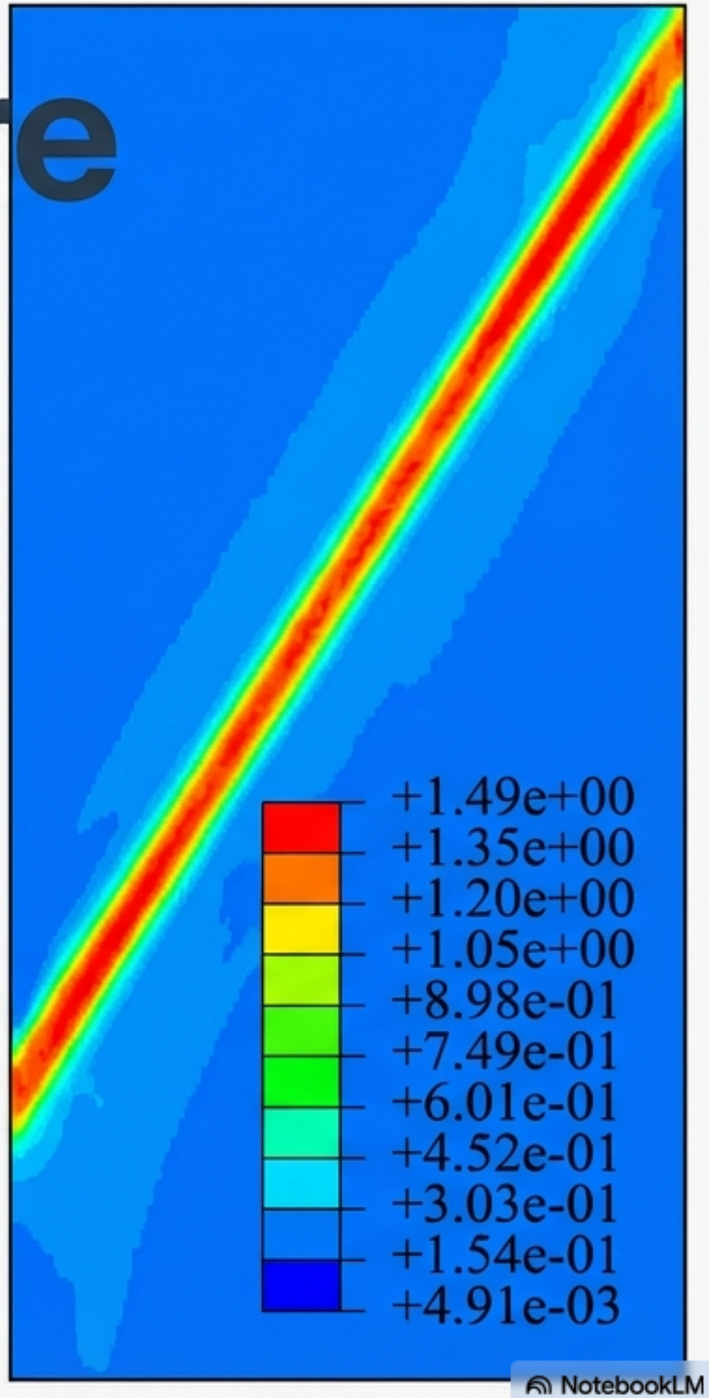
The Hidden Structure of Failure

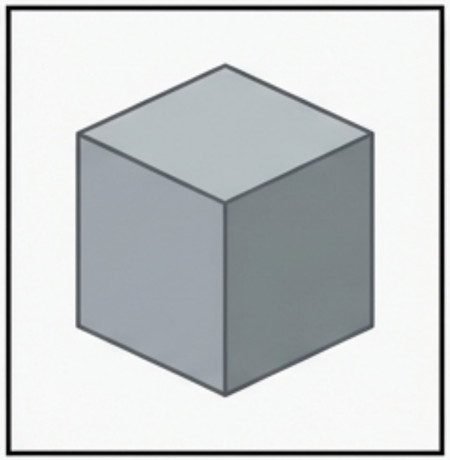
Revisiting Strain Localization through the Lens of Structured Inhomogeneity.

Revisiting Strain Localization through the Lens of Structured Inhomogeneity.

Investigation by Zhihui Wang & Roberto Cudmani
Technical University of Munich



EXECUTIVE SUMMARY: THE CASE FILE

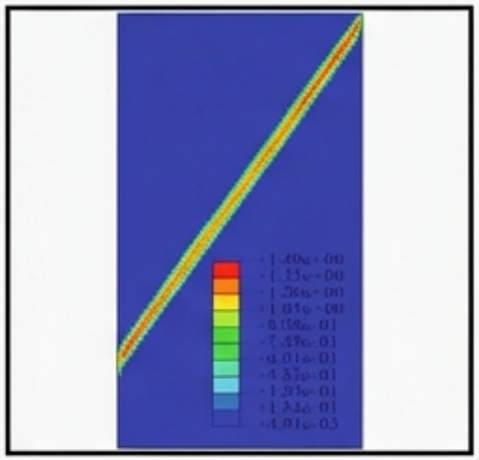


The Suspect: Homogeneous Models

Simulation Challenge: Simple models fail to reproduce realistic shear bands, often relying on white noise or artificial complexity.

The Clue: Structured Inhomogeneity

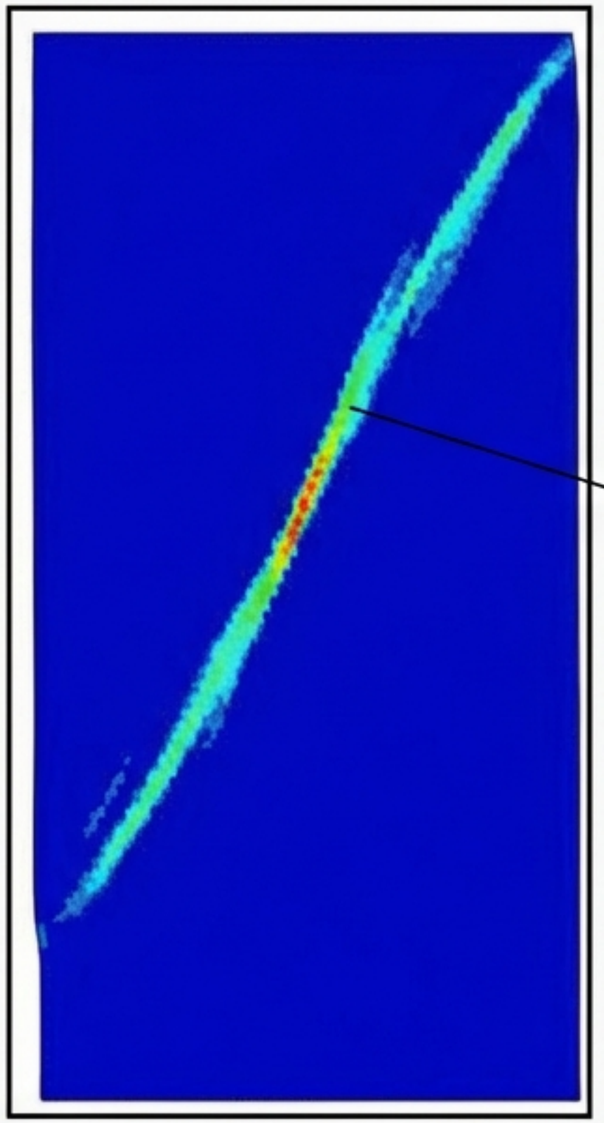
The Investigation: Applying Conditional Random Fields (CRF) to model the 'messiness' of sand density with spatial correlation.



The Verdict: Realistic Failure

The Impact: Realistic strain localization emerges naturally from structured initial states. Geometry is as critical as physics.

The Phenomenon: Strain Localization



1. What is it?

In sandy soils, deformation is rarely uniform. Under stress, it concentrates into narrow, intense zones.

2. The Mechanism

A bifurcation event—transitioning from homogeneous deformation to a localized failure mode.

3. The Key Driver

While stress and boundaries matter, this study isolates the critical role of **Initial Inhomogeneity**.

4. The Anomaly

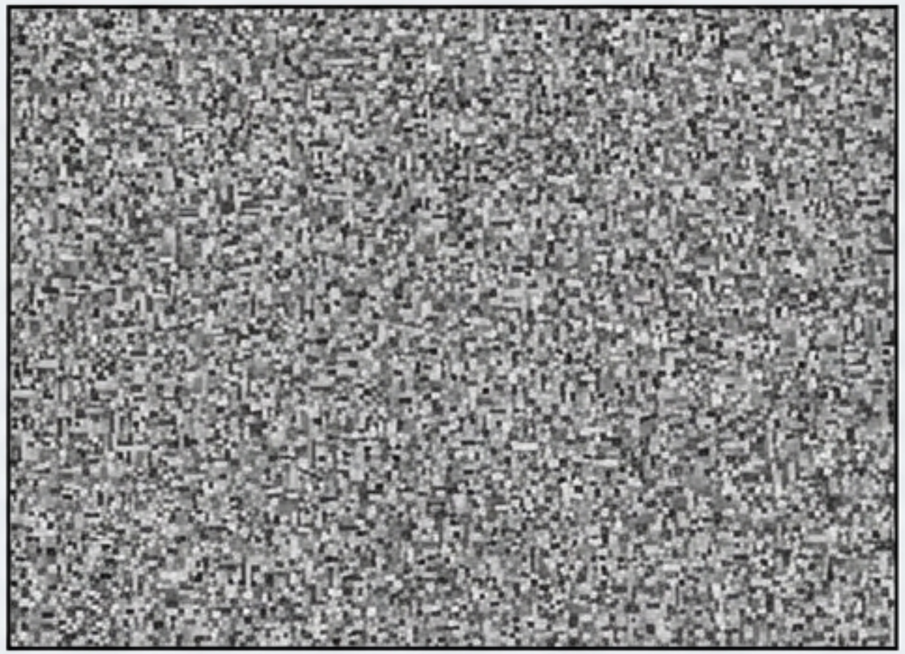
Occurs even in ‘uniform’ lab samples (40mm x 80mm), suggesting uniformity is an illusion.

THE BLIND SPOT IN CURRENT MODELING

THE HOMOGENEITY MYTH

Assuming soil is perfectly uniform ignores natural variations caused by gravity and sedimentation.
Roboto Mono

THE WHITE NOISE FLAW



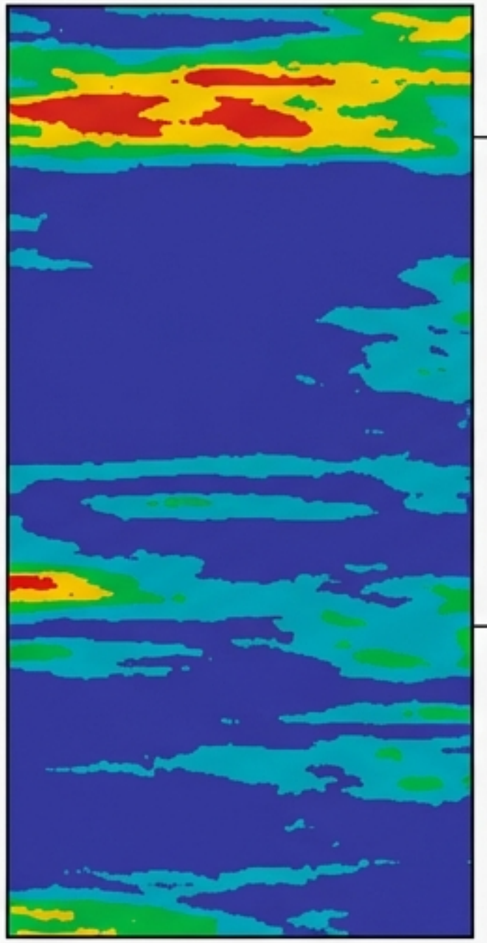
Adding unstructured randomness fails because it lacks **spatial correlation**. Real soil doesn't change pixel-by-pixel; it has structure.

Consequence: These approaches fail to capture the ‘history’ of the soil fabric.

Modeling the ‘DNA’ of the Specimen

The Solution: Conditional Random Fields (CRF)

Inter Regular is considered to the condlicted heatnap to continct the natural tod Spectral heating distributions are noyologa, mawing dense; analysis patents on the movage lowts mfect. green, void continental Red, Warning, Yellow, and Cool Blue etms.

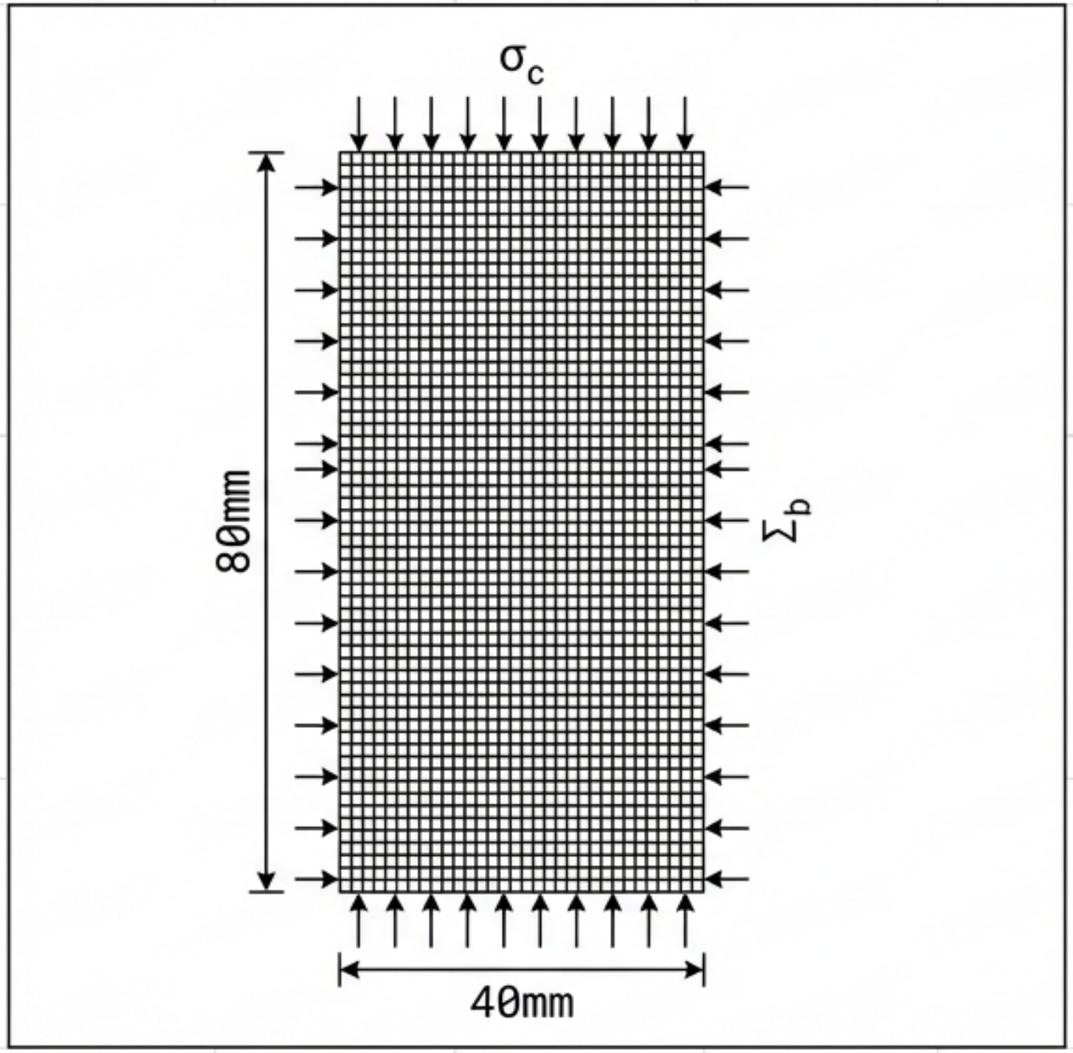


A “Virtual Specimen” possessing structured inhomogeneity.

1. **Probability Density Function**
   Respects the global max/min void ratios and statistical distribution.
   `Inter Regular`

2. **Spatial Correlation**
   Ensures neighboring points are related. If point A is dense, point B is likely dense. This mimics natural deposition.
   `Roboto Mono Medium`

The Experimental Setup



Technical Specs

Geometry

Plane strain compression
(40mm width x 80mm height).
2048 elements (1.25mm x 1.25mm mesh).

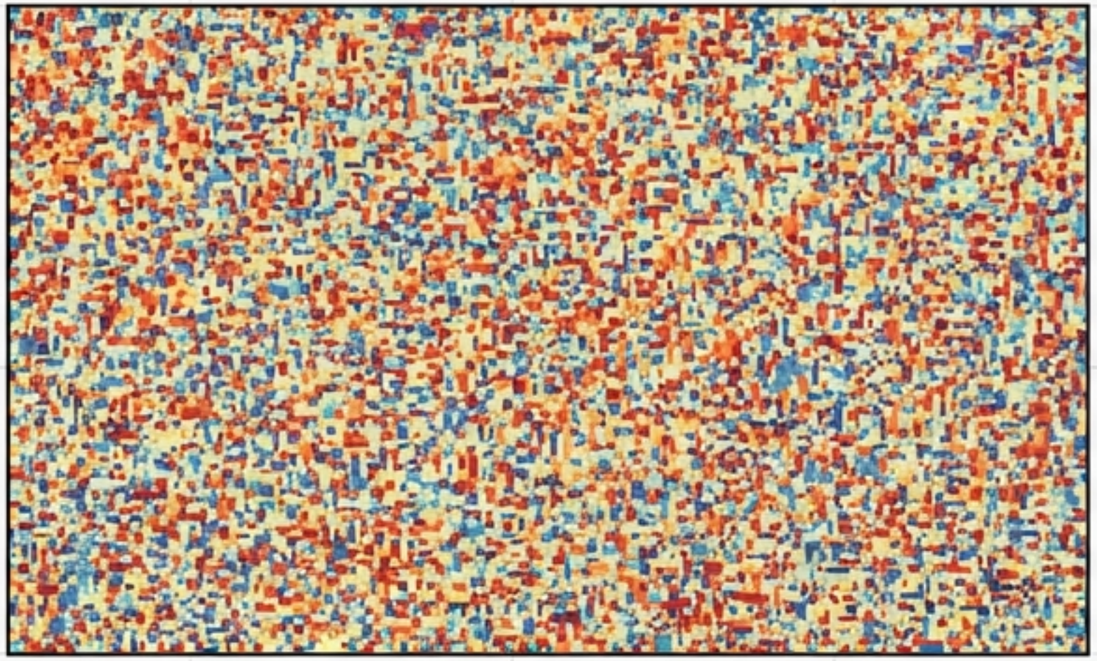
Constitutive Model

Hypoplasticity (von Wolffersdorff, 1996).
Note: Captures pressure/density dependence but NO complex fabric tensors.

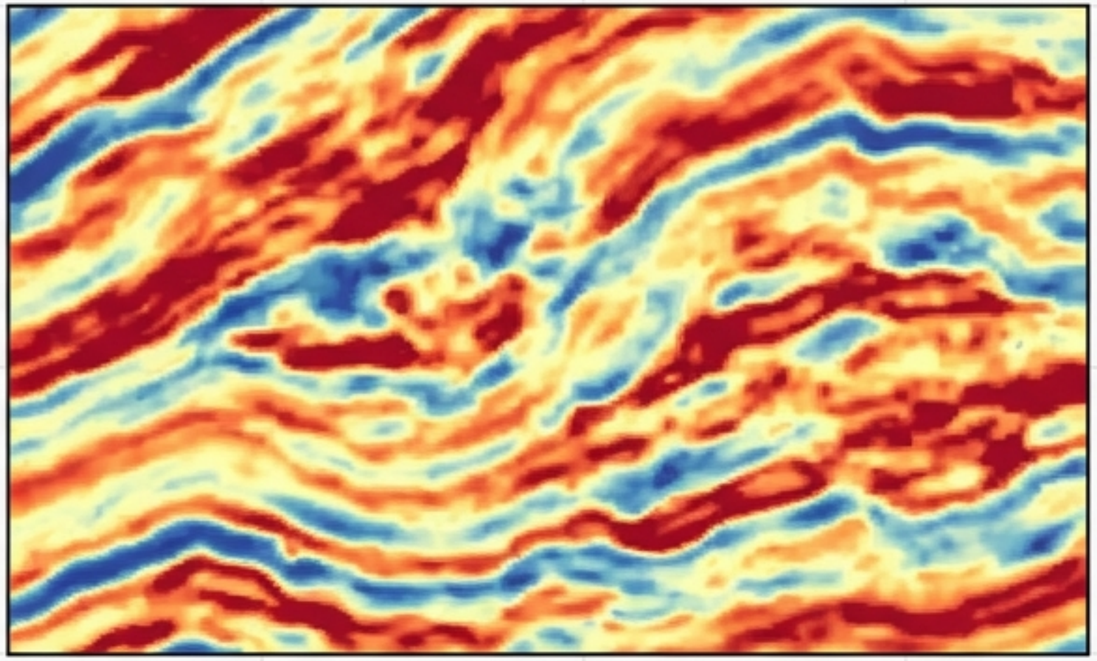
The Controlled Variable

Material parameters remain constant.
Only the **spatial distribution** of the initial void ratio changes.

Visualizing the Input Fields



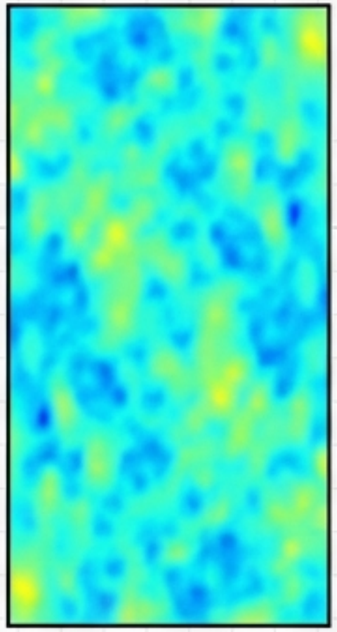
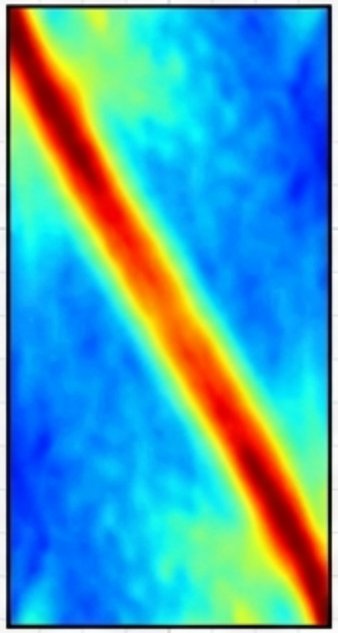
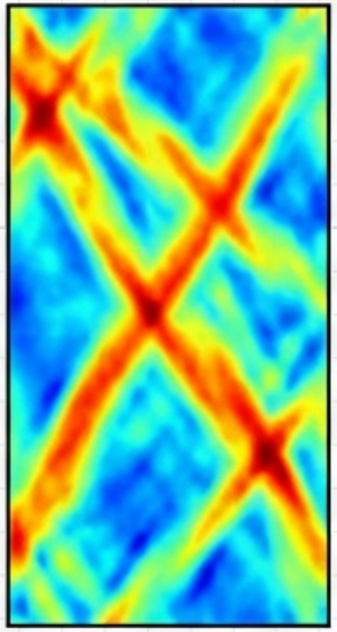
Unstructured White Noise
(Ignores physical neighbors)



Structured Inhomogeneity (CRF)
(Respects autocorrelation & sedimentation)

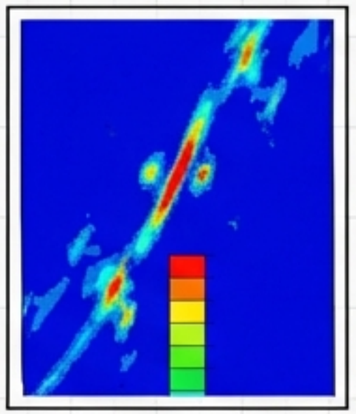
The structural realism of the right-hand field is the key differentiator in predicting realistic failure.

Global Behavior: Three Modes of Failure

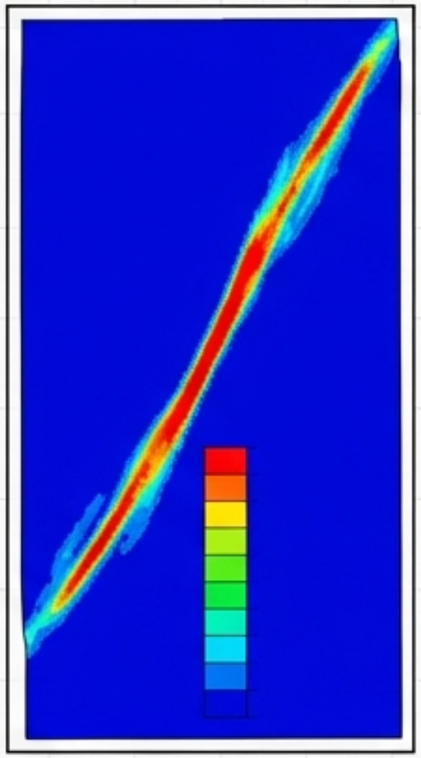
1. No Shear Band (Diffuse deformation - 45 cases)	2. Single Shear Band (Classic diagonal failure - 15 cases)	3. Multiple Shear Bands (Complex/Conjugate failure - 46 cases)
		

Key Insight: Even with the same global density, different arrangements of voids lead to dr**asti**cally different failure modes.

Anatomy of a Shear Band



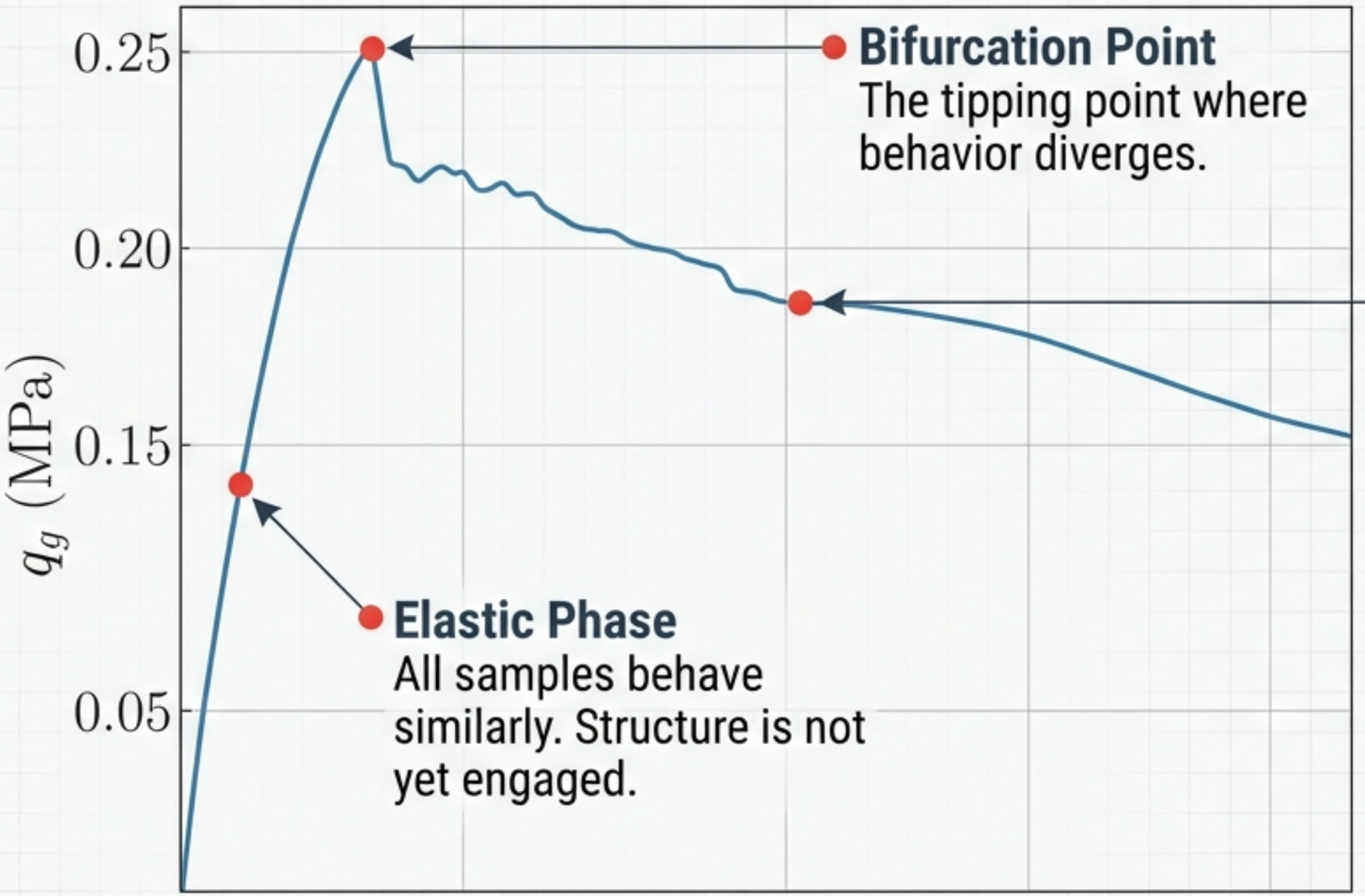
The shear band acts as a zone of intense dilatancy (volume expansion).



Pre-Peak
Localized zones form but are disconnected.

Post-Peak
A dominant band connects. Global stress drops as the band accommodates all further deformation.

The Stress-Strain Fingerprint



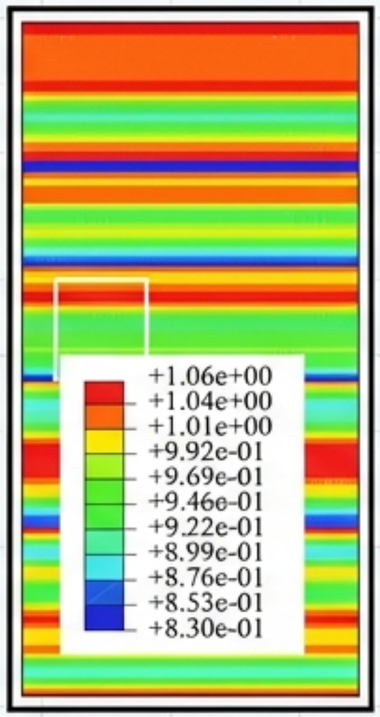
Bifurcation Point
The tipping point where behavior diverges.

Post-Peak Softening
Structural response. The steepness depends on the specific shear band geometry.

Elastic Phase
All samples behave similarly. Structure is not yet engaged.

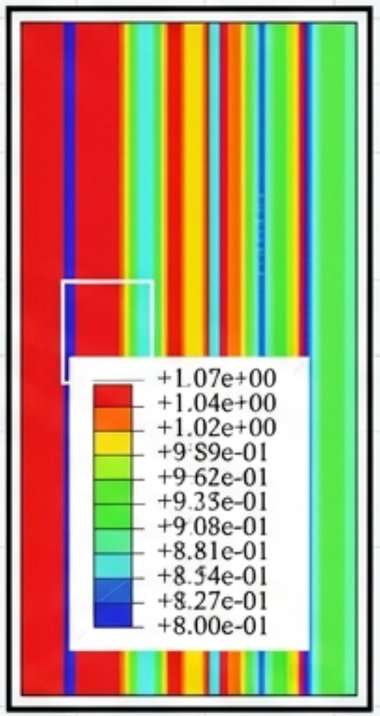
The Criticality of Direction

Not All Randomness is Created Equal.



Horizontal Layering

Suppresses localized shear bands due to symmetry.



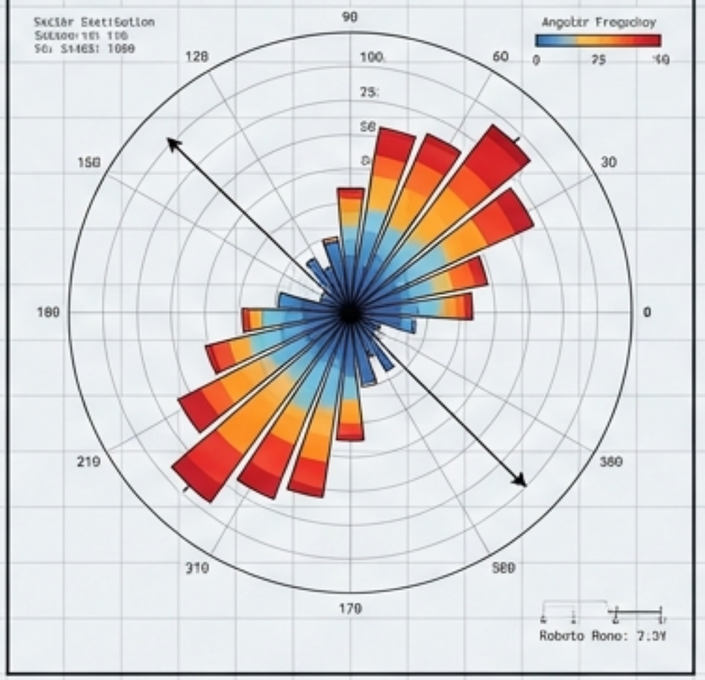
Vertical Variations

Essential for triggering the shear band. The void ratio gradient drives the failure path.

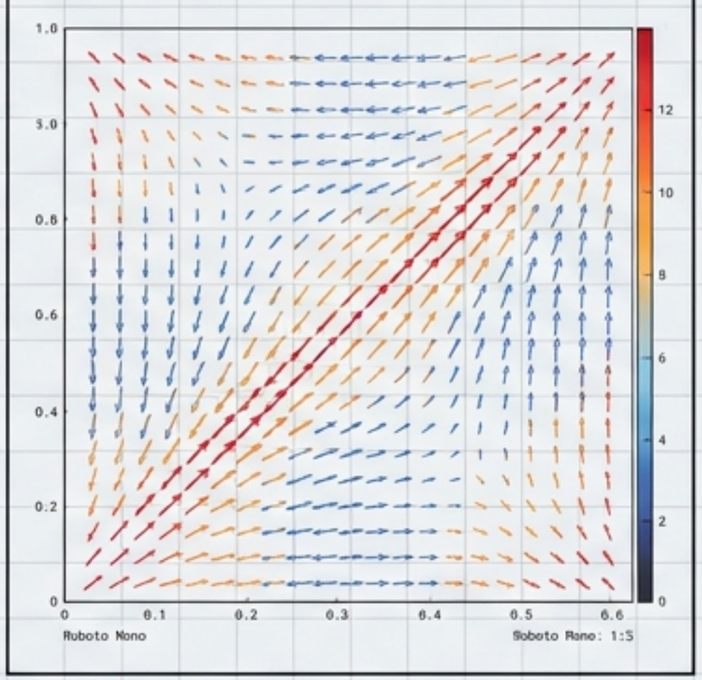
Forensics: The Hessian Analysis

By analyzing the mathematical curvature of the void ratio field **(Hessian Matrix)**, we reveal the hidden **“grain” “grain”** of the soil.

Angular Distribution (Rose Diagram)



Vector Field Directionality



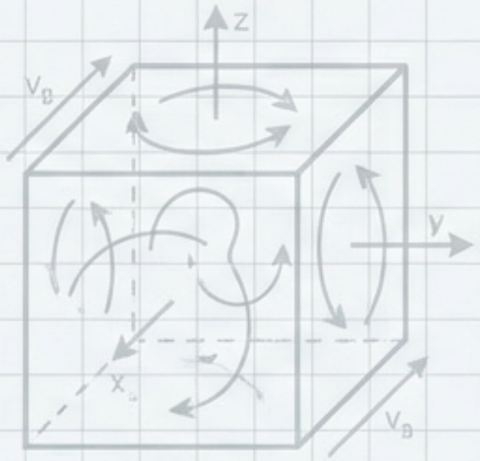
The Discovery: The principal direction of the inhomogeneity aligns with the normal direction of the shear band. The failure is ‘pre-written’ in the structure.

Complexity vs. Reality vs. Reality

Standard Approach

Simple Geometry + Complex Constitutive Models

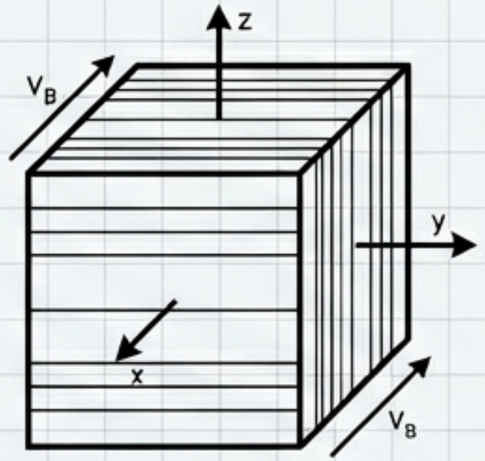
(Fabric Tensors, Forced Anisotropy)



This Study's Approach

Structured Inhomogeneity + Simple Model

(CRF Geometry + Hypoplasticity)



Conclusion: If you model the initial geometry correctly, the complex behavior emerges naturally.

Implications for Engineering

01. Lab Testing

Realize that “**uniform**” **samples** are a myth. Post-peak softening is often a **structural** response, not just a material property.

02. Numerical Modeling

Stop using white noise. Adopt **spatially correlated fields (CRF)** for realistic risk assessment in simulations.

03. Calibration

Exercise **caution** when **calibrating to post-peak data**; you may be calibrating to a specimen’s unique defects rather than the soil’s intrinsic physics.

From Random to Structured.

Accurate representation of the initial state is the missing link in predicting catastrophic soil failure.

Technical University of Munich // 2026