Evaluación de los efectos de falla de taludes utilizando un modelo 3D del suelo: Aplicación en los acantilados de la Costa Verde

Por Dr. Kohei Fujita y Mag. Julian Palacios
(Earthquake Research Institute, The University of Tokyo)

Speaker Profile and Current Research

- I **graduated from UNI** and am now a **Ph.D. student** at the Earthquake Research Institute (ERI), UTokyo.
- **Supervisor:** Prof. Kohei Fujita.
- Likewise, we are participating in the Peru–Japan **ProCiencia project** led by Prof. Miguel Diaz.

- **B.Sc. Thesis:** Structural assessment under seismic and tsunami loading (**UNI, 2019**).
- **M.Sc. Thesis:** Computation of crustal deformation to improve earthquake and tsunami source models (**UTokyo, 2023**).
- **Current Ph.D. Focus:** Analysis of massive 3D simulation outputs for engineering assessment (**UTokyo, 2025-28**).

Research Motivation

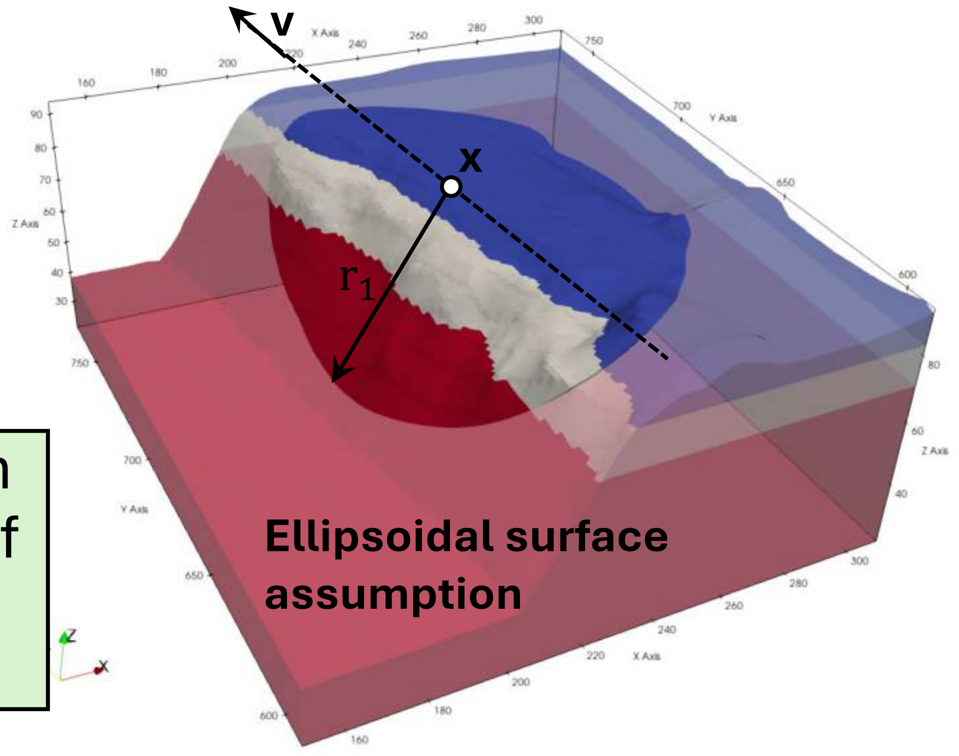
In the research, the following parts are proposed:

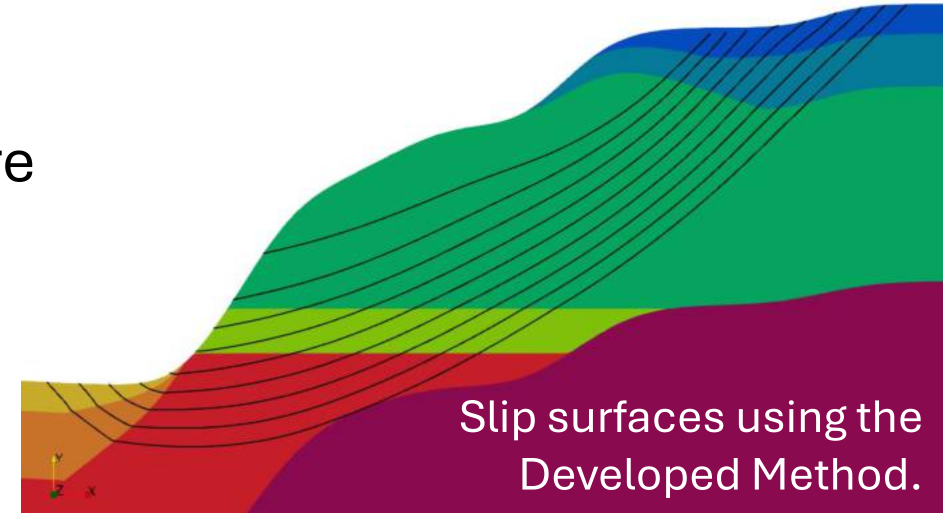
Part 1 (Presentation by Dr. Fujita): 3D ground motion simulation to assess dynamic wavefield acting on cliff
Part 2 (This Presentation): Visualization + assessing slope stability on 3D models.

- Previous studies conducted 2D analyses; however, Costa Verde Cliffs have a **complex 3D geometry**.
- Usually, to estimate Factor of Safety (FS) or permanent displacements, **parametric surfaces** are assumed.

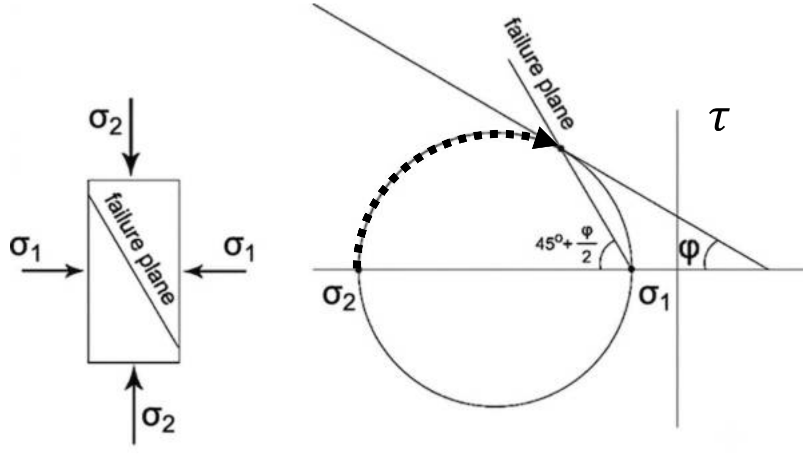
However, in 3D, this assumption comes with a **large parameter set** (**r**[3], **x**[3], **v**[3]). How can we define a smaller set?

We are developing a method to define a smaller set.





Proposed Method

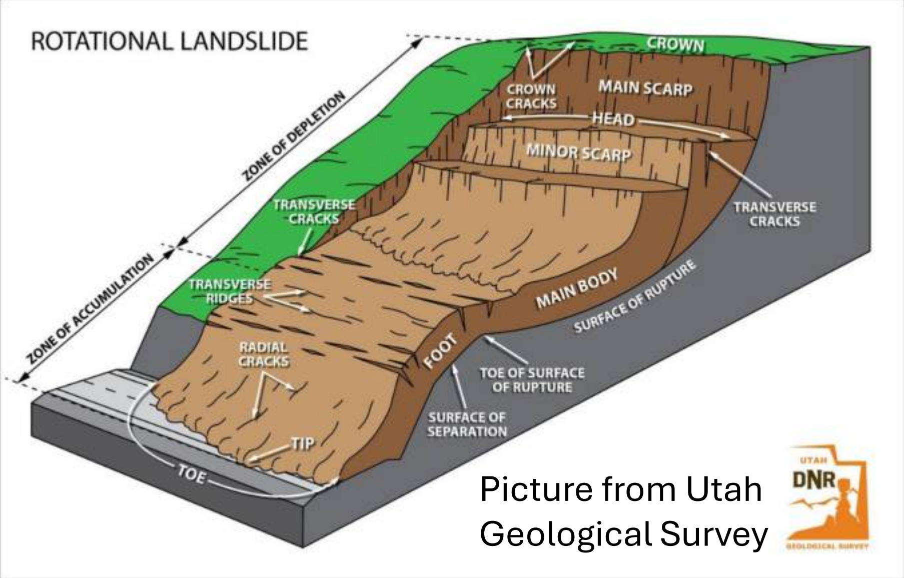


❖The actual failure plane is expected to occur at the direction of $45 + \frac{\phi}{2}$ **from the principal stress axis**. By **connecting the failure direction** in a discretized domain, we can estimate slip surfaces.

❖In other words, by **analyzing the stress field**, given a load state, we can **determine candidate slip surfaces**.

✓This **stress field-based approach** is convenient as the #of candidate slip surface is much smaller than parametric surfaces.

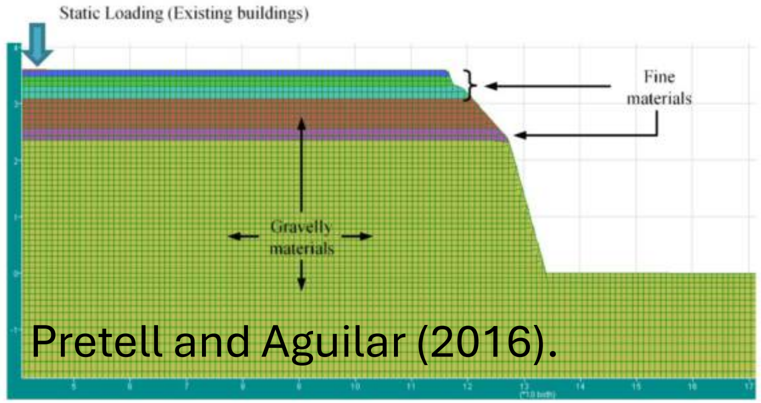
✓We are developing a **method** in which we can **directly** obtain candidate slip surfaces in 3D.



Picture from Utah Geological Survey

Generation of 3D Ground Model

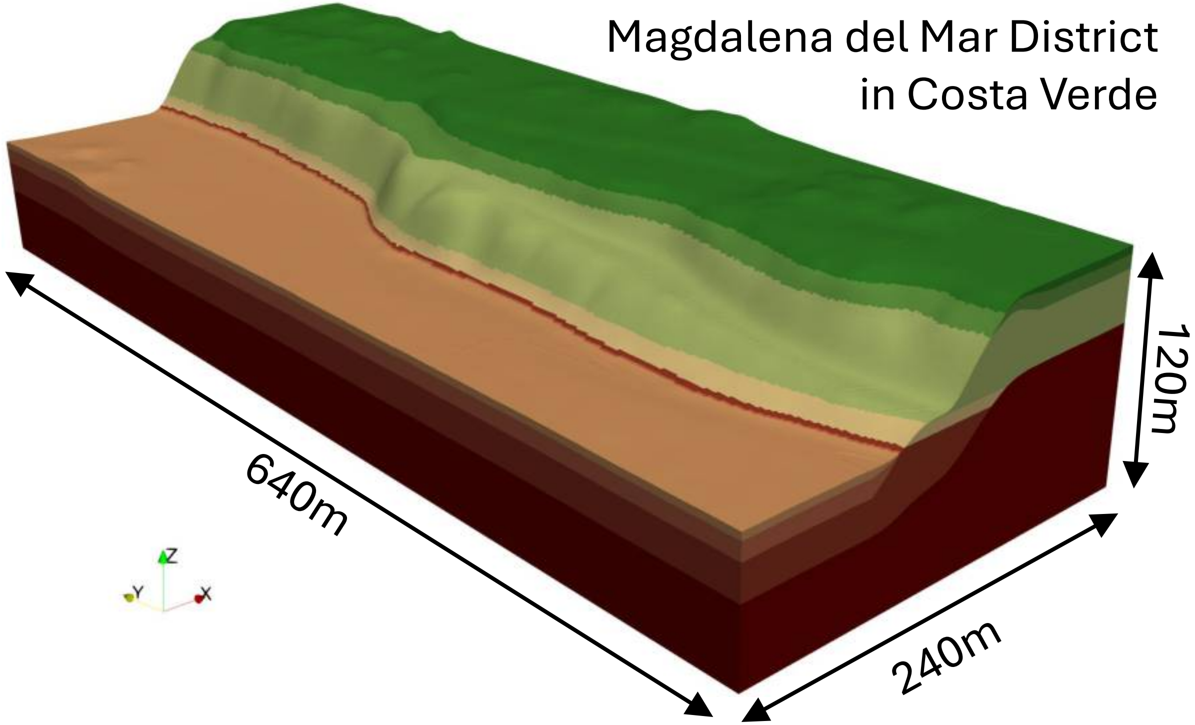
According to **field observation**, there are some layers of sand/fine materials in Lima Cliffs. **Previous SSA studies** also considered this field data.



Pretell and Aguilar (2016).

Fig. 3- Costa Verde Cliff Model (FLAC).

Magdalena del Mar District in Costa Verde



Field Observation data from IGP (2021).

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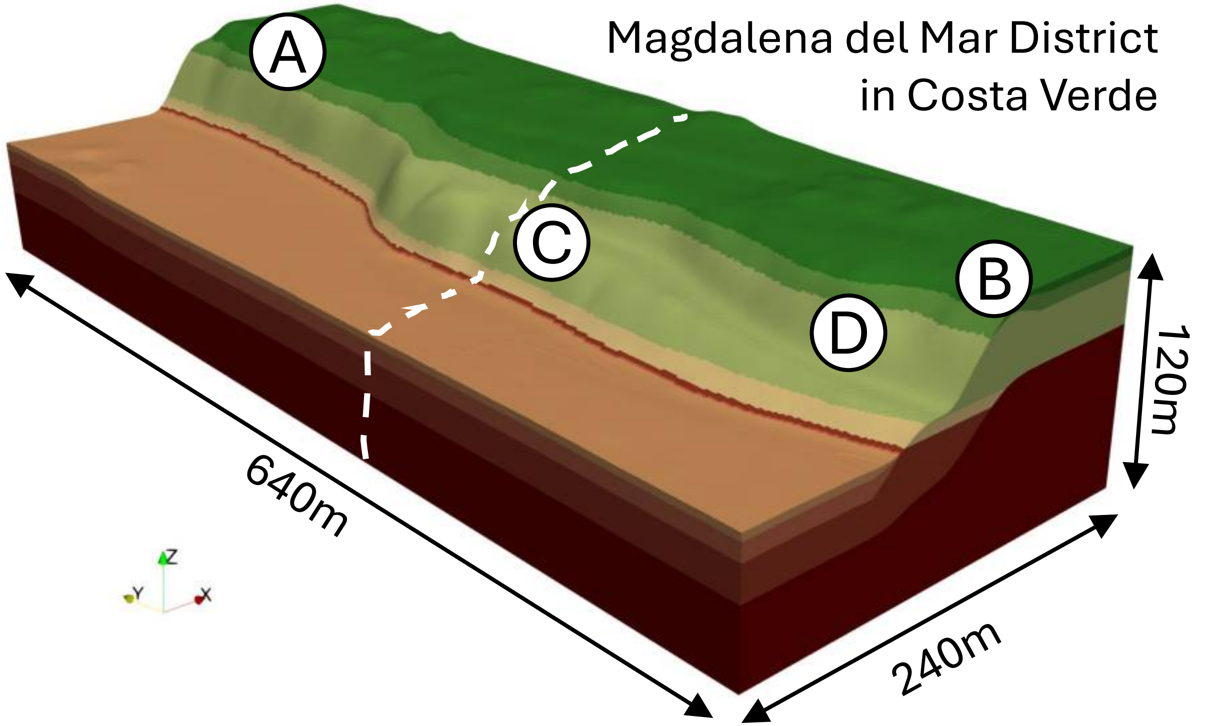
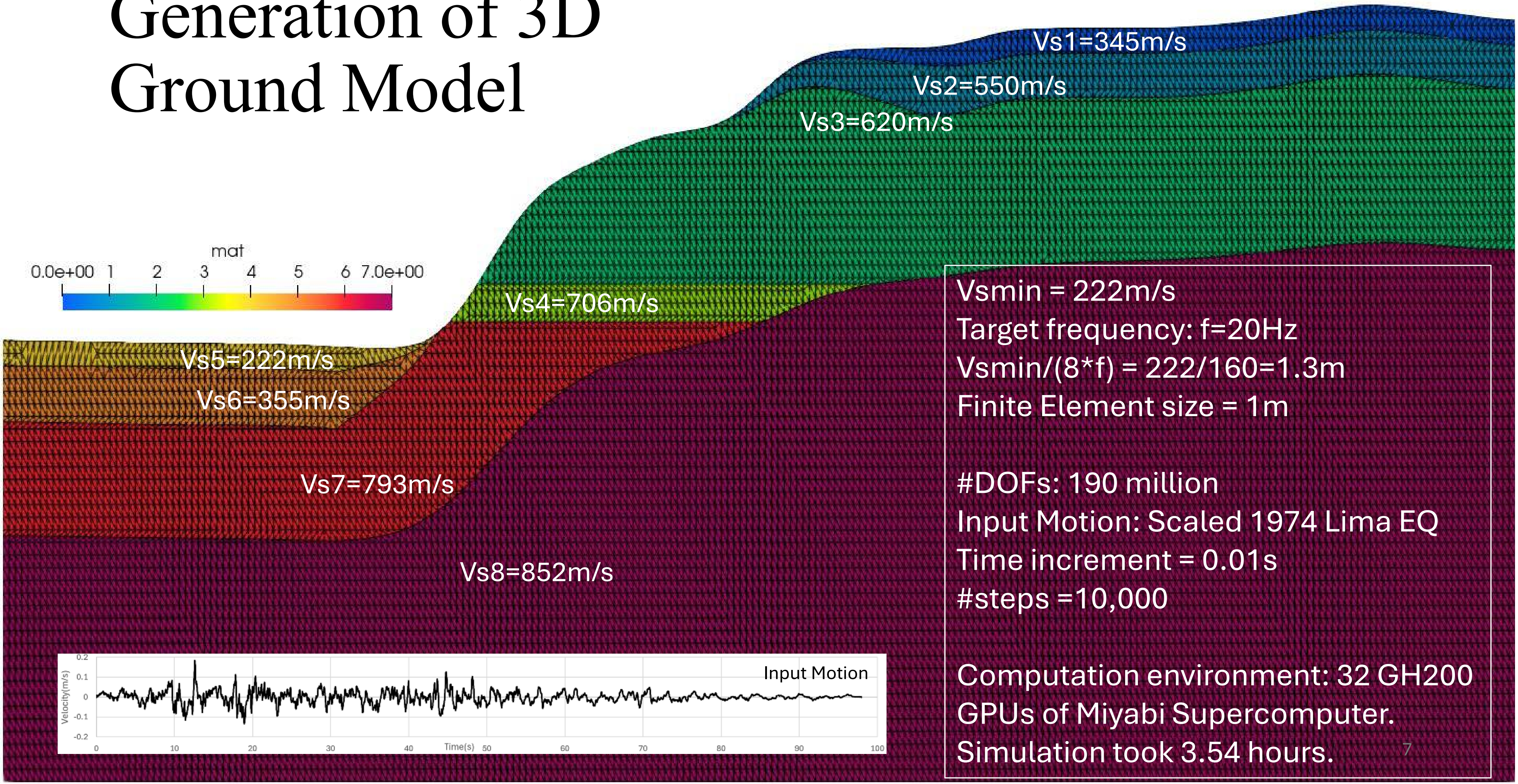


Field Visit 02/08/2026.

Generation of 3D Ground Model



Vsmin = 222m/s
Target frequency: f=20Hz
Vsmin/(8*f) = 222/160=1.3m
Finite Element size = 1m

#DOFs: 190 million
Input Motion: Scaled 1974 Lima EQ
Time increment = 0.01s
#steps =10,000

Computation environment: 32 GH200 GPUs of Miyabi Supercomputer.
Simulation took 3.54 hours.

Part 1. Nonlinear Earthquake Simulation

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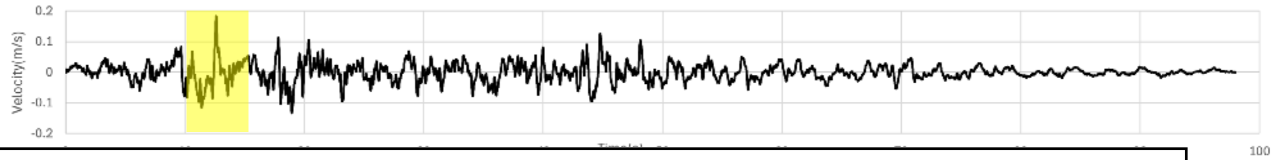


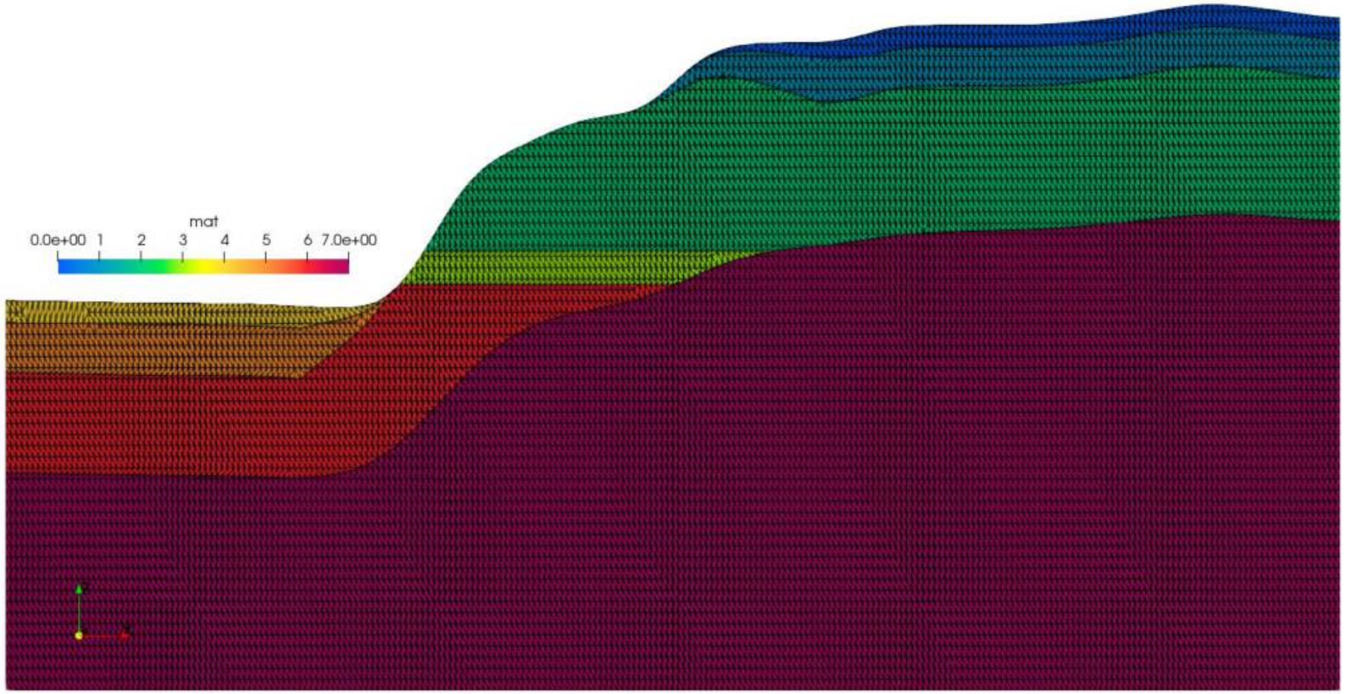
Part 1. Nonlinear Earthquake Simulation

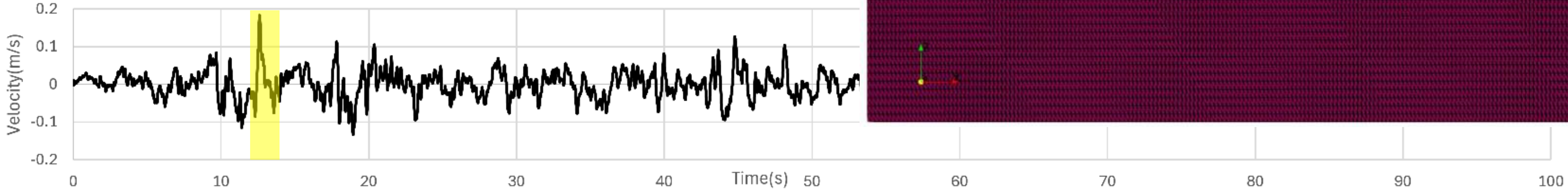
We used the FEM because it can handle complex geometries. Also, the nonlinear wave equation was discretized by Newmark-β method:

$$\left(\frac{4}{dt^2}\boldsymbol{M}+\frac{2}{dt^2}\boldsymbol{C}^n+\boldsymbol{K}^n\right)\delta\boldsymbol{u}^n=\boldsymbol{f}^n-\boldsymbol{q}^{n-1}+\boldsymbol{C}^n\boldsymbol{v}^{n-1}+\boldsymbol{M}\left(\boldsymbol{a}^{n-1}+\frac{4}{dt}\boldsymbol{v}^{n-1}\right)\rightarrow\boldsymbol{A}^n\delta\boldsymbol{u}^n=\boldsymbol{b}^n$$

Here, $\boldsymbol{K}^n$ and $\boldsymbol{C}^n$ are the stiffness and damping matrix at the n-th step.

Here, we consider Rayleigh Damping for $\boldsymbol{C}^n$ and the nonlinear behavior of soil employs the modified Ramberg-Osgood model and Masing rule.





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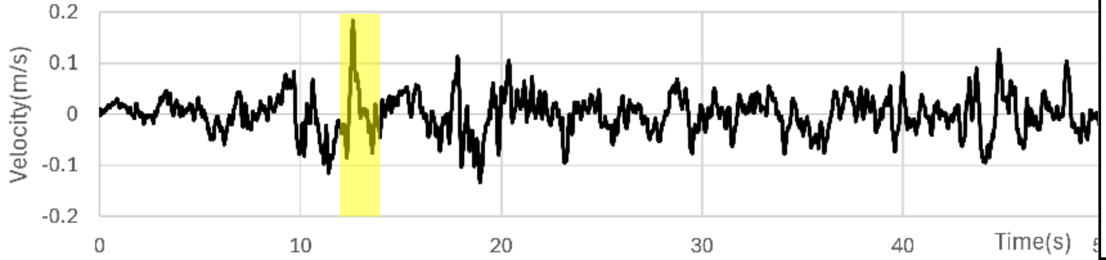
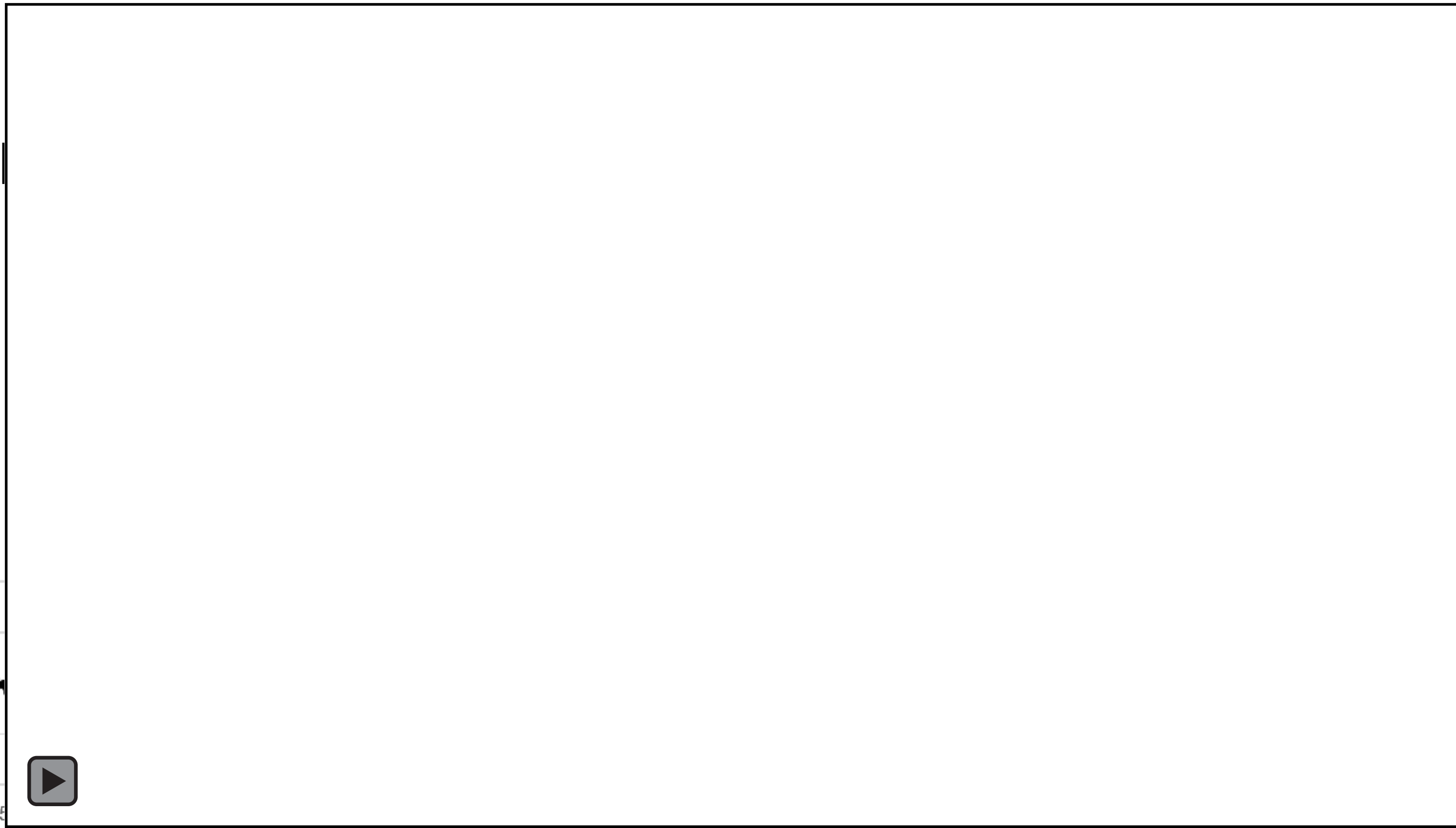
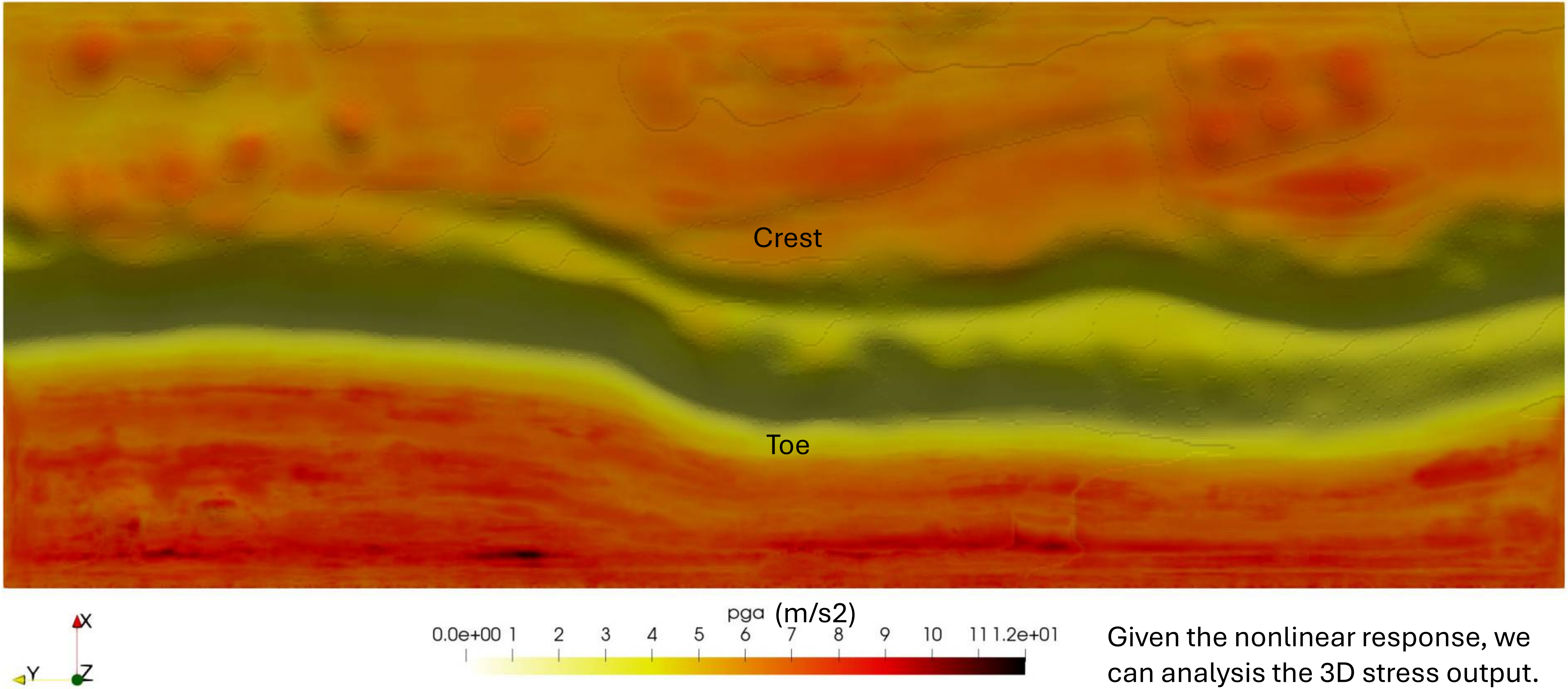


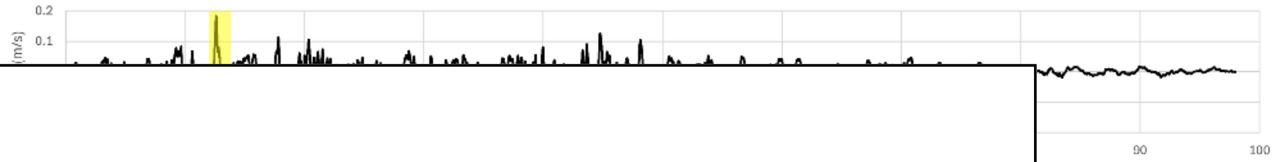


Part 1. Nonlinear Earthquake Simulation



Given the nonlinear response, we can analysis the 3D stress output.

Part 1. Nonlinear Earthquake Simulation



Part 2. Estimation of Permanent Displacements

Considering any rotational surface, the **moment equilibrium**:

$$M_{Driving\ forces} = M_{Resisting\ forces}$$
$$M_{DW} + kM_{DK} = [M_{RW} - kM_{RK}] + M_{RC}$$

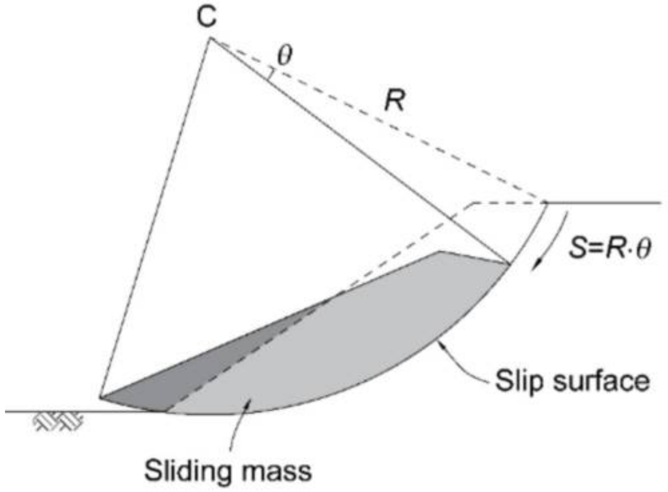
Then the **yielding acceleration** coefficient is:

$$k_y = \frac{M_{RW} + M_{RC} - M_{DW}}{M_{DK} + M_{RK}}$$

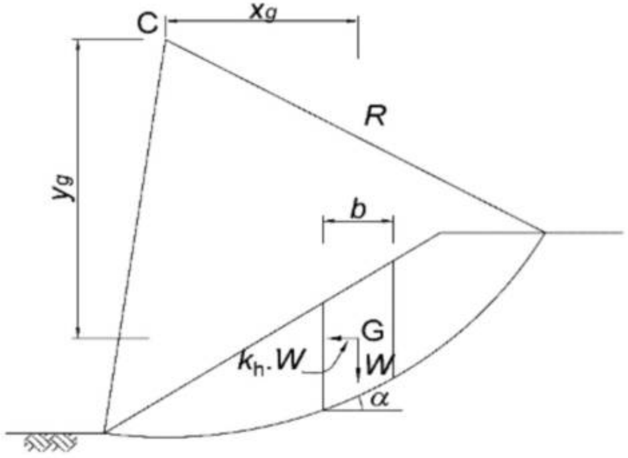
where:

$$M_{DW} = \sum W \cdot d_g, \qquad M_{DK} = \sum W \cdot z_g$$
$$[M_{RW} - kM_{RK}] = R\sum W(\cos\alpha - k\sin\alpha)\tan\phi$$
$$M_{RC} = R\sum Ac$$

d_g is the horizontal distance from G to the rotation axis $\boldsymbol{e}$.
$\cos\alpha$ and $\sin\alpha$ are related to the normal vector $\boldsymbol{n}_i$ of bottom plane A_i. The shear resisting direction is given by $\boldsymbol{t}_i(\boldsymbol{e}, \boldsymbol{r}_i)$.

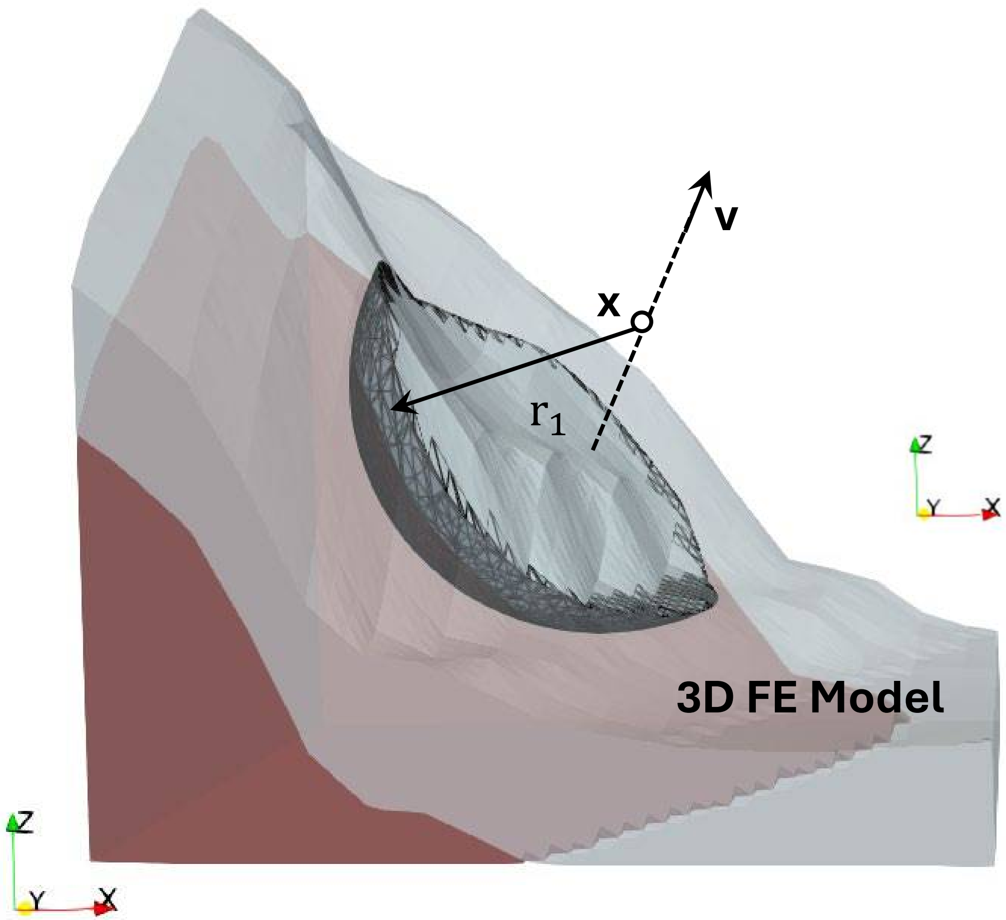


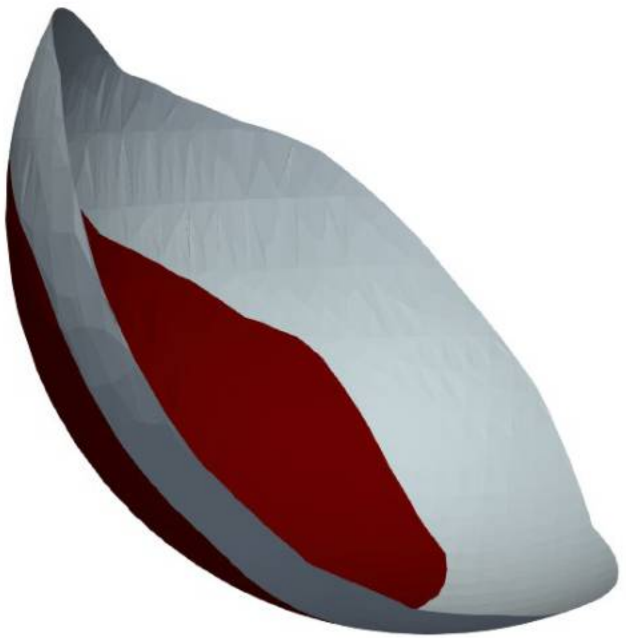
a) Schematic diagram of rotational slide



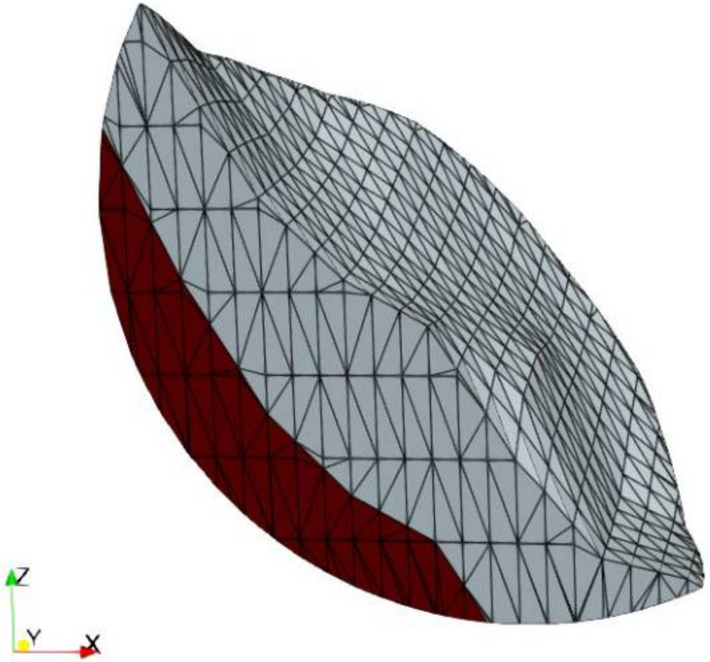
$$M_R = \sum R_i(N_i\tan\phi + A_i c)t_i$$
$$M_R = \sum R_i([W_i \cdot n_i]\tan\phi + A_i c)t_i$$

Part 2. Estimation of Permanent Displacements





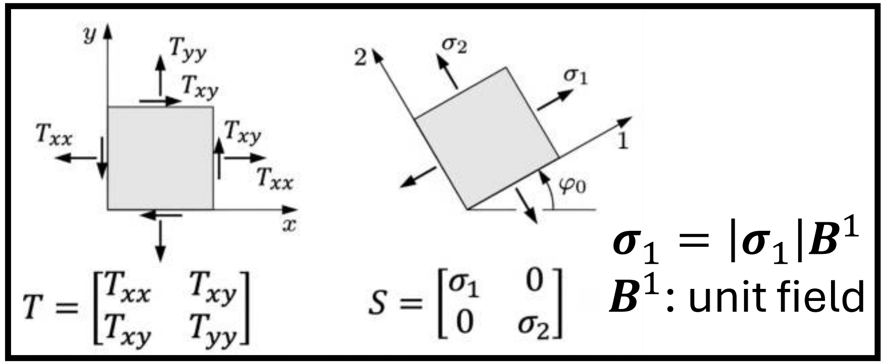
Failure Surface **Area** .



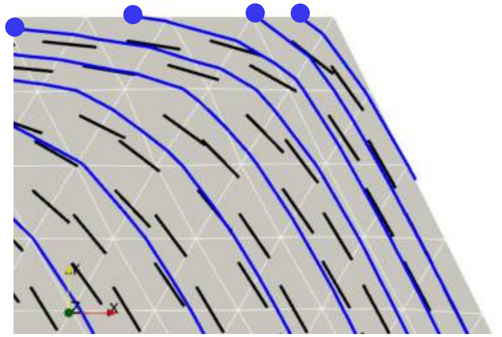
Volume of the sliding block.

- Given a set of slip failure surfaces ($\mathbf{r}[3]$, $\mathbf{x}[3]$, $\mathbf{v}[3]$), we can select the worst case with **largest displacement**. However, this assumption comes with a **large parameter set**.

Proposed Method to Define Slip Surfaces



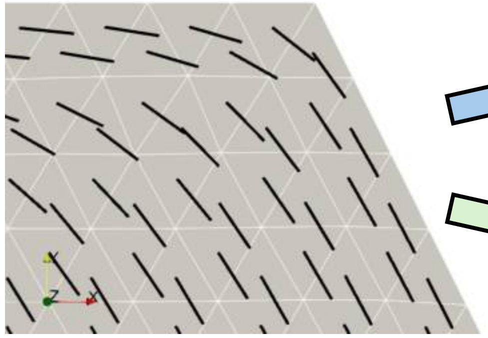
Hyperstreamlines $\boldsymbol{x}^1$ starting at points $\boldsymbol{x}_0^1$



1 Conventionally, **hyperstreamlines** can be utilized by setting starting points $\boldsymbol{x}_0$. A streamline $\boldsymbol{x}(l)$ is a vector function, satisfying:

$$\frac{d\boldsymbol{x}}{ds} = \boldsymbol{B}(\boldsymbol{x}), \qquad \boldsymbol{x} = [x_1, x_2, x_3]$$

Hyperstreamline method comes with the **redistribution of points** *(seeding)* and **additional steps** to construct surfaces from lines.

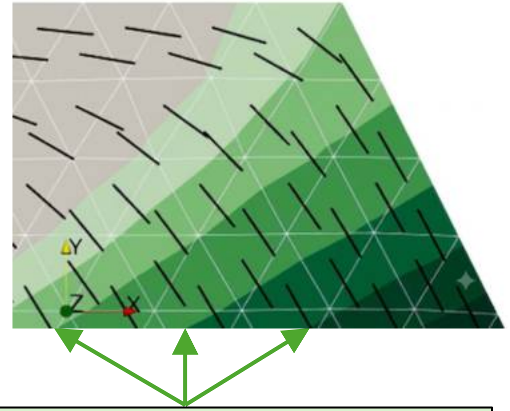


Input field $\boldsymbol{B}^1(\boldsymbol{x})$ (e.g. compression stress)

2 We can define a scalar field $\boldsymbol{s}(\boldsymbol{x})$ whose gradient is as parallel as possible to $\boldsymbol{B}(\boldsymbol{x})$. Then, we can define an error function to minimize:

$$E(s) = \int_V \sum_{i=1}^{3} s_{,i} s_{,i} - \left(\sum_{i=1}^{3} B_i s_{,i} \right)^2 dv$$

Iso-surface method



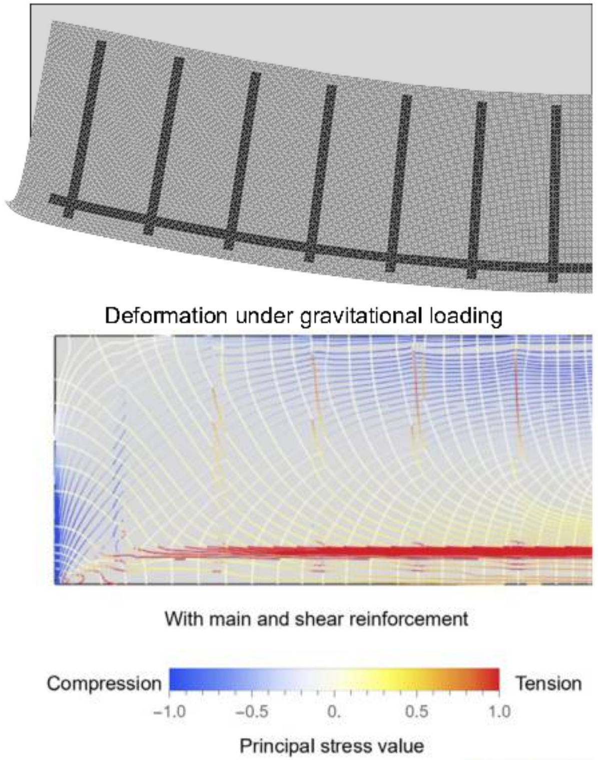
Contours $\boldsymbol{s}^1(\boldsymbol{x}) = const.$ or **iso-surfaces** becomes hyperstreamlines $\boldsymbol{x}^2$.

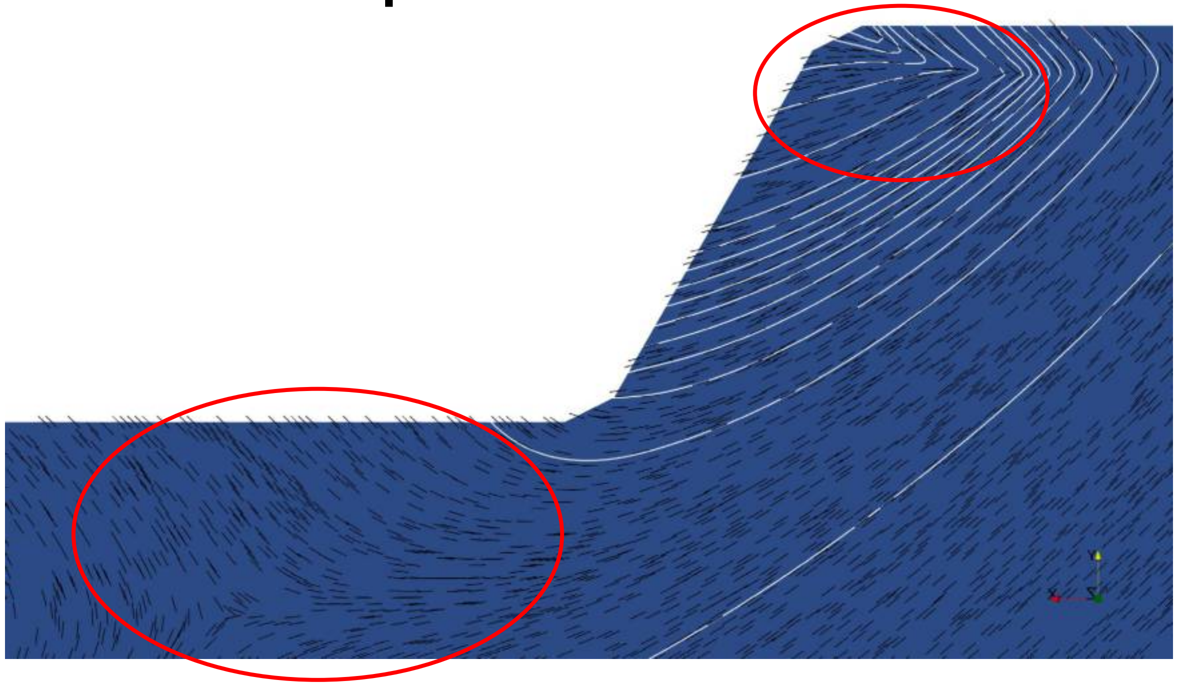
Because $\boldsymbol{B}^1$ and $\boldsymbol{B}^2$ are orthogonal, contours of $\boldsymbol{s}^1(\boldsymbol{x})$ are iso-surfaces conjugate to hyperstreamlines $\boldsymbol{x}^1$

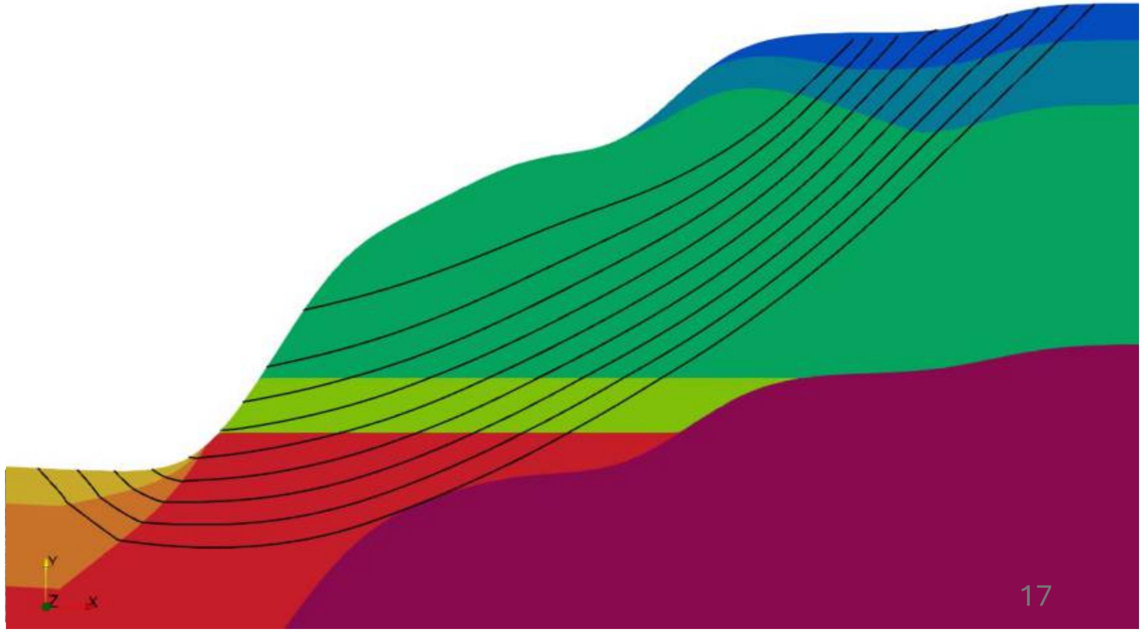
Proposed Method to Define Slip Surfaces

In 2025, the iso-surface method was applied to **visualize stress distribution** e.g. in a RC beam.
Here, we adapt this method to estimate **slip surfaces in a 2D slope** using the **max. shear stress field**; however, it fails in certain areas.

✓ By analyzing the stress field's features—an approach known as **Tensor Field Topology**—we performed topology-based partitioning to obtain **slip surfaces for 2D sections**.







Conclusions and Future Work

- A key challenge in slope stability analysis is the definition of an optimal set of slip surfaces.
- The proposed method leverages 3D stress fields obtained from simulations to construct slip surfaces, substantially reducing the search space.
- So far, the methodology has estimated candidate slip surfaces on 2D cross-sections extracted from the 3D stress field.

➢ Future work will extend this approach to the direct identification of 3D slip surfaces, enabling the assessment of complex failure mechanisms.

➢ Continue the Japan–Peru research collaboration under ProCiencia project.

Gracias

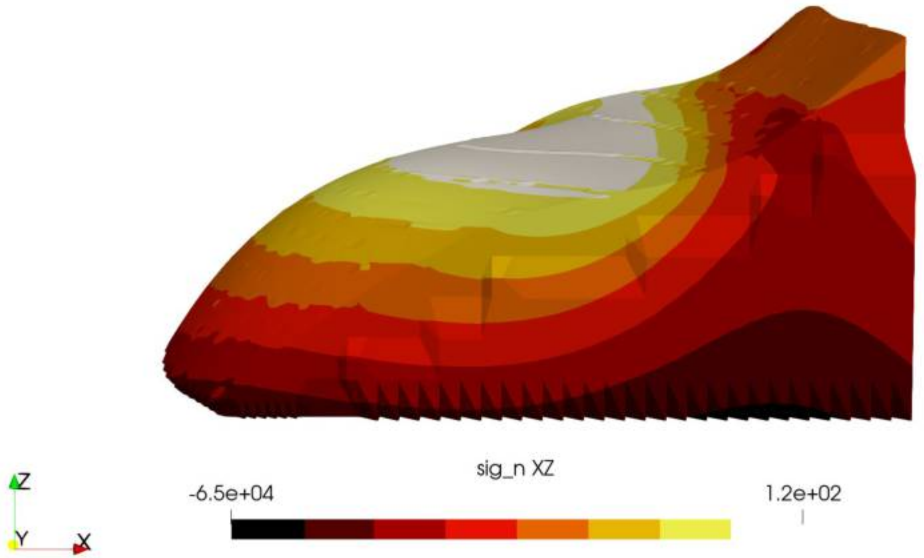
2. Nonlinear Earthquake Simulation

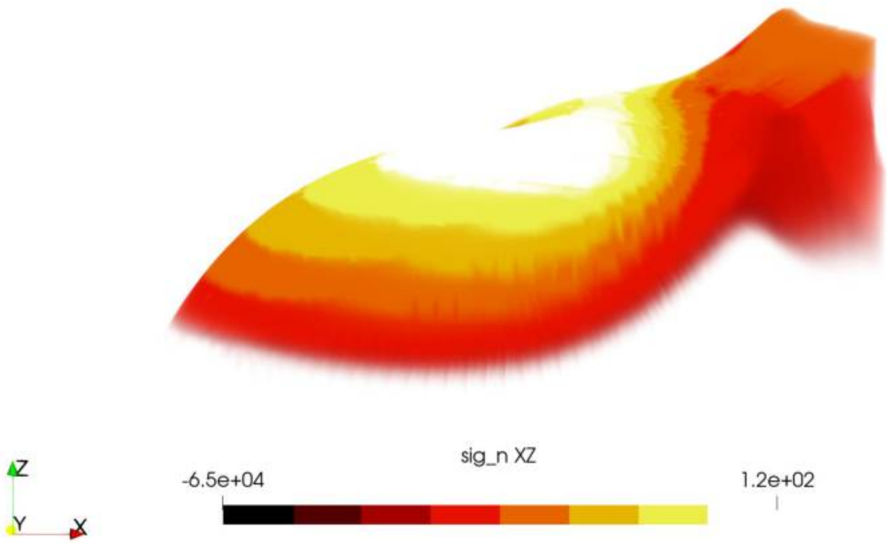
3D visualization using Volume Rendering

What to visualize, deviatoric stress or Maximum principal strain.

Required storage for stress[ne,6,nt]: 67MB x 32procs x 200steps = less 2.2TB

Max shear strain - Tokyo area. Max shear stress OK. Test withc 2D section before.





End of Presentation…

- Comments:
  - Add text to shared word synapsis. Ask about the dates of insurance until 9th.
  - Start writing paper chapter 1 and 2.
- Define the slides that will be technical*
- Remaining task: 3D visualization. Discuss about it. Error on Nvidia Index.
- Explain template of presentation [logos].
- Notification of Travel – sign.
- Define the titles for the presentations in School of Civil Eng. FIC-UNI.
- Ask for the document shared by Hori sensei (divergence).
- Plan for Sunday 2nd August.

Nvidia Index error

Solution: first in paraview load pvIndex plugin.

```
jpalaciose@lynx-vis01:/data7/jpalaciose$ module load ParaView/5.13.2-egl
jpalaciose@lynx-vis01:/data7/jpalaciose$ pvserver --force-offscreen-rendering -p 45678
Waiting for client...
Connection URL: cs://lynx-vis01:45678
Accepting connection(s): lynx-vis01:45678
Client connected.
-----------------------------------------------------
By loading the 'pvNVIDIAIndeX' plugin you have accepted the EULA shipped with it.
If that is not acceptable, please restart the application without loading
the 'pvNVIDIAIndeX' plugin.
-----------------------------------------------------
( 41.887s) [pvserver ]vtkSocketCommunicator.c:774 ERR| vtkSocketCommunicator (0x1e83f880): Could not receive tag. 1
( 41.888s) [pvserver ]vtkTCPNetworkAccessMana:284 ERR| vtkTCPNetworkAccessManager (0x1e721050): Some error in socket processing.
Exiting...
```

4. Proposed Method to Define Slip Surfaces

In 2025, the iso-surface method was applied to **visualize stress distribution** e.g. in a RC beam.
Here, we adapt this method to estimate **slip surfaces in a 2D slope** using the **max. shear stress field**; however, it fails in certain areas.

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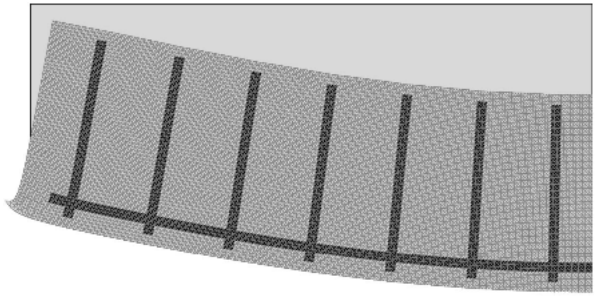
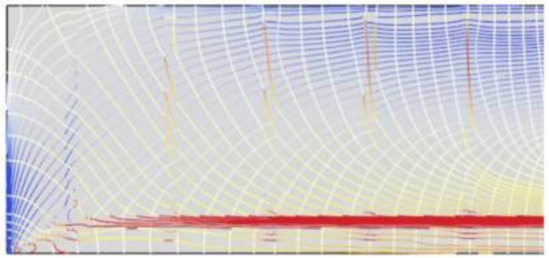
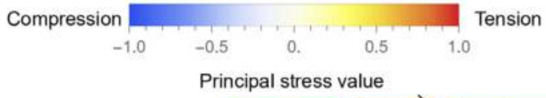
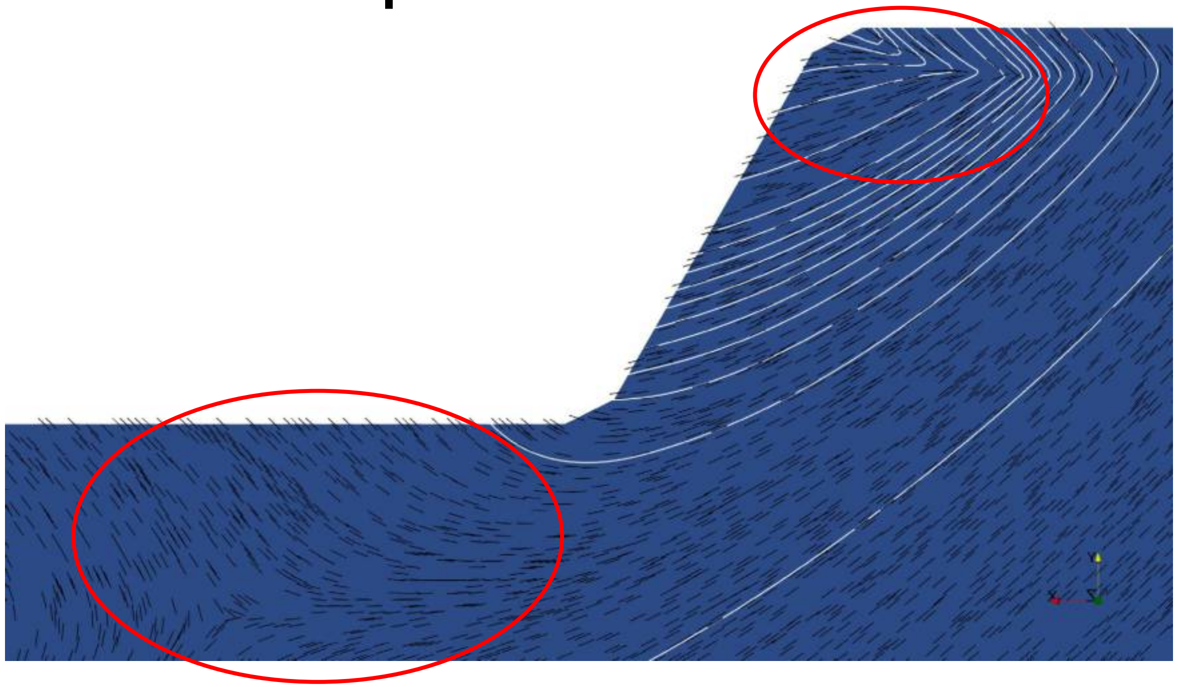


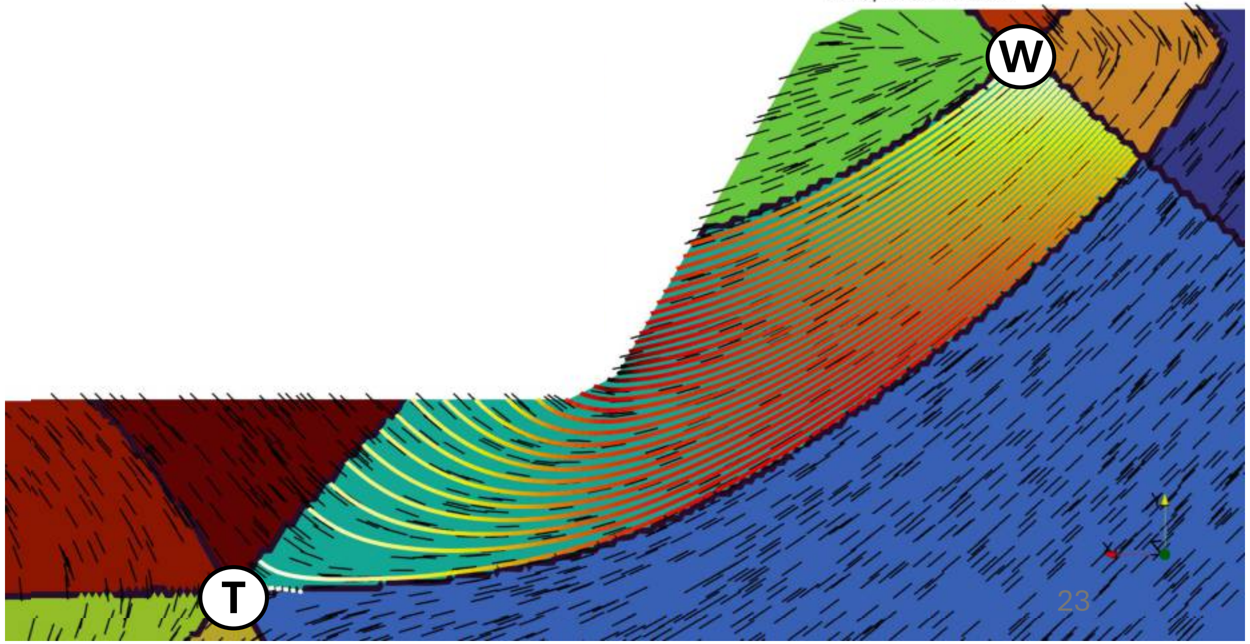
Deformation under gravitational loading



With main and shear reinforcement

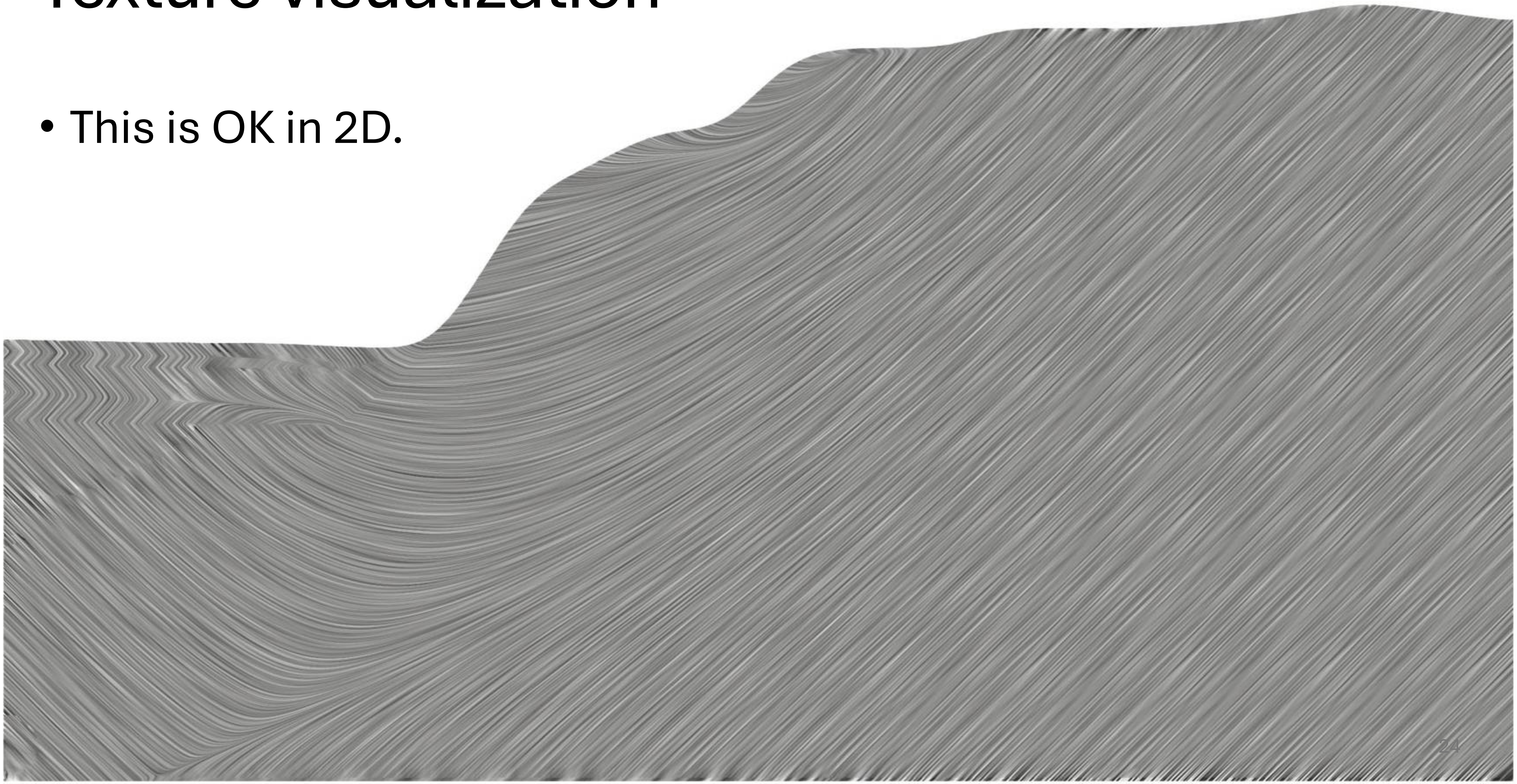






Texture visualization

- This is OK in 2D.



3. Estimation of Permanent Displacements

The **equation of motion** for rotational sliding:

$$J\ddot{\theta} = (k_h - k_y)(M_{DK} - M_{RK})$$

This equation can be solved with Newmark time integration:

$$\dot{\theta}_{n+1} = \dot{\theta}_n + \Delta t \left[(1-\gamma)\ddot{\theta}_n + \gamma\ddot{\theta}_{n+1}\right]$$

$$\theta_{n+1} = \theta_n + \Delta t\,\dot{\theta}_n + \Delta t^2 \left[\left(\tfrac{1}{2} - \beta\right)\ddot{\theta}_n + \beta\ddot{\theta}_{n+1}\right]$$

Then, the rotational permanent **displacement** is $S = R\theta$.

To compute the average acceleration k_h, we can use the following equation from the FE approach:

$$k_h = \frac{\int_{\Omega_e} \rho_e(\mathbf{x})\boldsymbol{N}_e(\mathbf{x})\boldsymbol{a}_e d\Omega}{\int_{\Omega_e} \rho_e(\mathbf{x}) d\Omega}$$