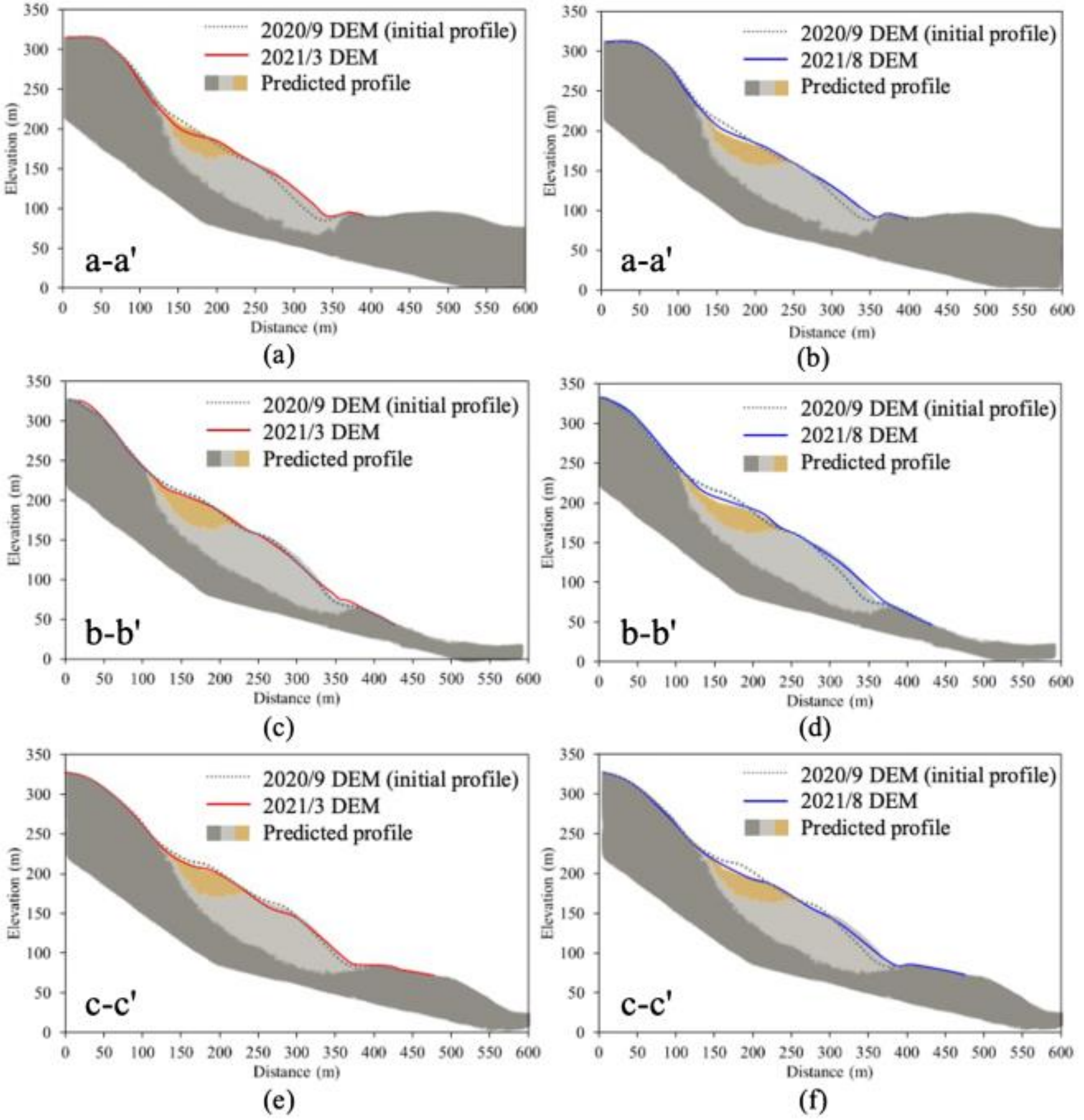
4. 3D Model and Validation

Surface Deformation Pattern



2021/3 DEM

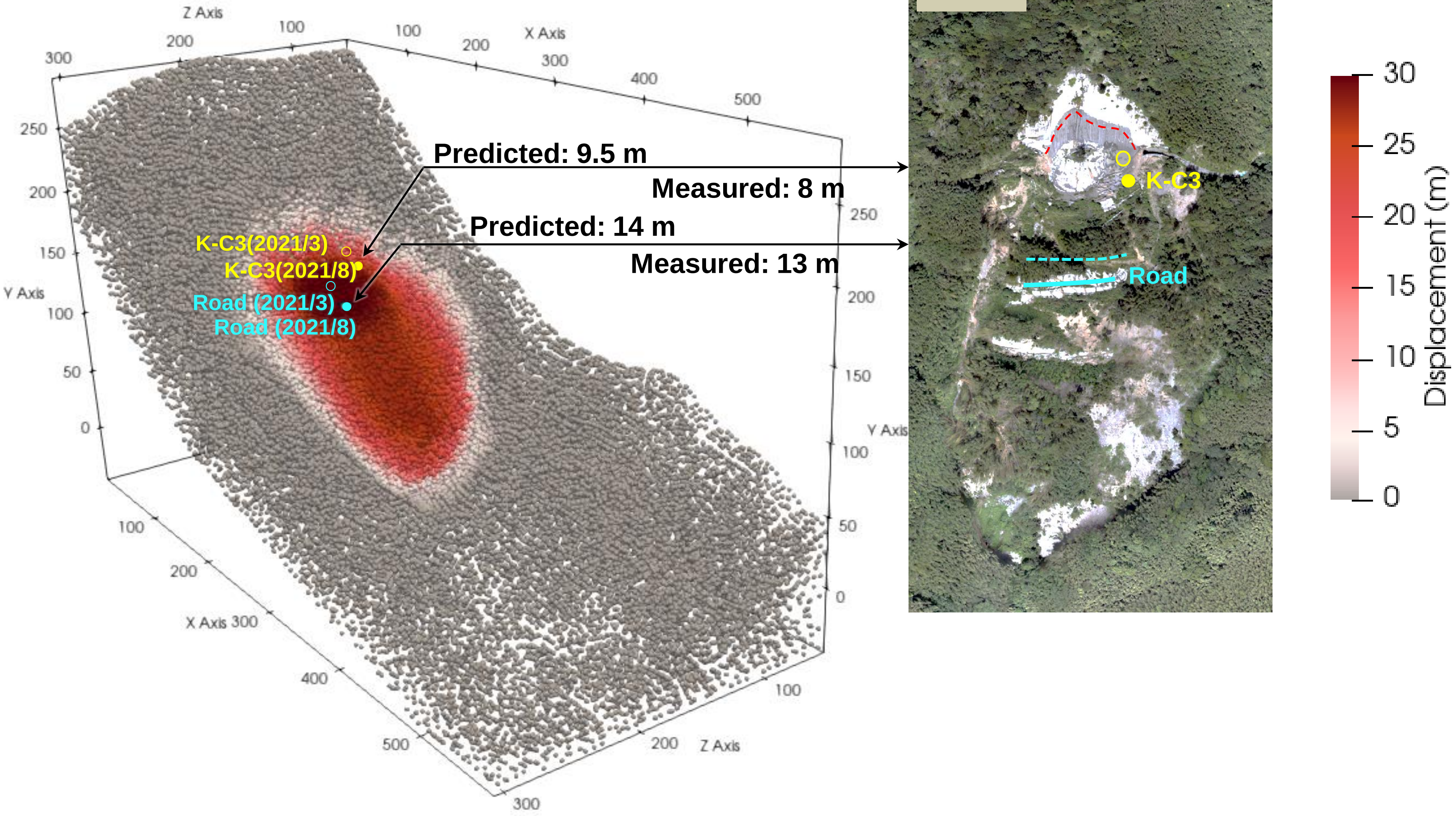
2021/8 DEM



Digital Elevation Model (DEM)

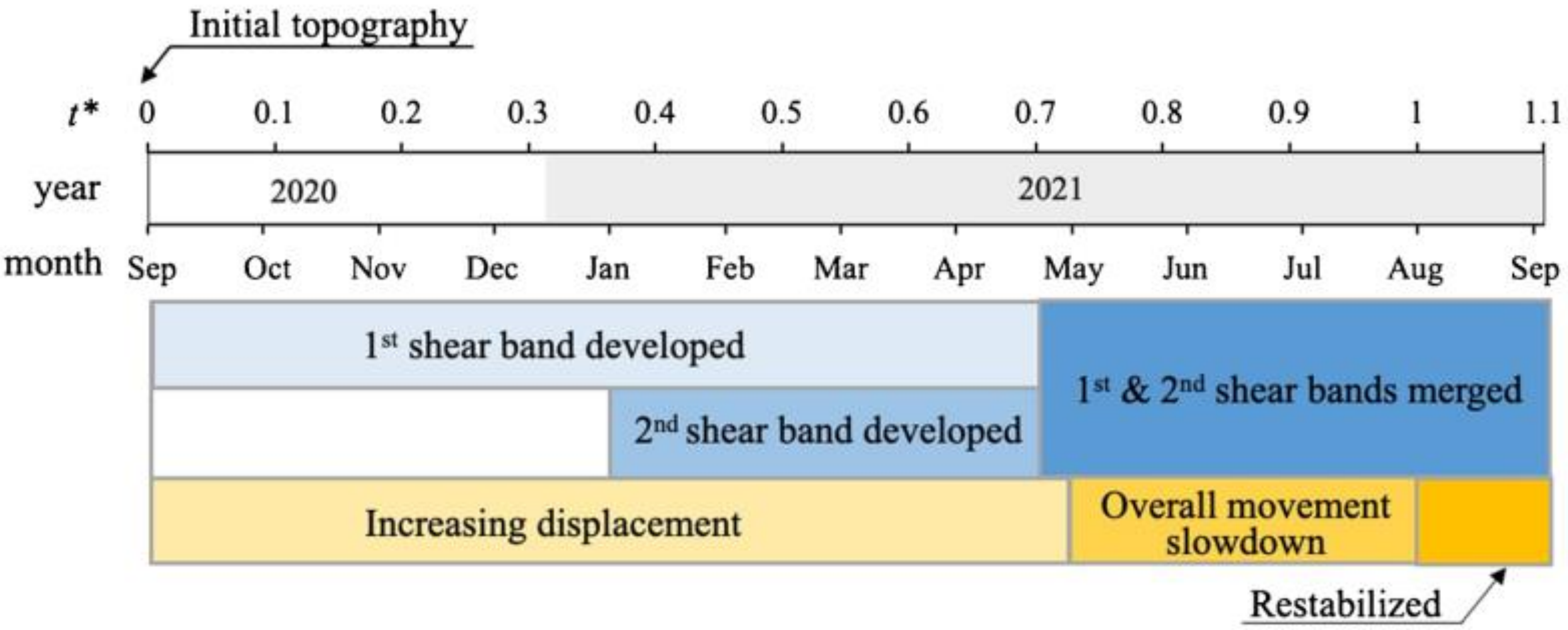
4. 3D Model and Validation

Slope Surface Deformation

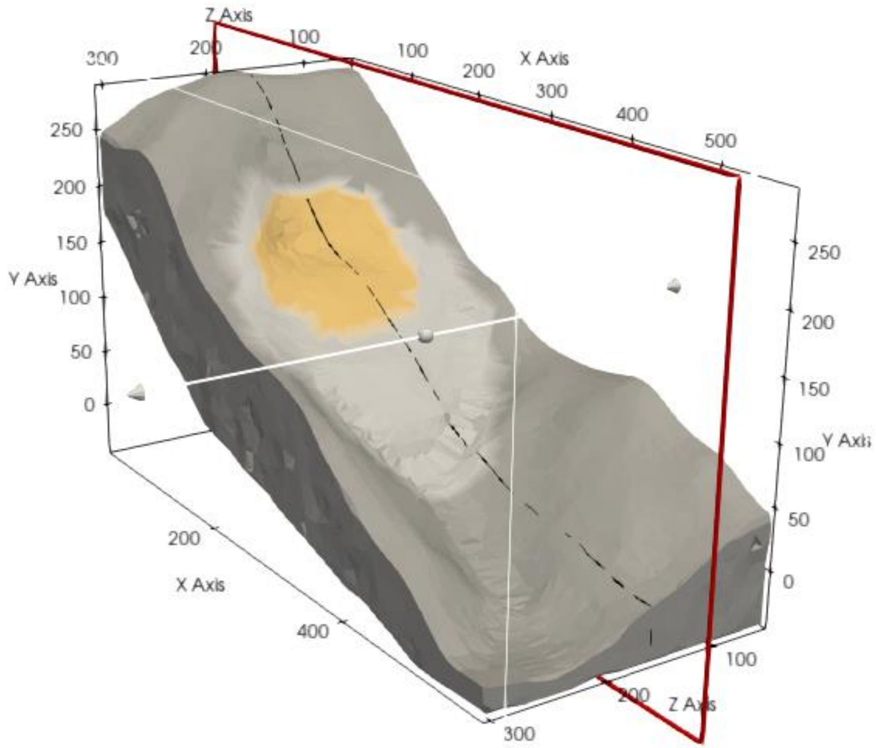


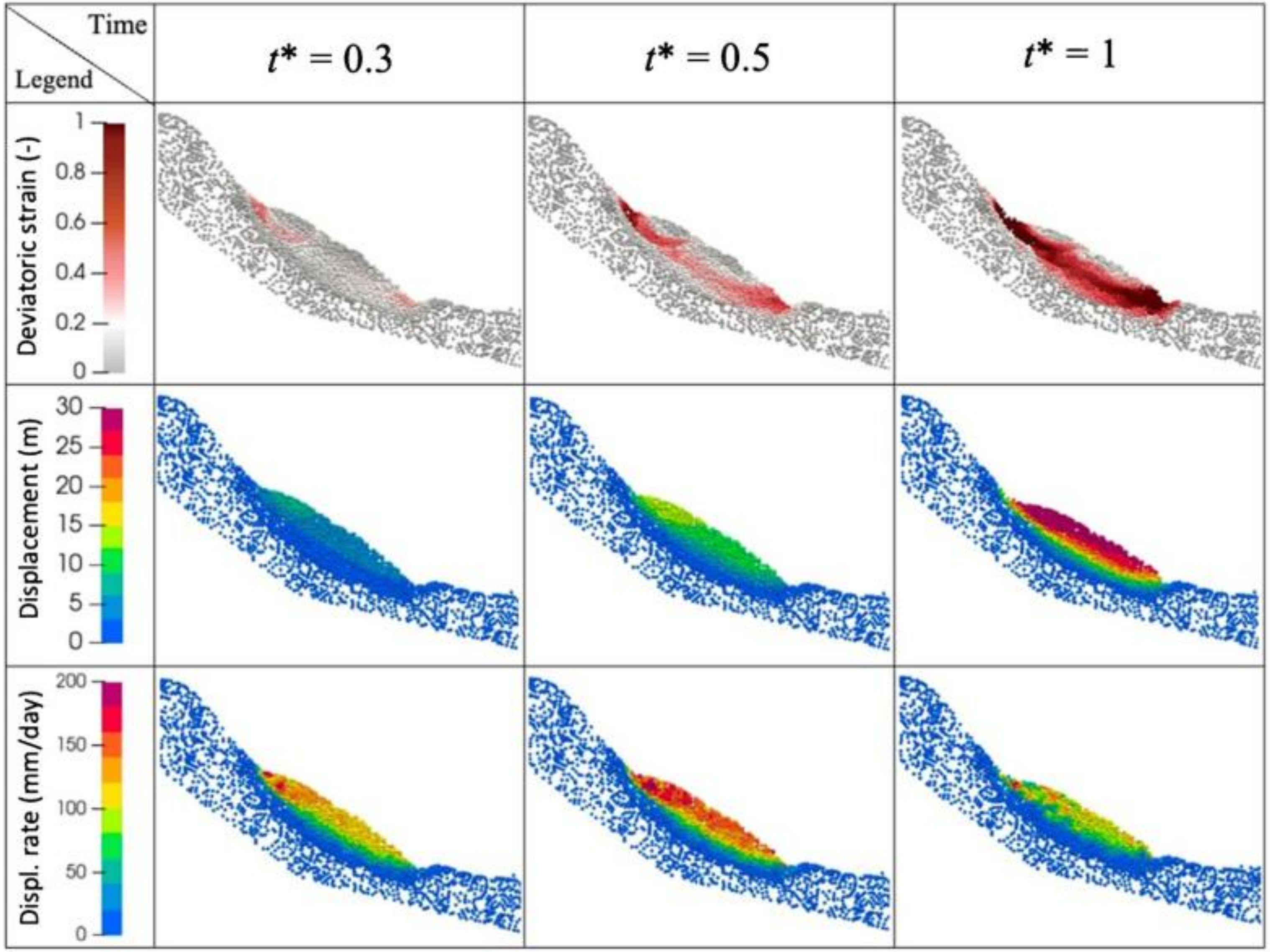
5. Failure Mechanism and Kinematic Behavior

Normalized Time Factor *t**



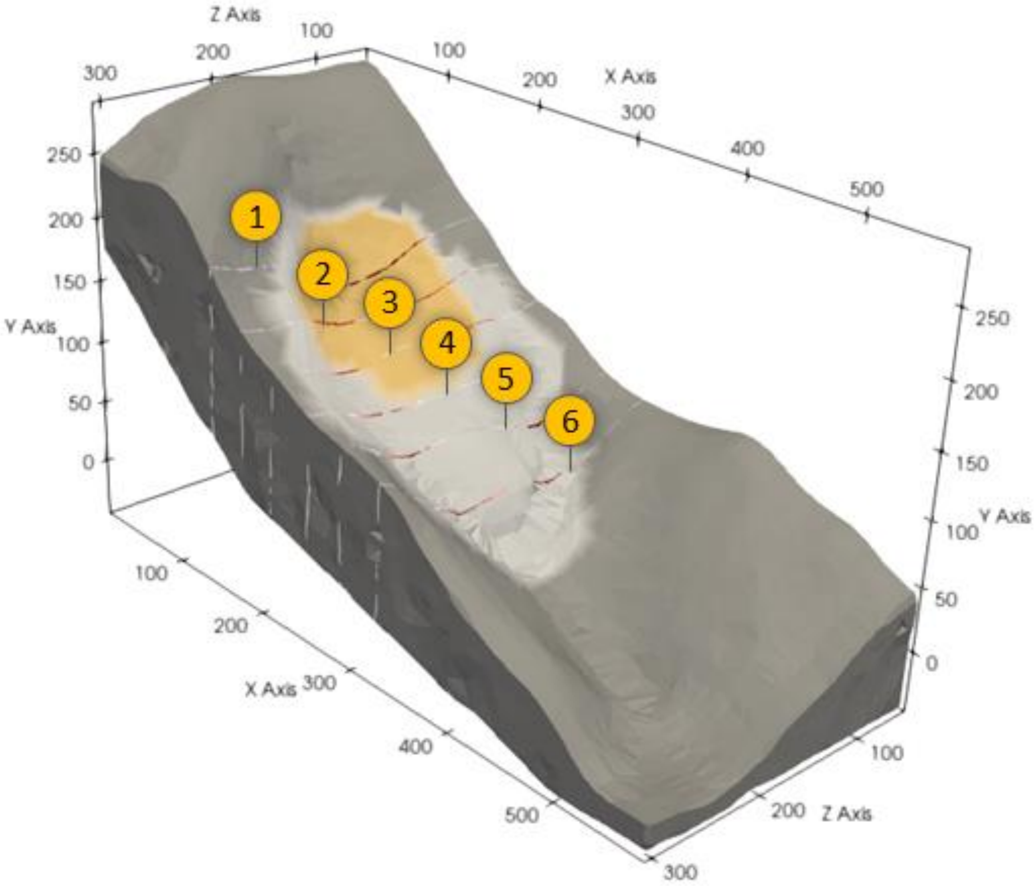
5. Failure Mechanism and Kinematic Behavior

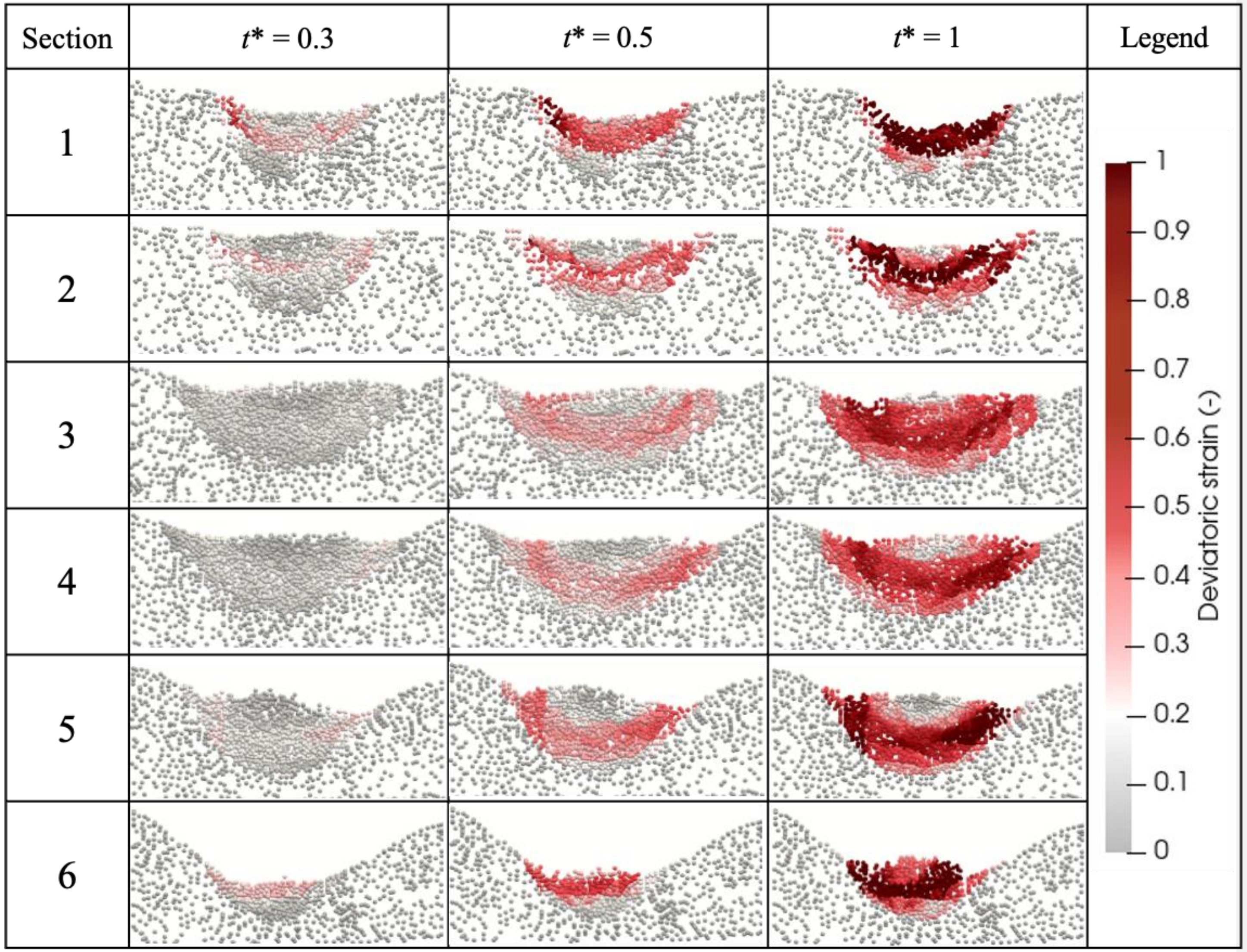




5. Failure Mechanism and Kinematic Behavior

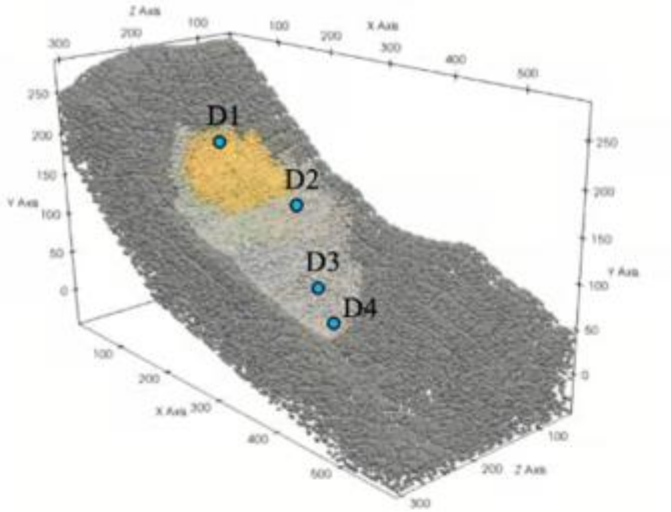
Shear Band Development





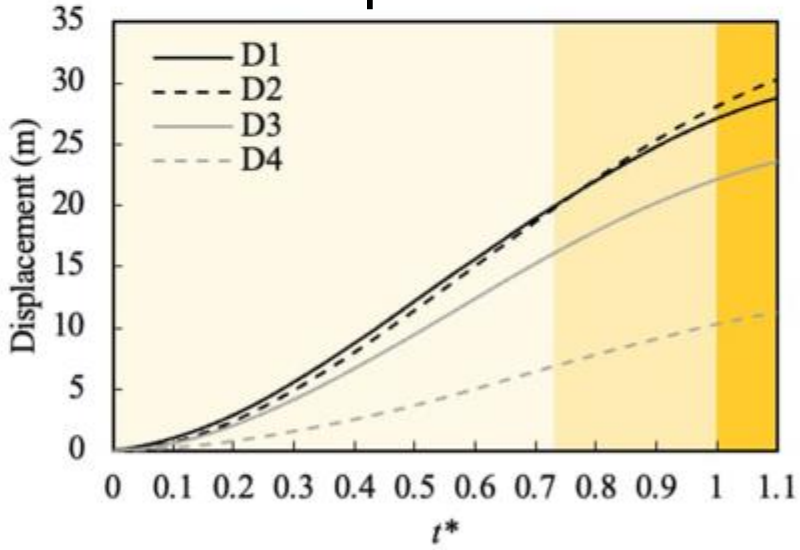
5. Failure Mechanism and Kinematic Behavior

Displacement and Velocity

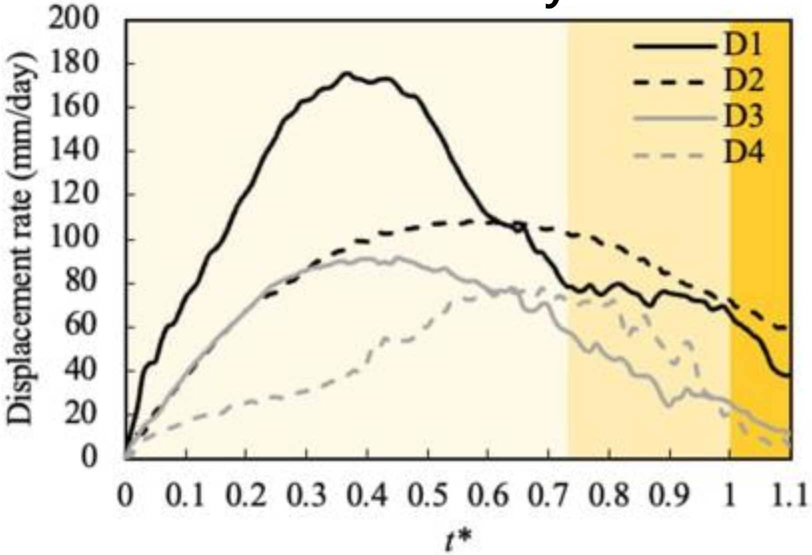


Increasing displacement
Overall movement slowdown
Restabilized

Displacement



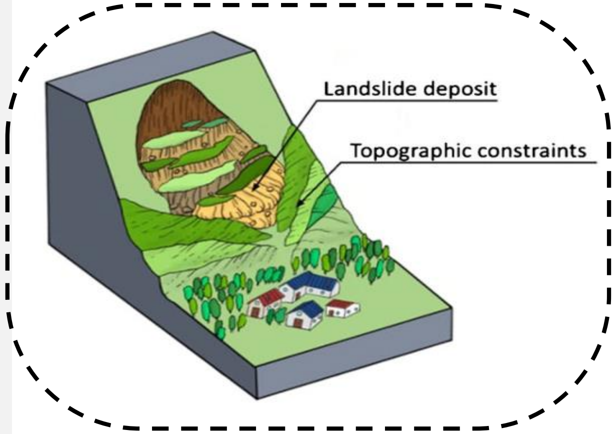
Velocity

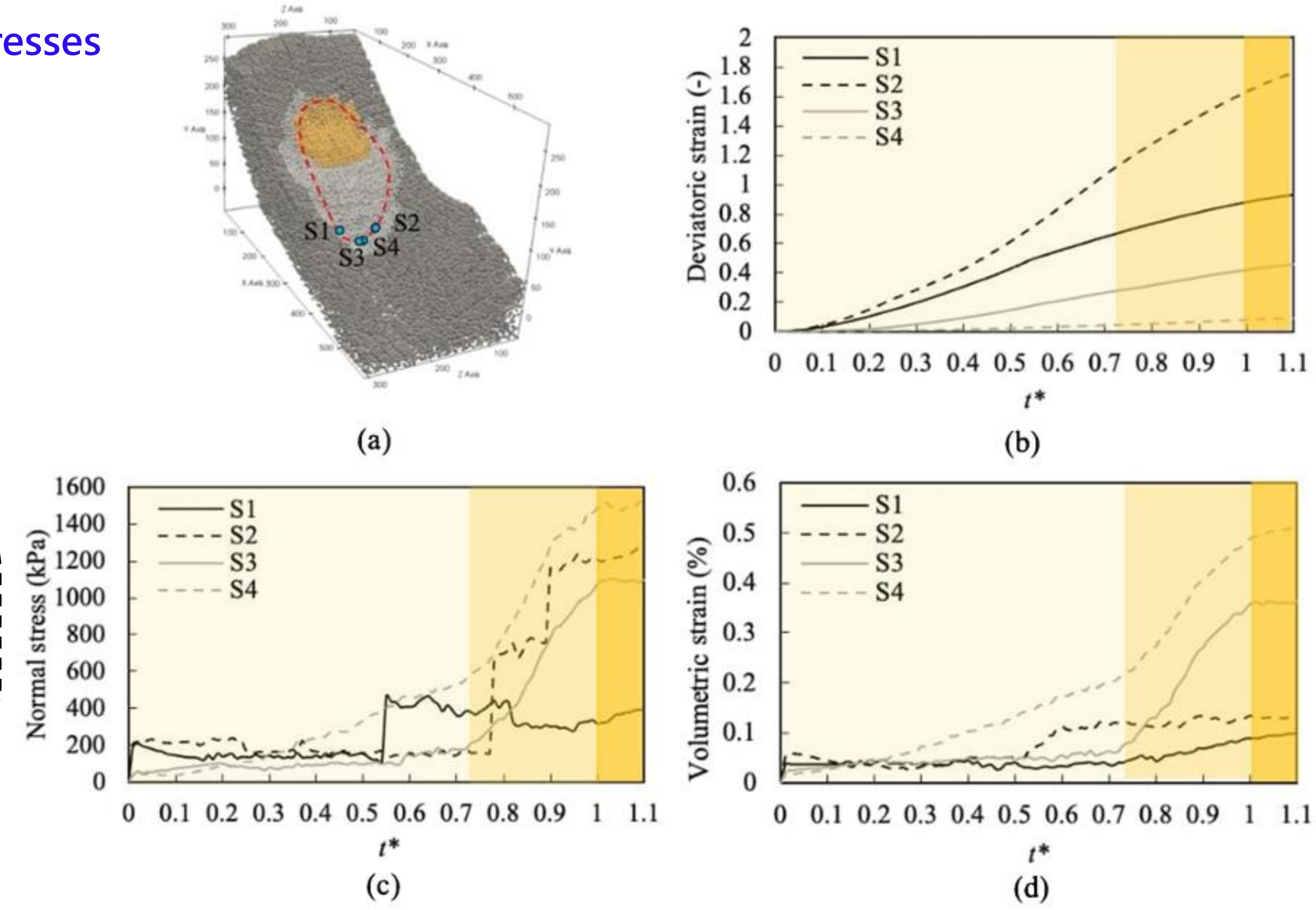


6. The Topographic Constraints

Normal and Shear Stresses

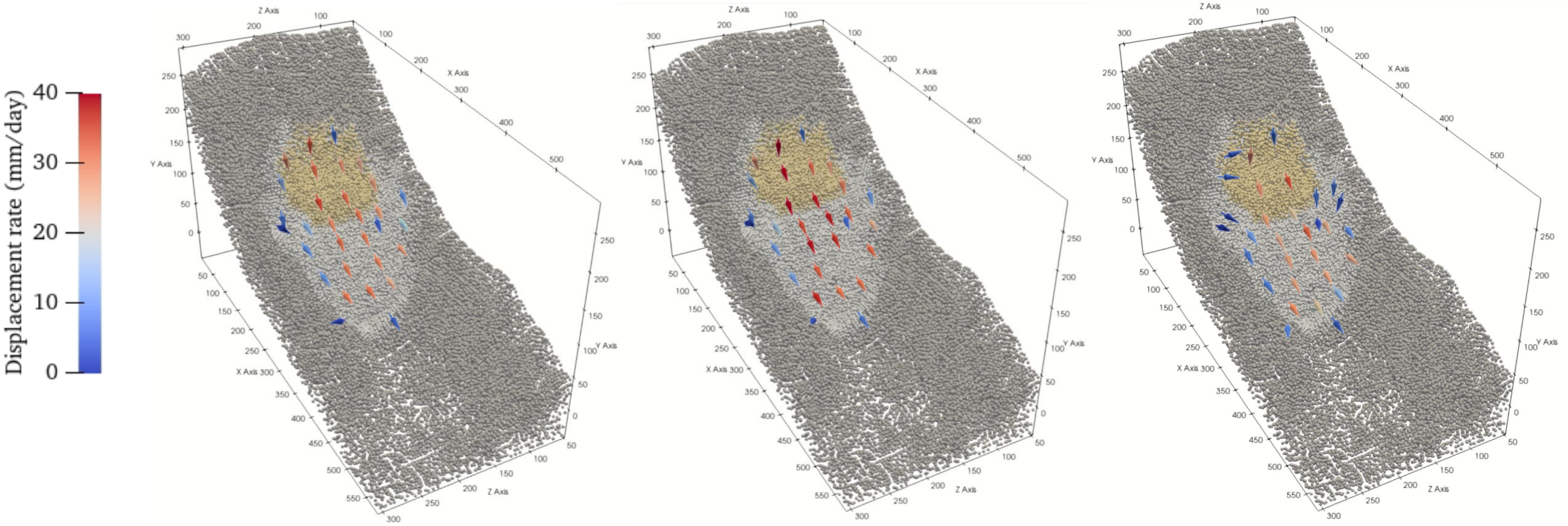
- S1, S2: 2 sides
  → Shear force
- S3, S4: tips
  → Normal stress





6. The Topographic Constraints

Velocity Vectors of Slope Movement



7. Conclusions

1. In the 3D analyses, the Guanghua Landslide develops two shear bands during the failure process.

2. Initially, the movement of the upper slope dominates, and as the second shear band develops and merges with the first one, the individual sliding behavior transitions into a whole movement.

3. The 3D analysis demonstrates that the sliding of the lower slope of Guanghua gradually stops due to topographic constraints.

4. MPM can effectively analyze the post-failure large deformation behavior and the influence of topographic constraints on their sliding.

致謝

彭逸蘋、李威霖、鄭世豪、郭治平、汪俊彥、陳昭維、朱世文、白朝金

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Thanks for Listening

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