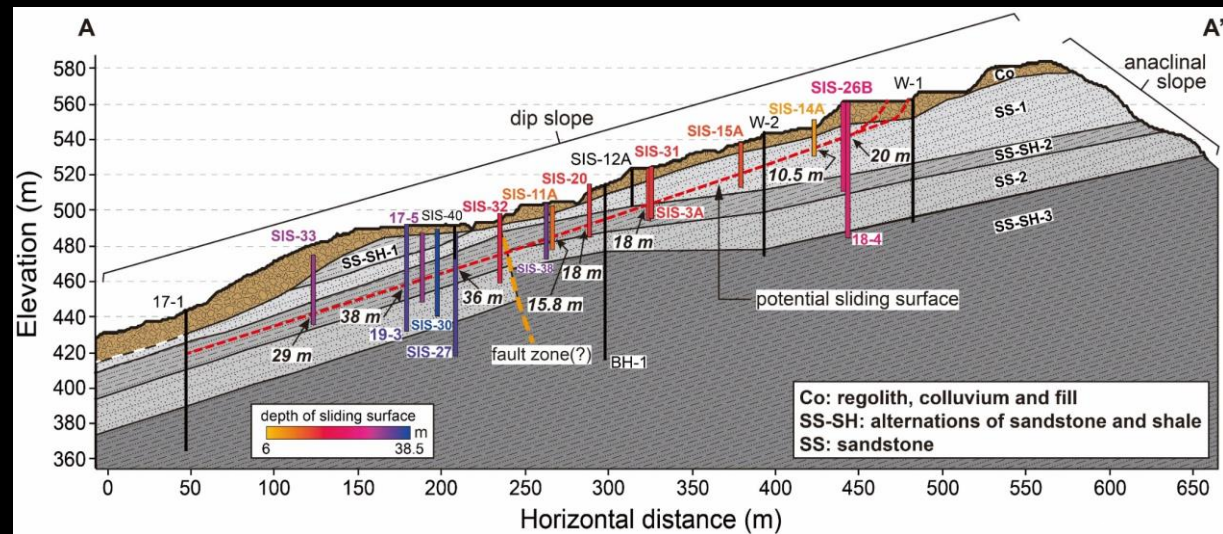
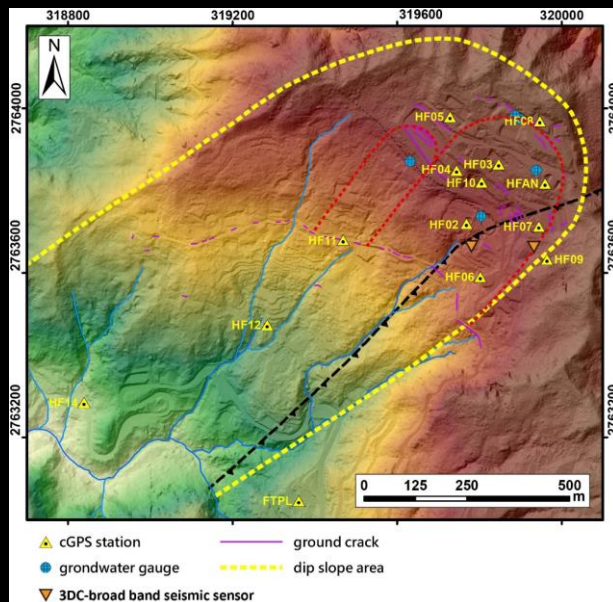


從連續微地動資料分析大規模崩塌土體在地震及強降雨時之穩定性

饒瑞鈞¹、張睿¹、吳澄峰¹、曾佳漢²

¹ 國立成功大學地球科學系

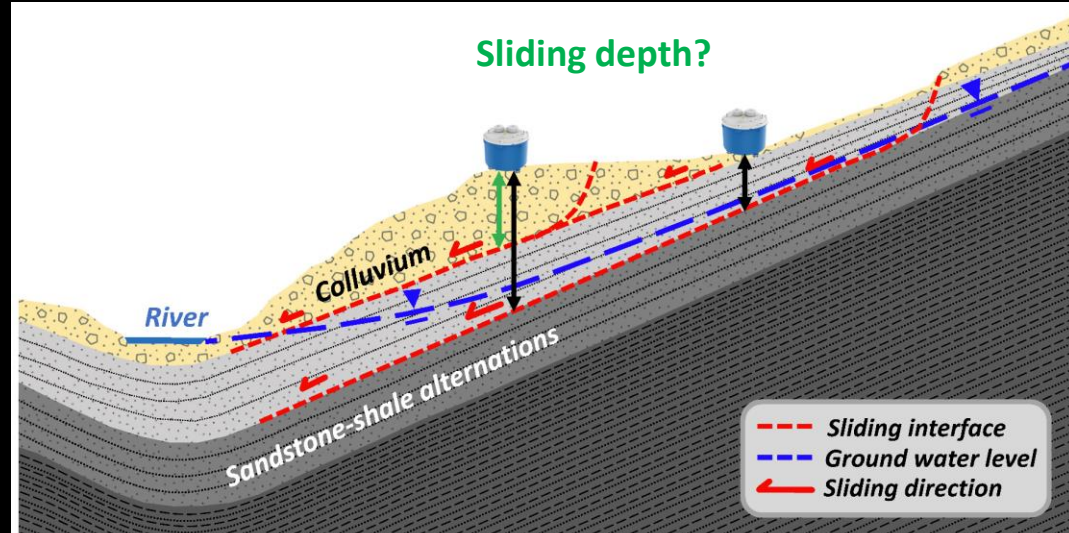
² 中國文化大學地質學系



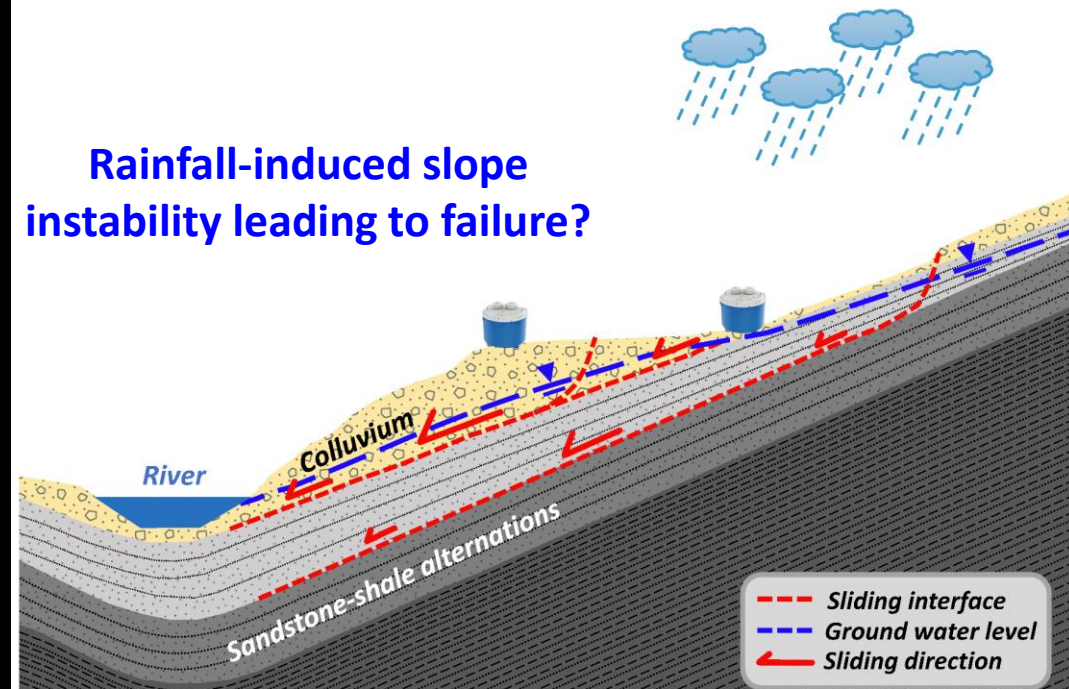
Kinematics of Deep-Seated Landslides

- What are the geometry and depth to the sliding surface of a deep-seated landslide?
- What is the impedance contrast at the sliding interface?
- Is the landslide body stable? What is the sliding direction and its stability?
- What are the responses of the landslide deposits to earthquakes and heavy rainfalls?

We use microtremor data to examine these questions!

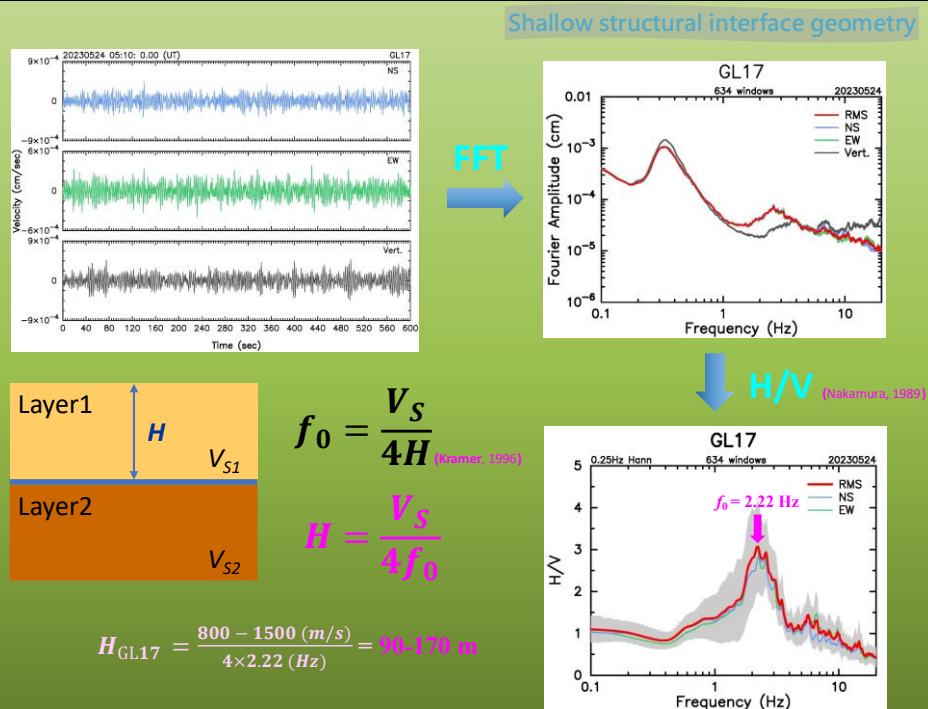


Rainfall-induced slope instability leading to failure?

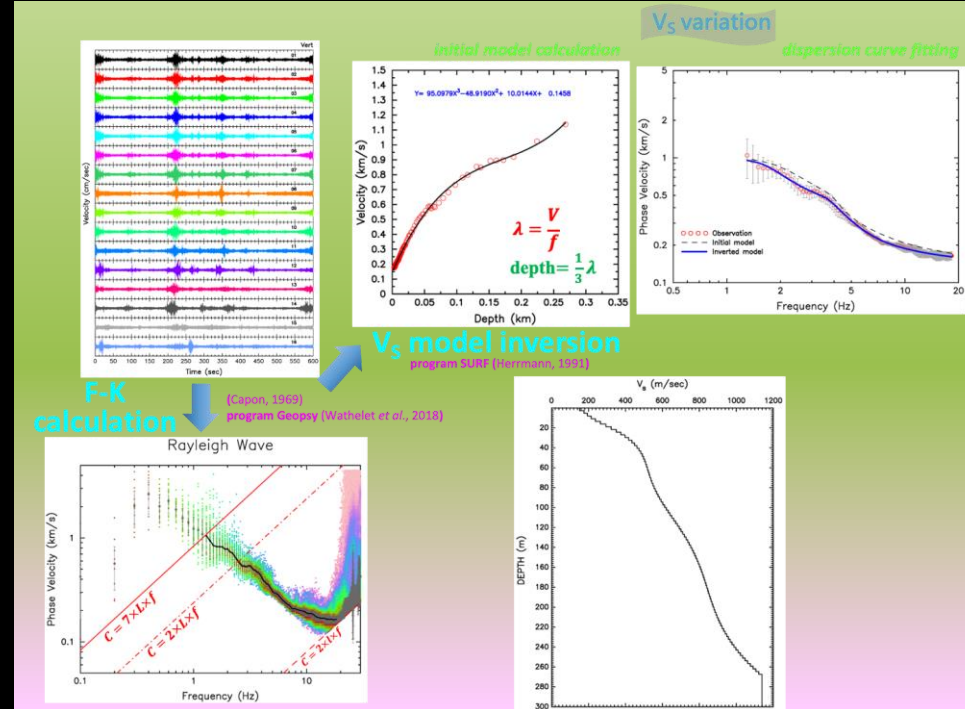


Microtremor Measurements

1. Horizontal to Vertical Spectral Ratio



2. Inversion of surface wave dispersion for shear wave velocity model



3. Time Frequency Polarization Analysis of Microtremor Signals

Google Earth

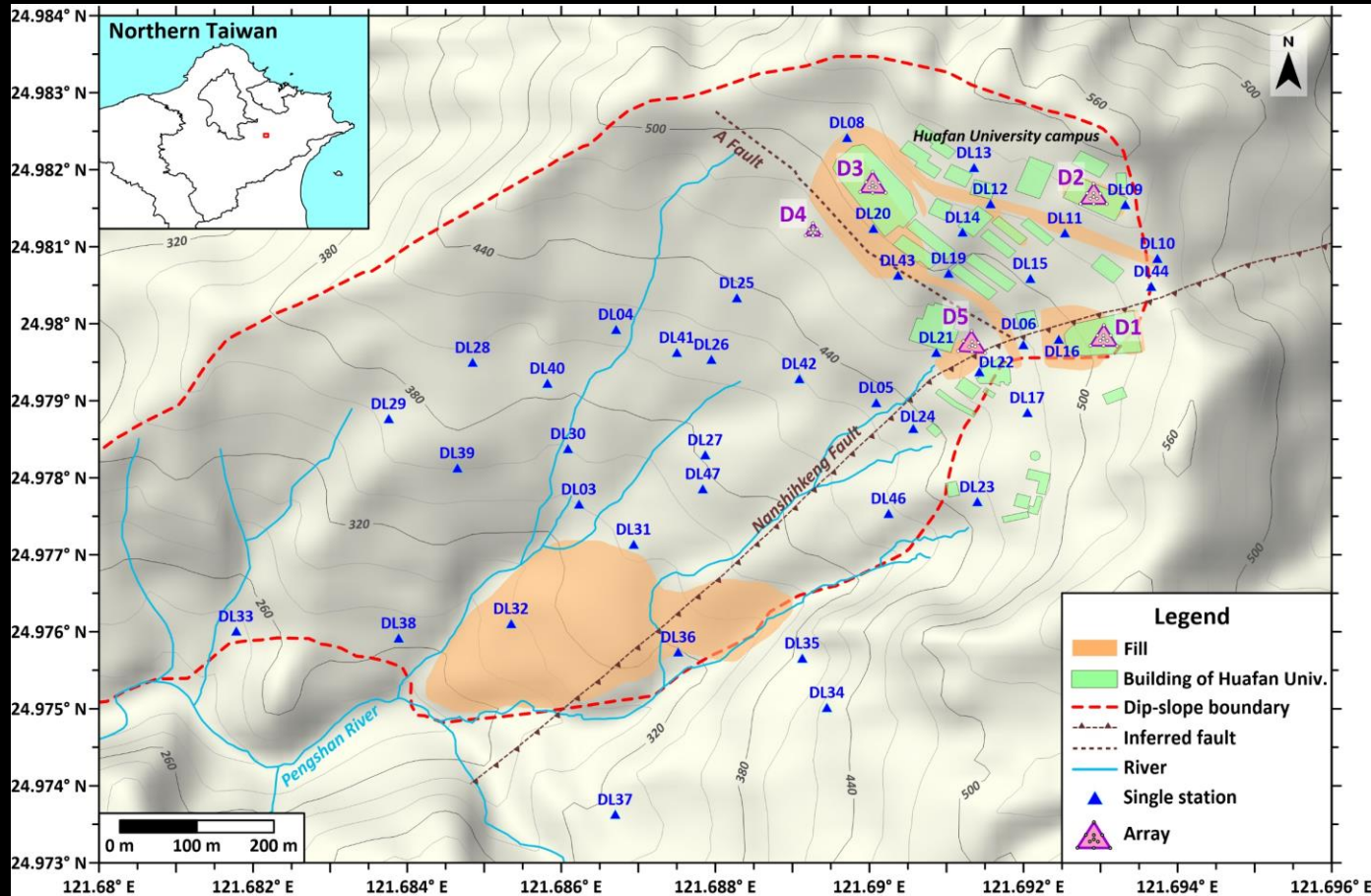


- (Tseng
- et al.*
- , 2021)



Microtremor Measurements

5 triangular arrays
33 single stations



DIGOS DATA-CUBE³



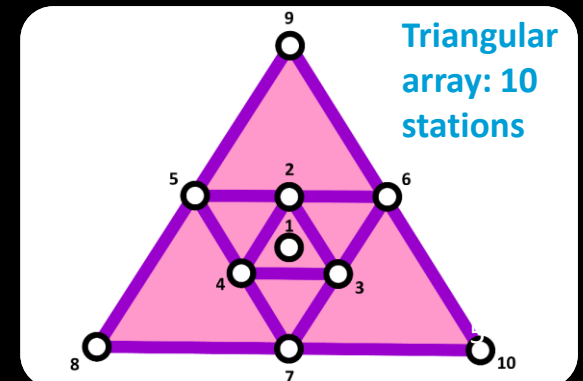
Purposes:

Array measurement: stratum velocity

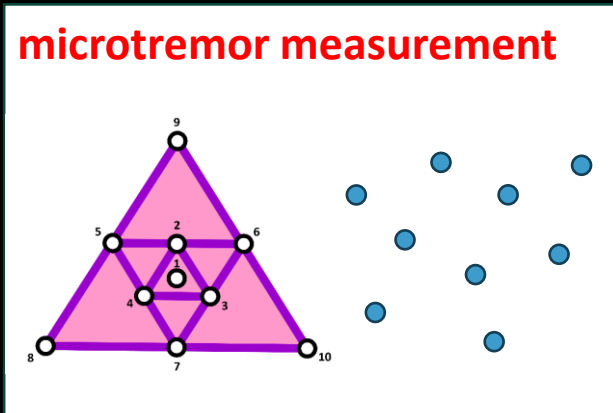
Single-station measurement: sliding-depth detection

Array measurement parameters:

- ◆ **Min. & max apertures: 3-21 m (D4); 4.5-35 m (D1, D2, D3, D5)**
- ◆ **Resolvable depths: 0 – 100 m**
- ◆ **Recording length: 2 hours**



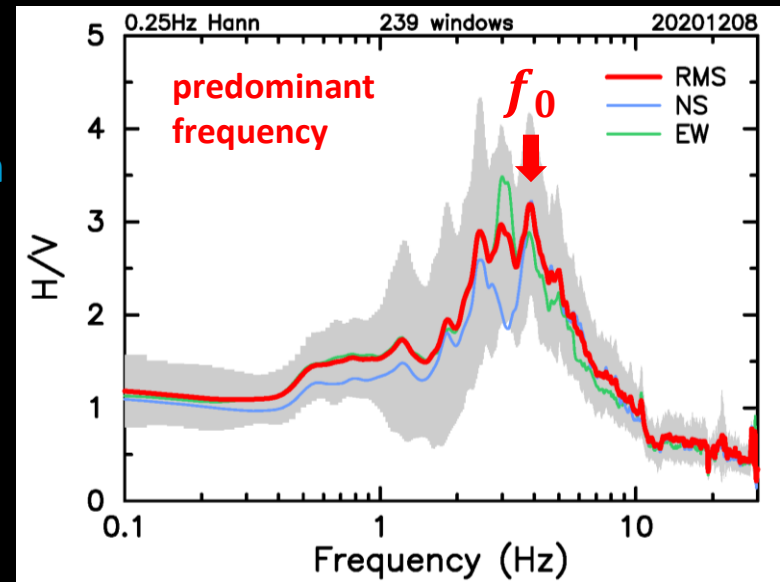
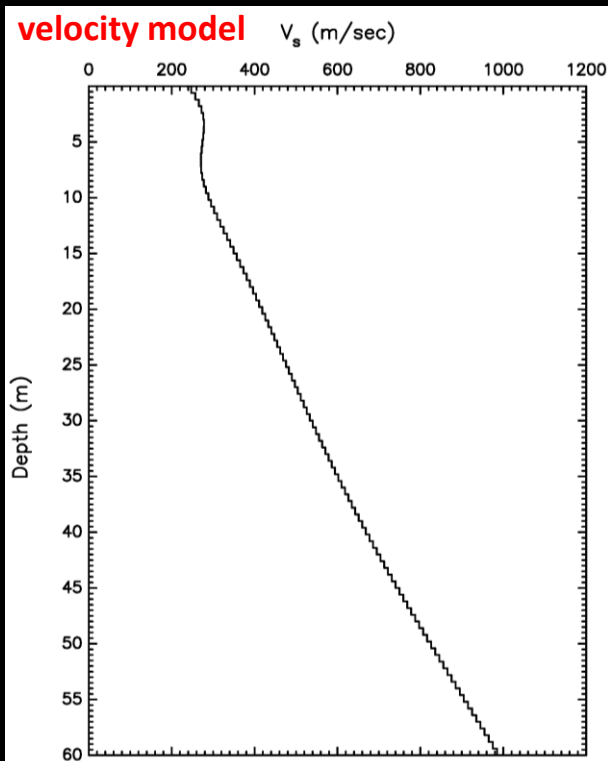
How to determine the sliding depth?



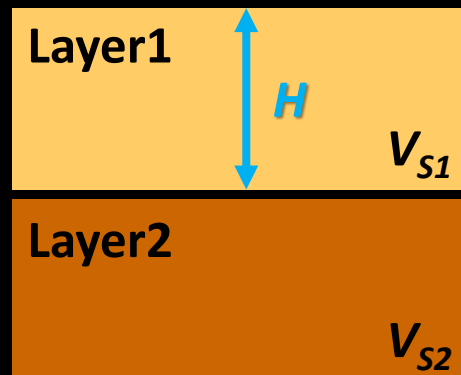
single station

H/V
(Nakamura, 1989)

array **F-K + inversion**
(Capon, 1969; Herrmann, 1991)



To find a high-impedance layer (sliding depth??)
e.g., layer between soil and rock

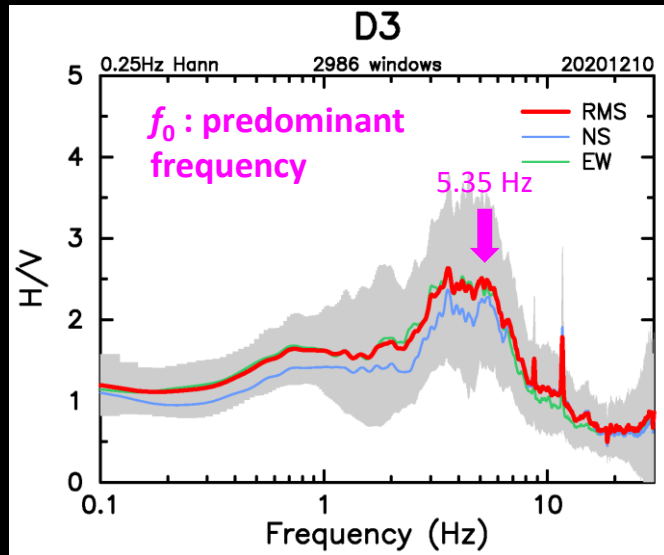


$$f_0 = \frac{V_{s1}}{4H}$$

$$H = \frac{V_{s1}}{4f_0}$$

Sliding Depth Comparisons

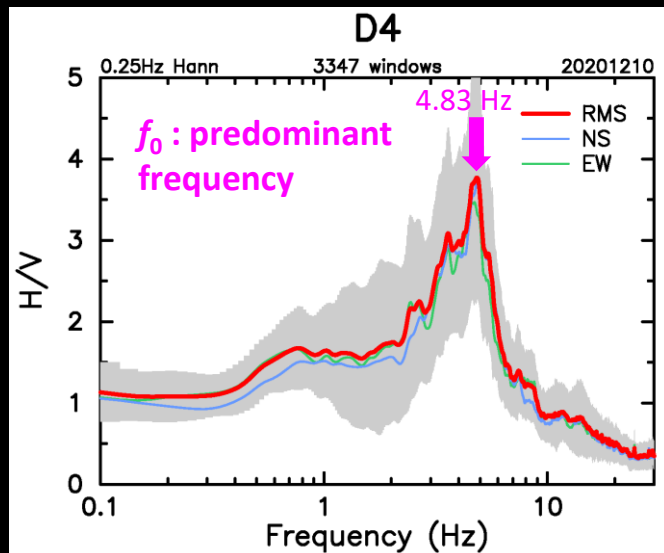
HVSR vs. Inclinometer



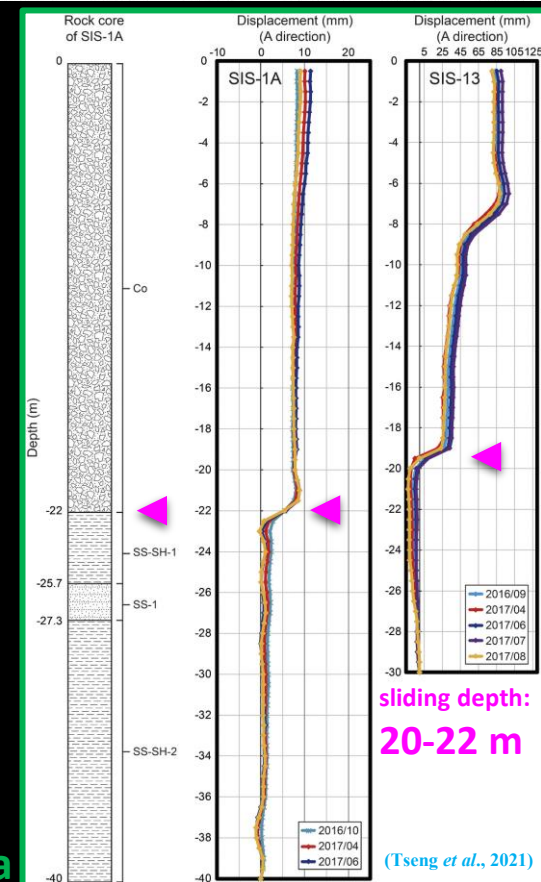
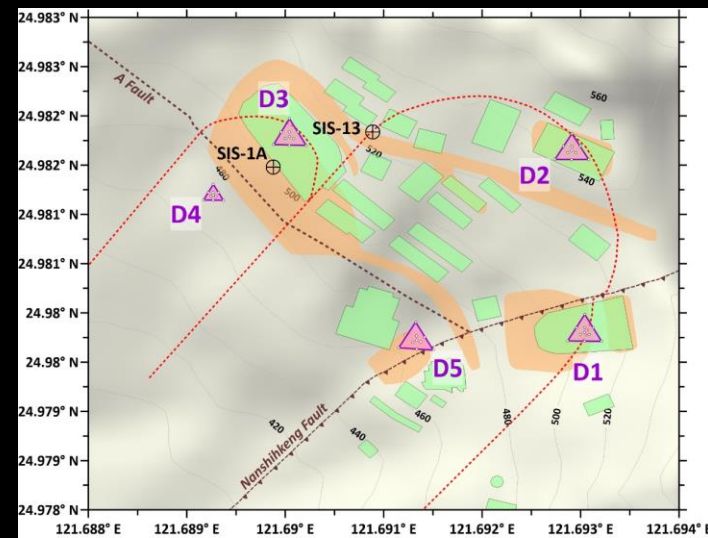
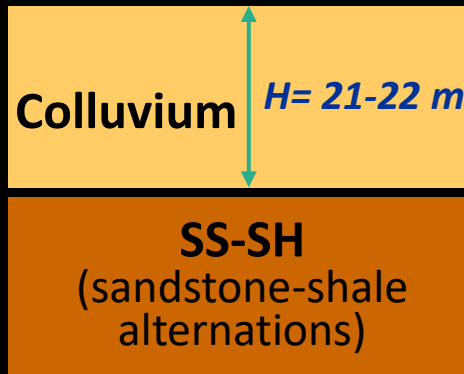
$$f_0 = \frac{V_s}{4H}$$

$$H = \frac{V_s}{4f_0}$$

$$H_{D3} = \frac{456.55 \text{ (m/s)}}{4 \times 5.35 \text{ (Hz)}} = 21.33 \text{ m}$$

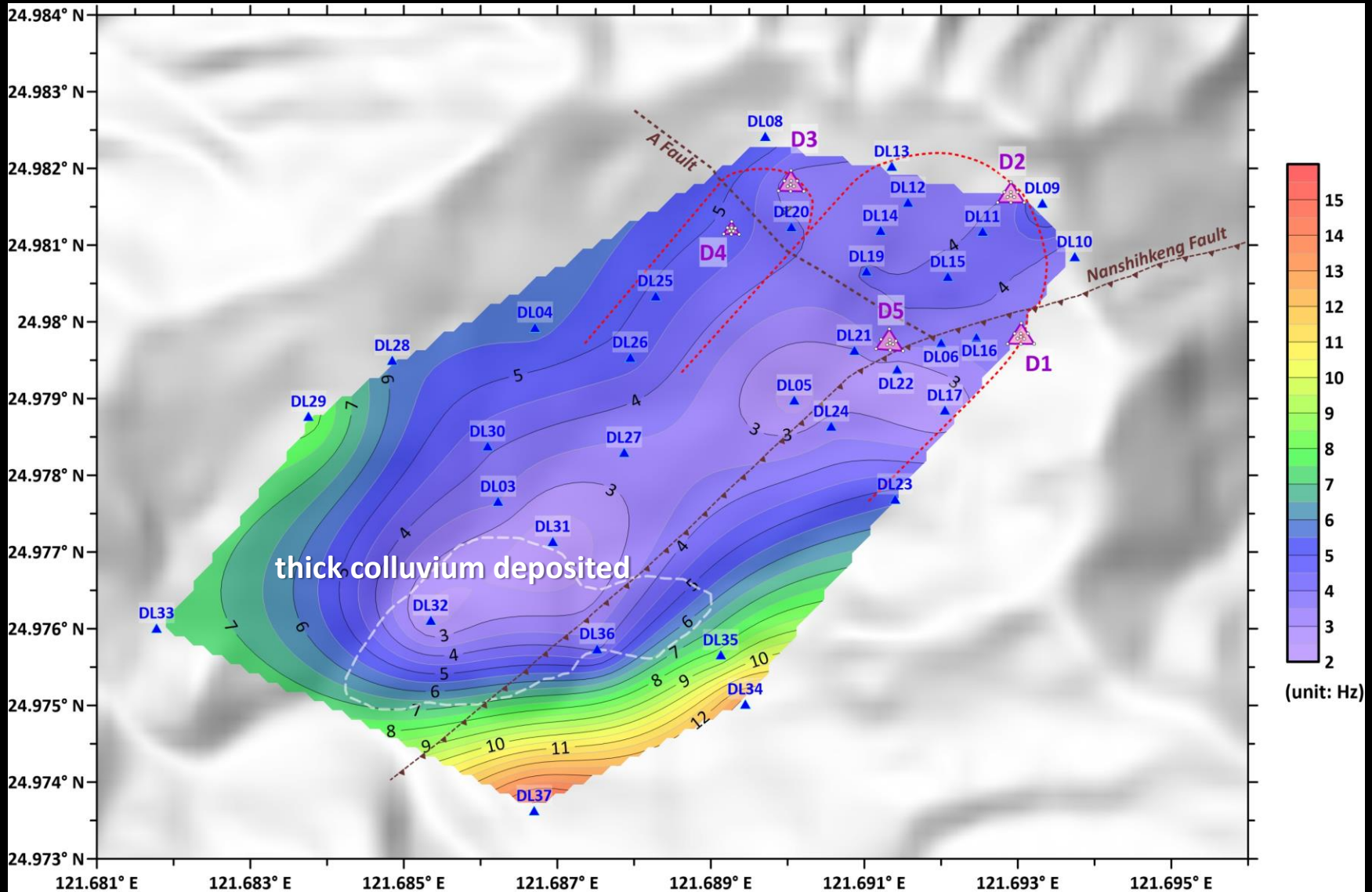


$$H_{D4} = \frac{426.90 \text{ (m/s)}}{4 \times 4.83 \text{ (Hz)}} = 22.09 \text{ m}$$



Inclinometer data

Predominant Frequency (f_0) + V_s Data ➡ Sliding Depth (H)

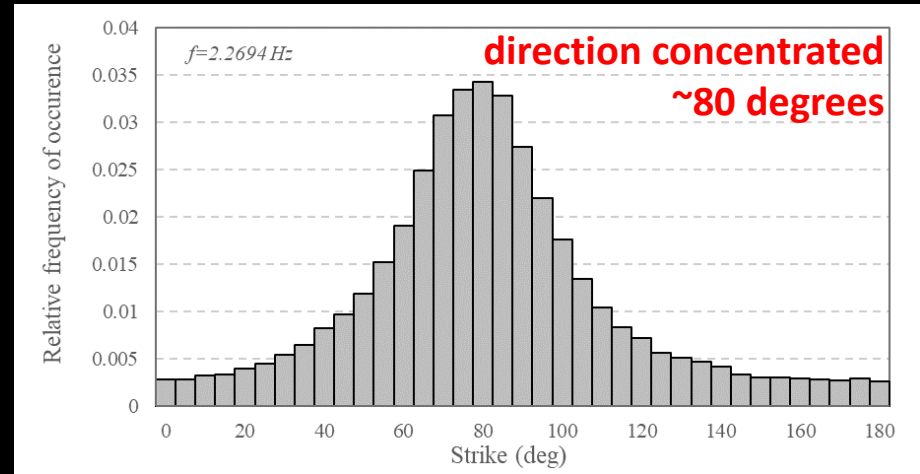
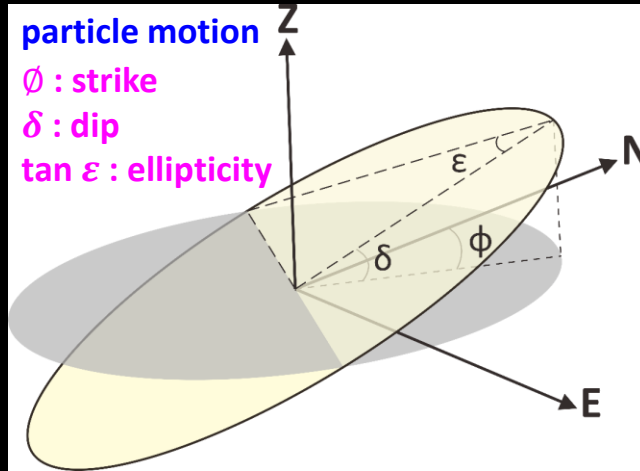


$$H = \frac{V_s}{4f_0}$$

Assuming $V_s \sim 440$ m/s for colluvium, sliding depths are 7-55 m.

Two deeper sliding depth areas: intersection of two faults, and the toe of slope.

How to determine the sliding direction and stability?



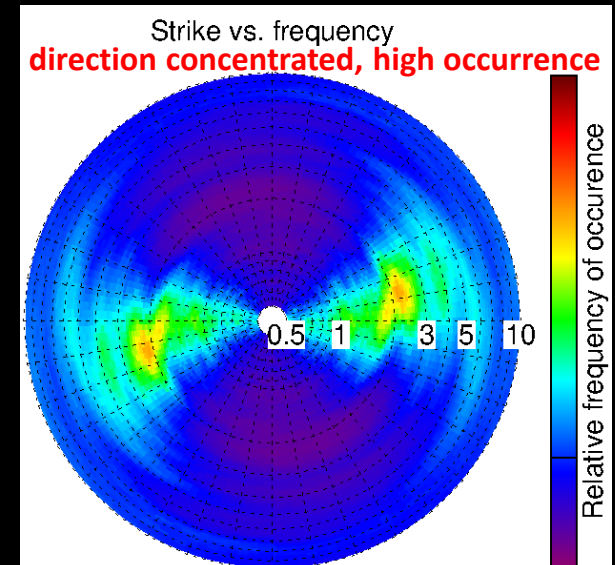
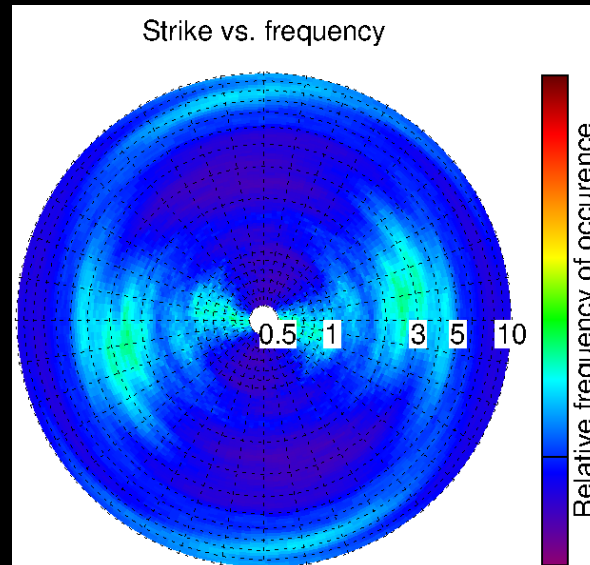
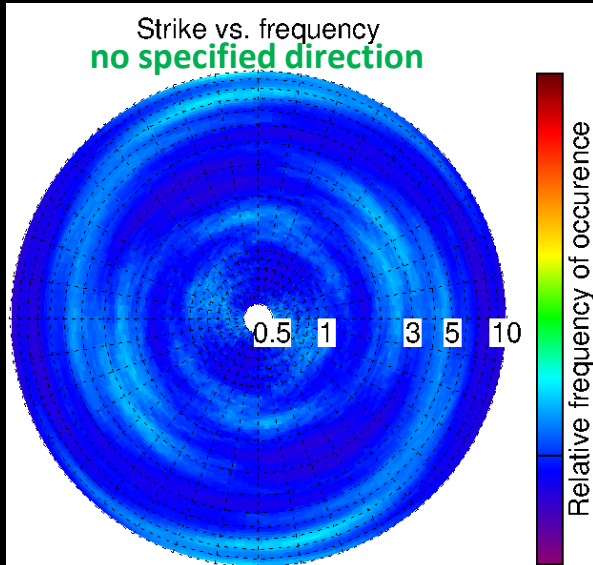
complex polarization analysis + continuous wavelet transform

(Burjáněk *et al.*, 2010)

stable

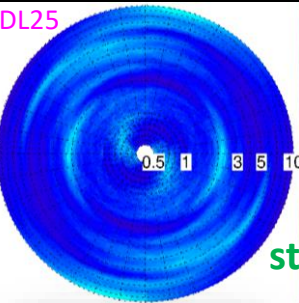
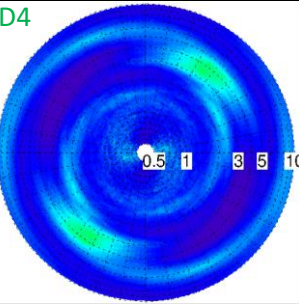


unstable

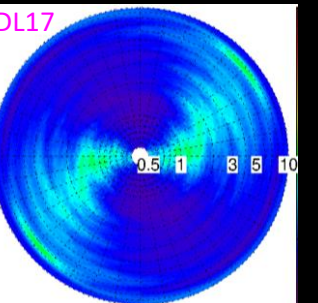
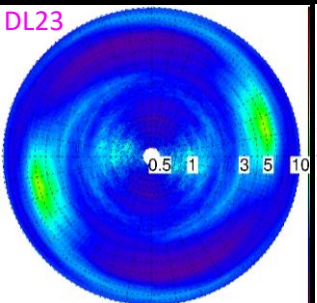
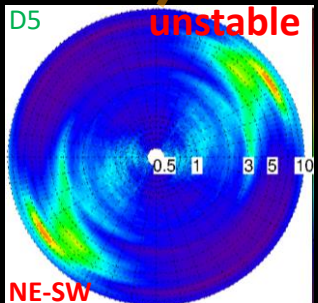
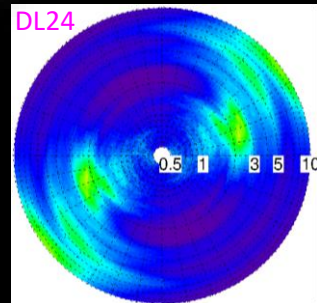
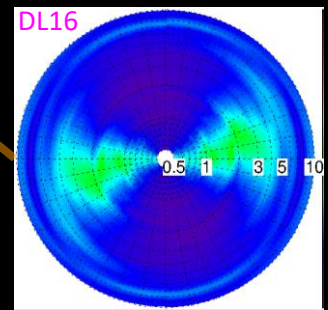
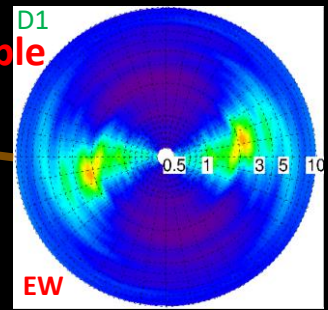
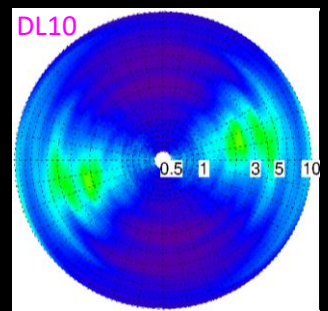
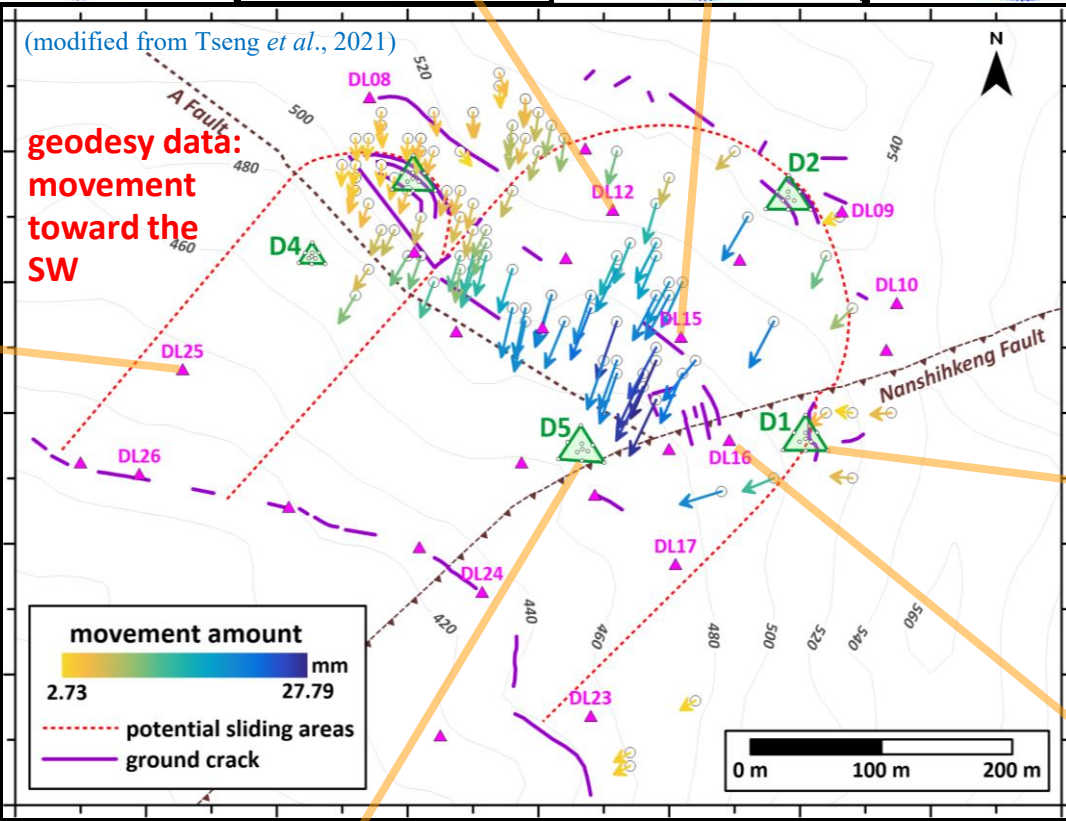
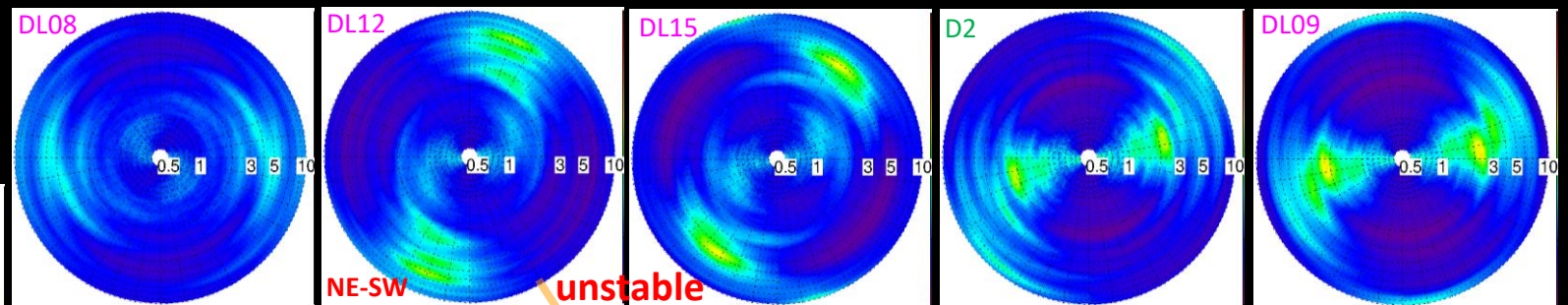
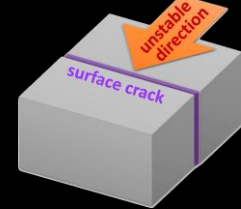


We assess slope stability by examining the frequency recurrence rate in polarization analysis.

Polarization vs. Movement Direction

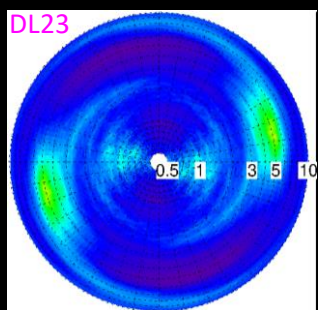
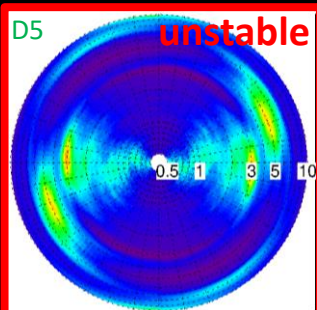
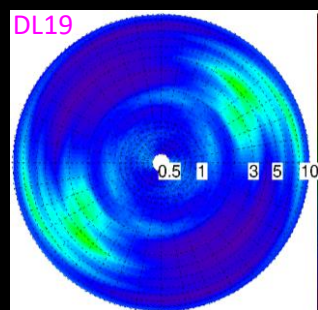
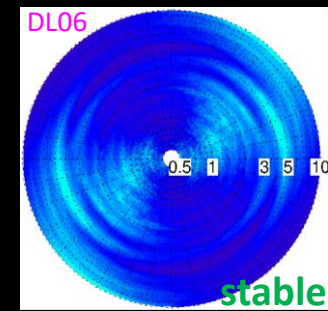
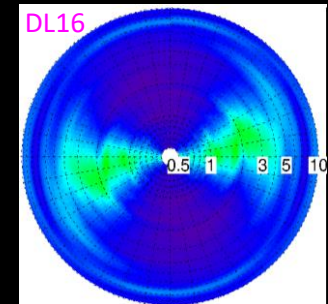
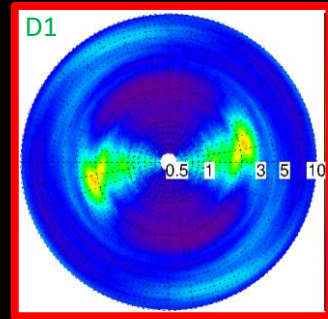
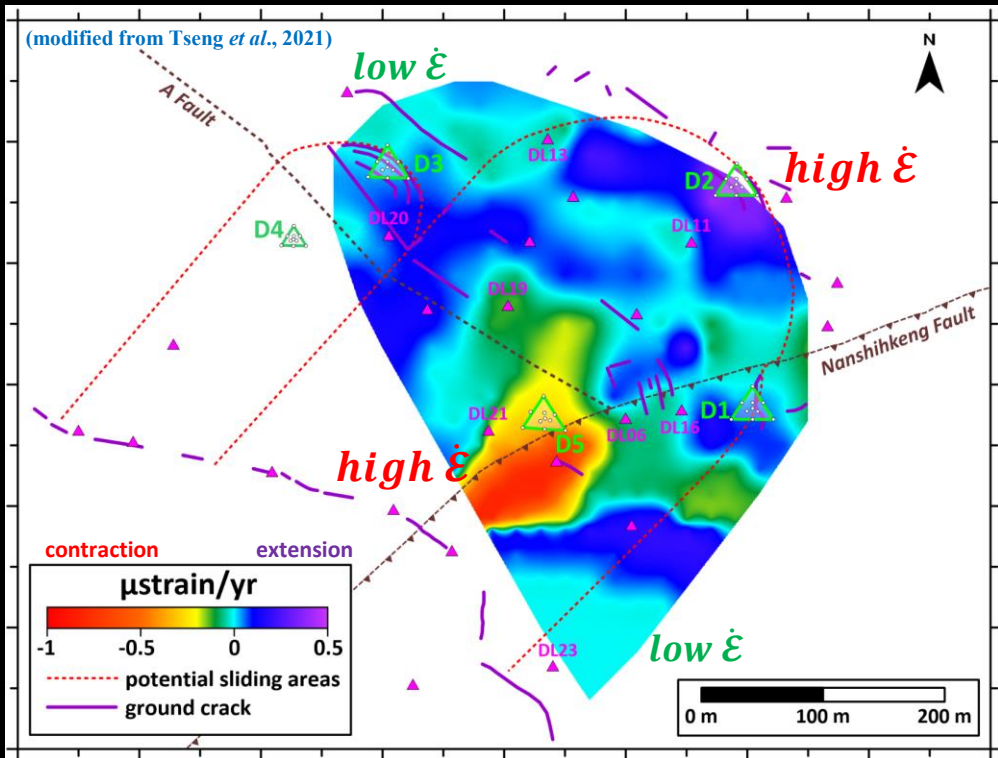
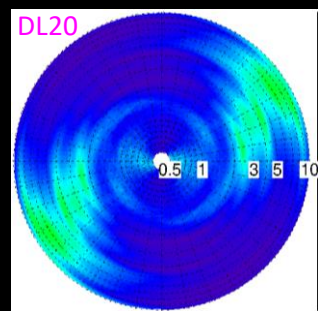
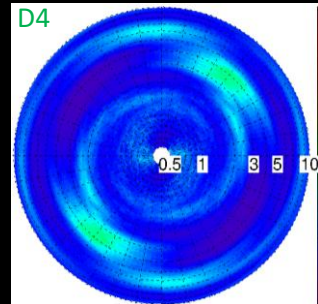
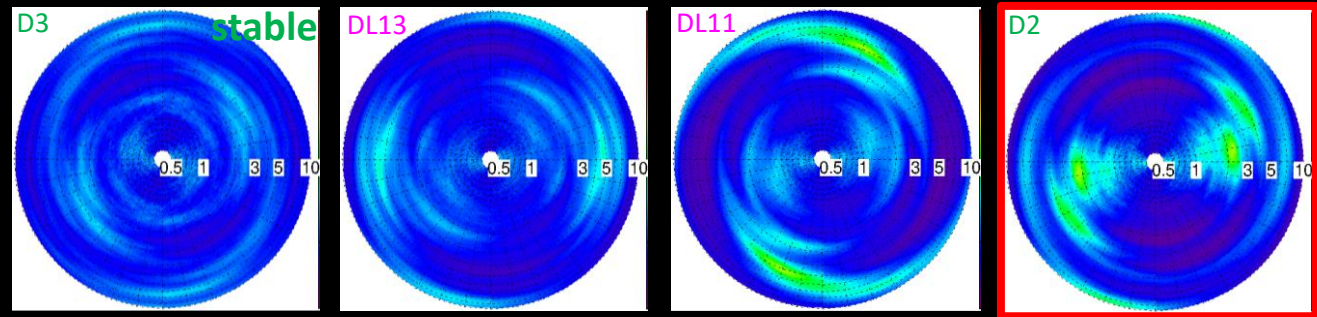


Polarization is orthogonal to the fault (crack).



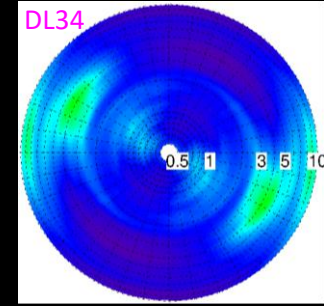
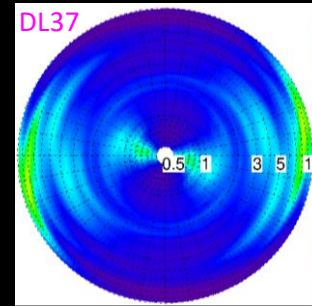
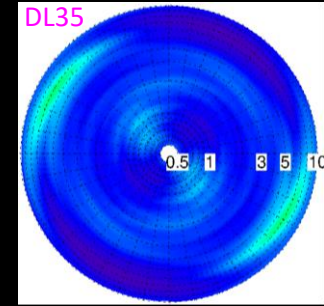
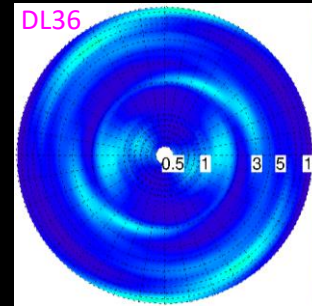
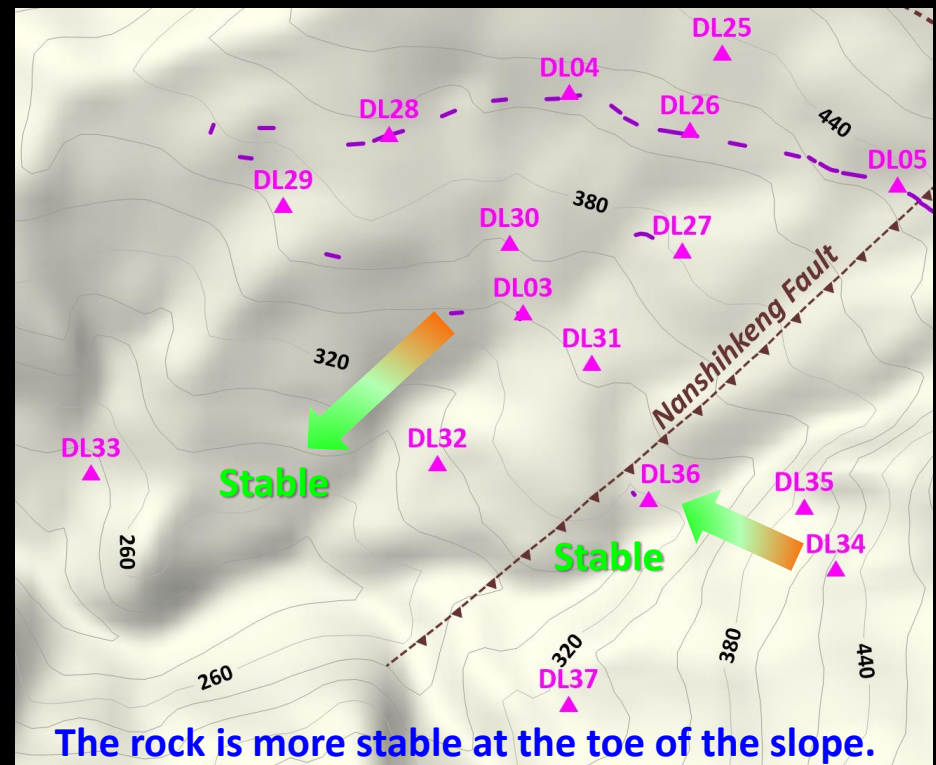
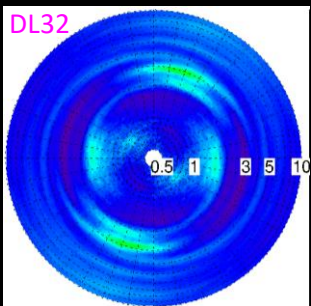
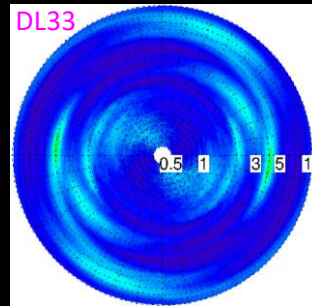
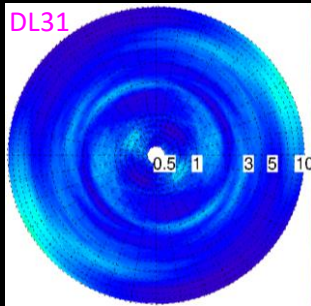
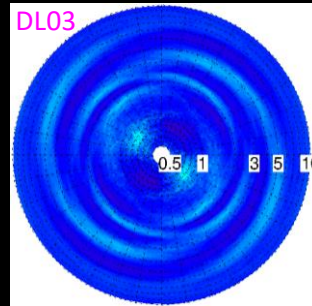
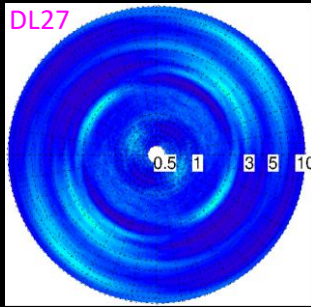
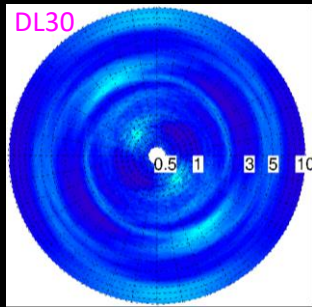
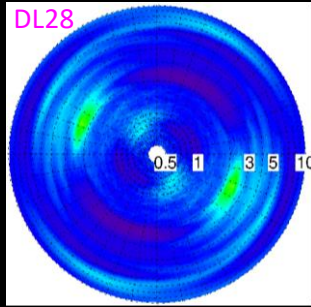
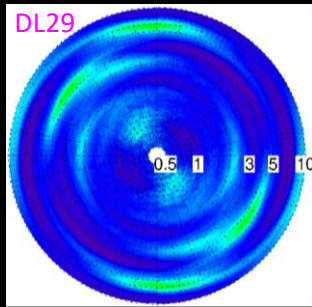
Polarization vs. Strain Rate

$\dot{\epsilon}$ ↑ moving fast



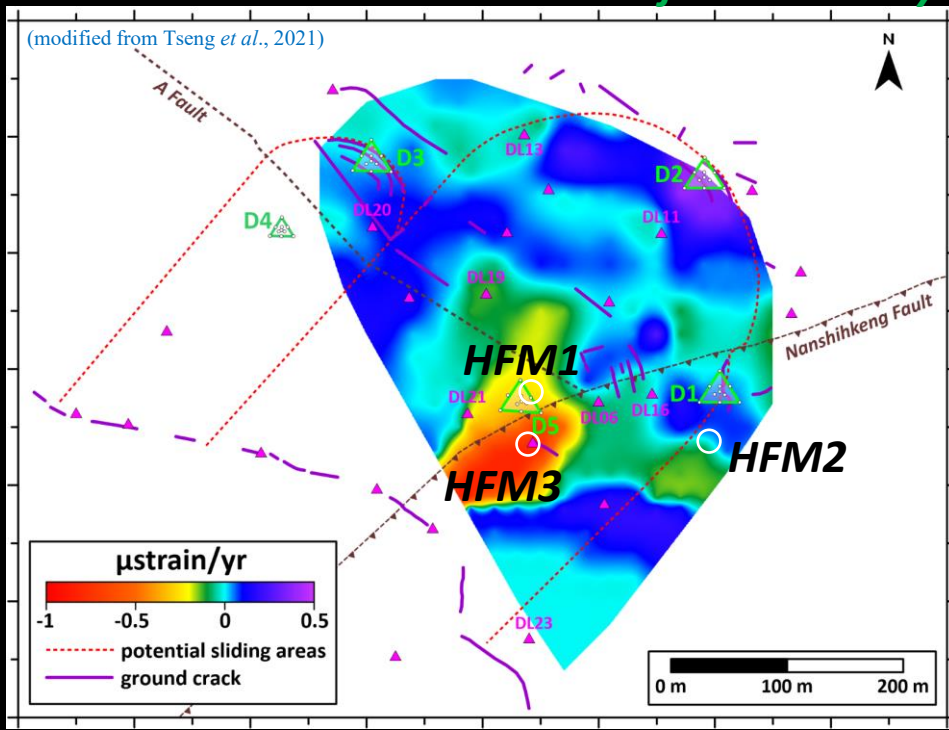
High strain rate areas are closer to unstable areas! (D5, D1 and D2)

Polarization for Stability Evaluation



Towards Real-Time Monitoring

Huafan University



Long-term monitoring in high-strain-rate areas

Monitor changes in sliding characteristics under different forces (earthquake and heavy rainfall)



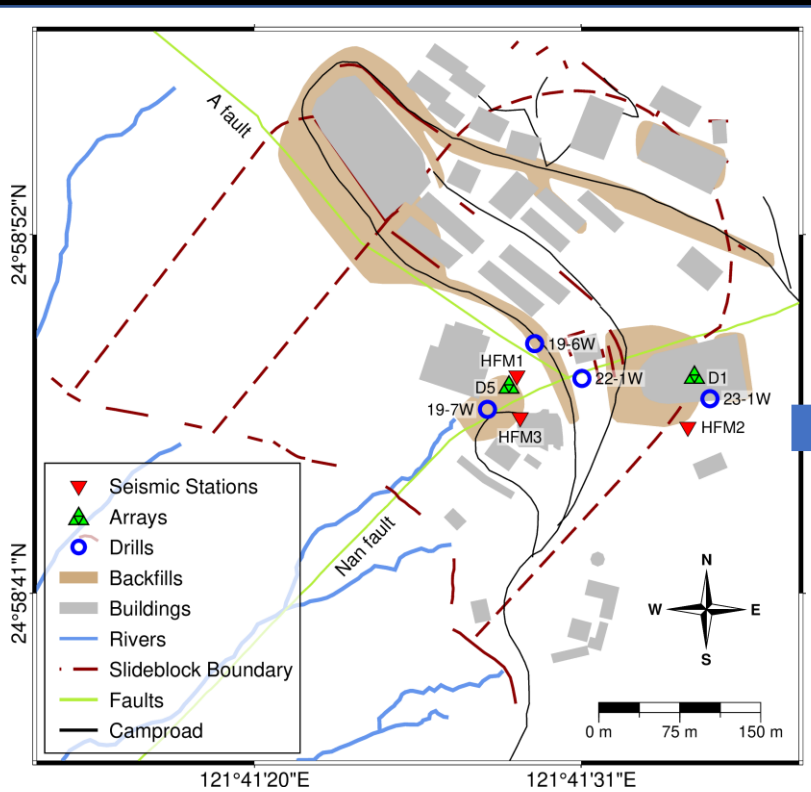
SmartSolo IGU-BD3C-5
(geophone, semi-broadband)



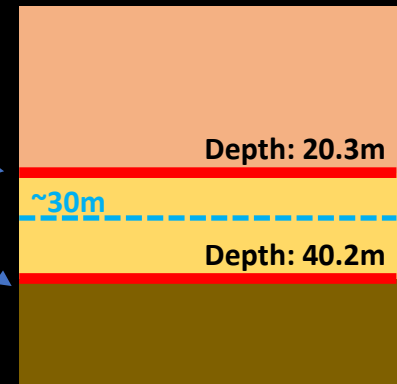
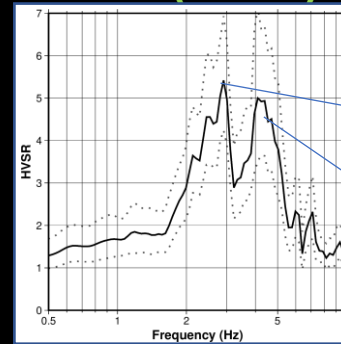
0.2 Hz



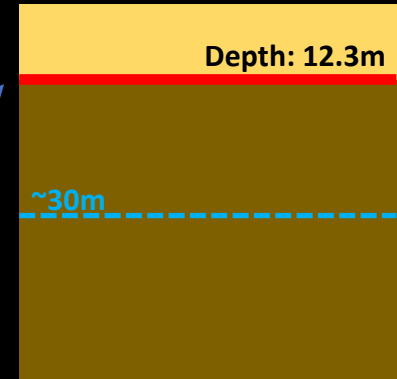
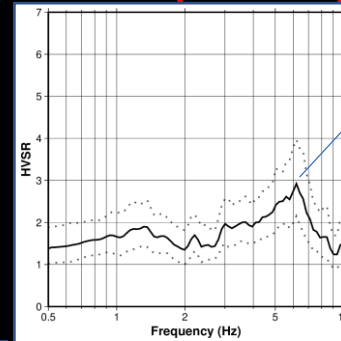
Water level and interface at each station



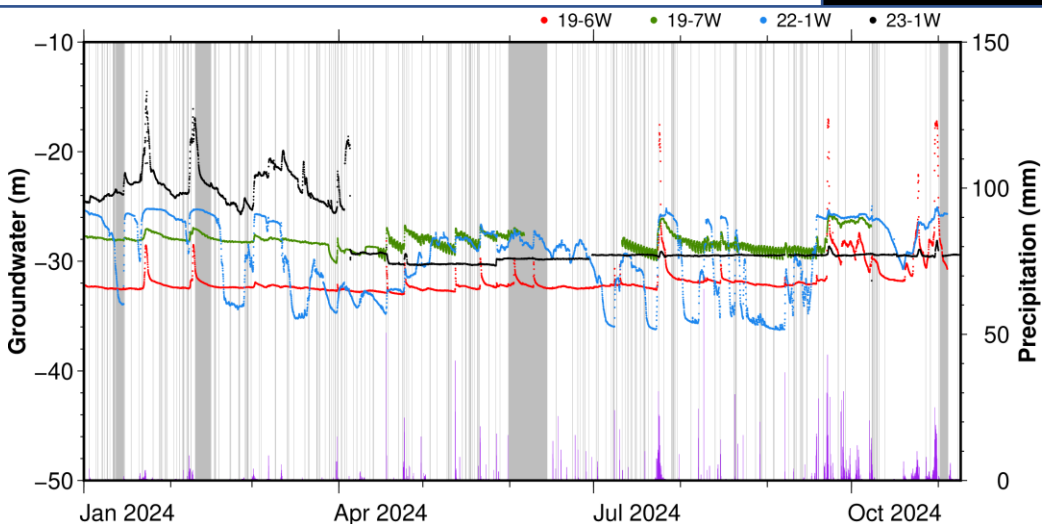
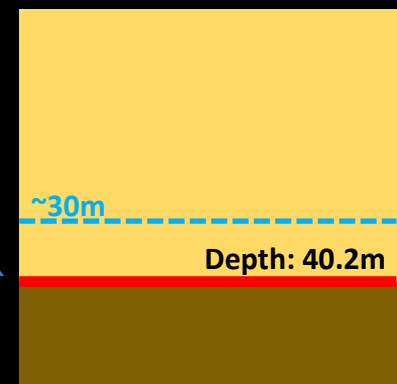
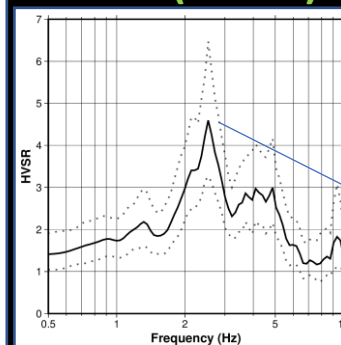
HFM1 (inside)



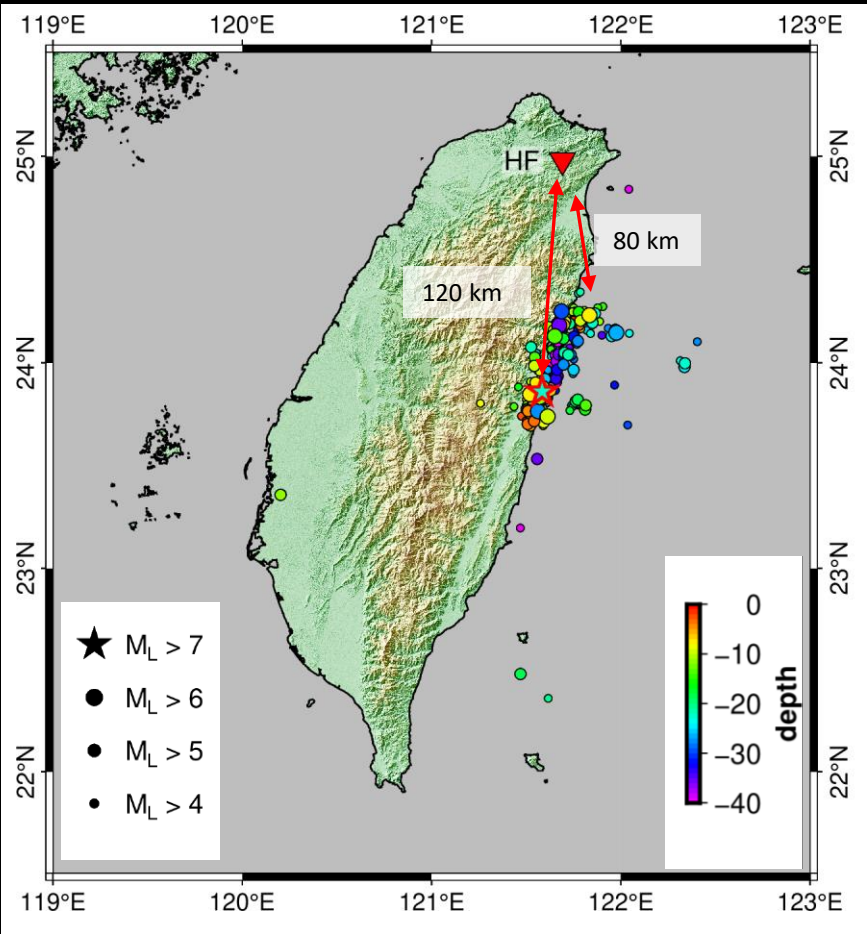
HFM2 (outside)



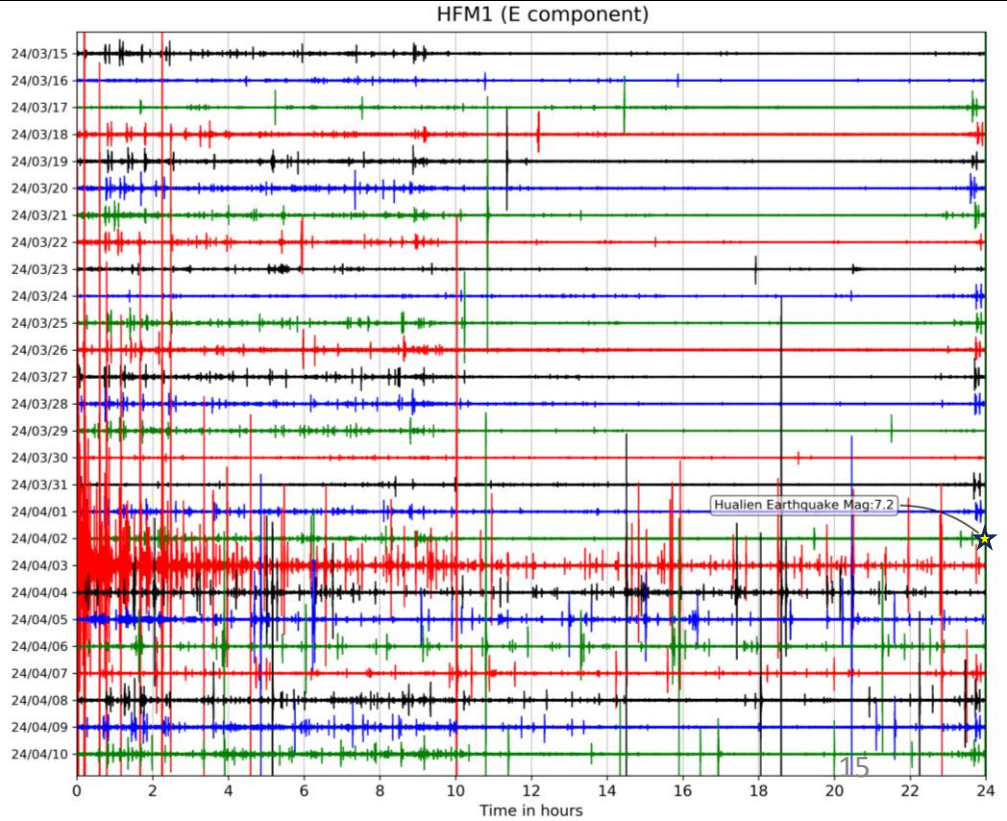
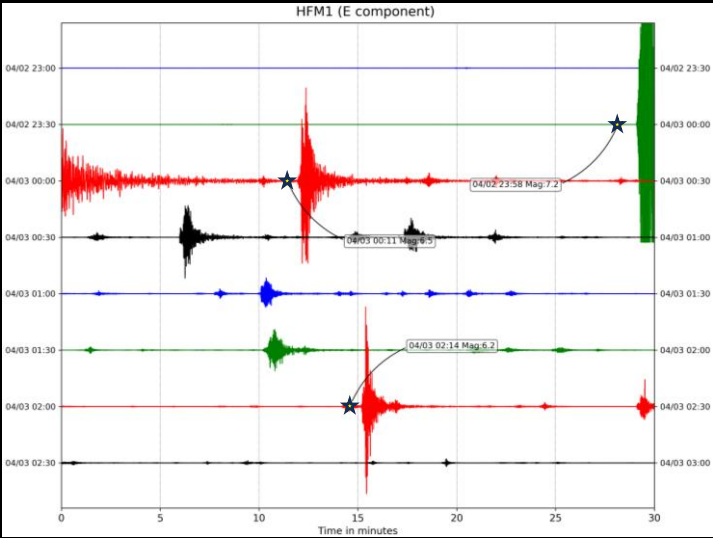
HFM3 (inside)



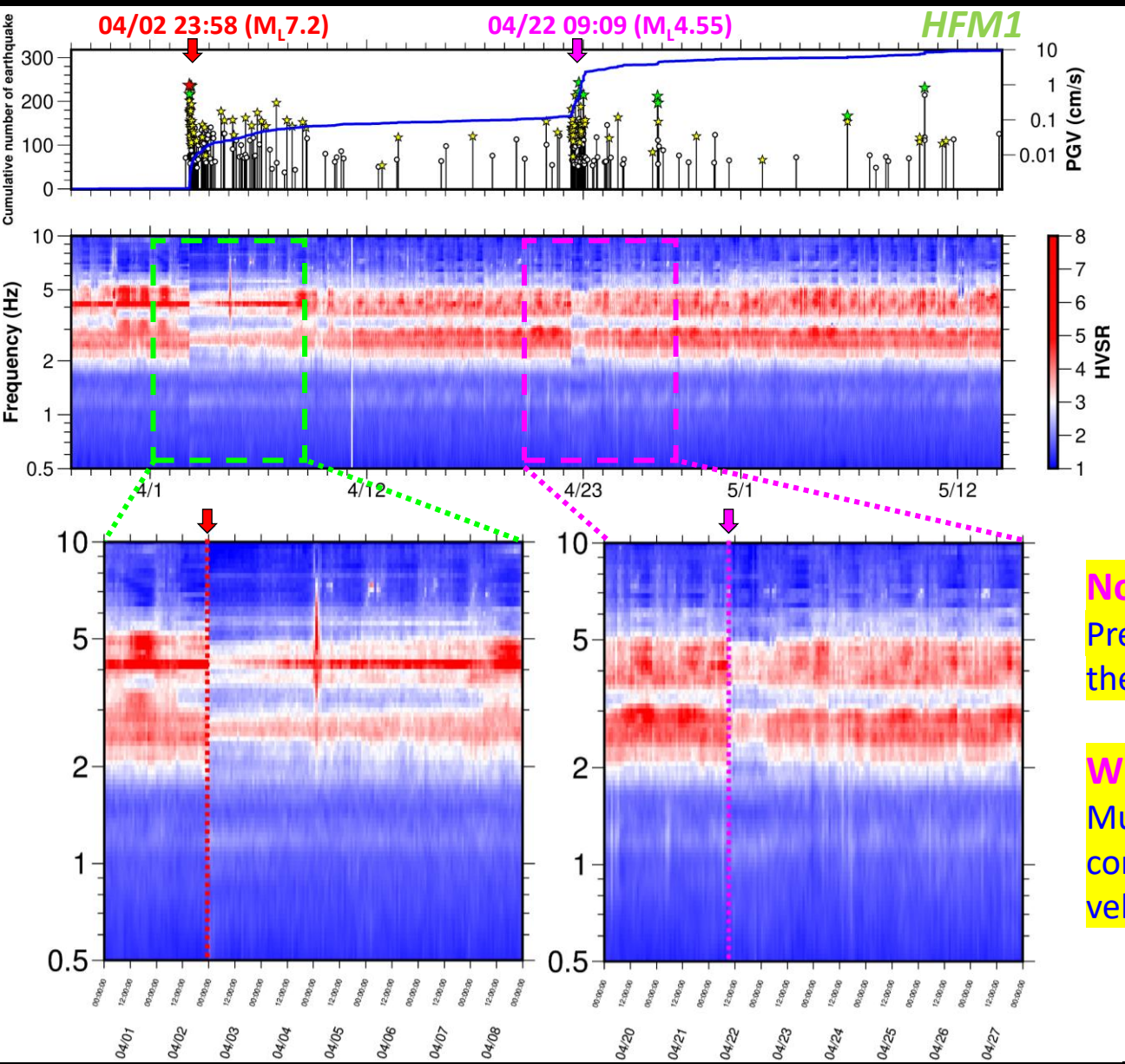
2024-04-03 M_L 7.2 Hualien earthquake



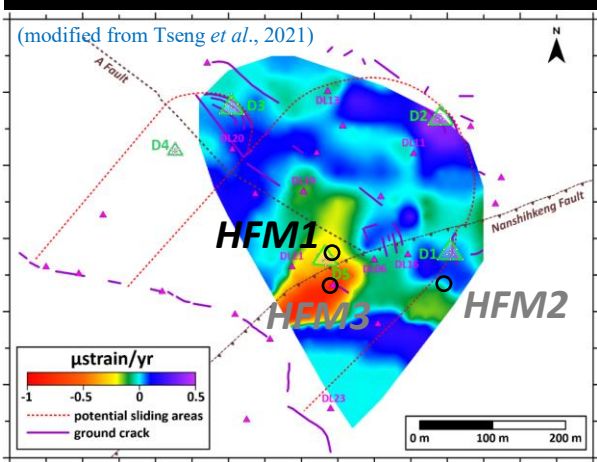
Epicentral distance of 80-120 km
away from the Huafan campus



Temporary Variation of HVSRs (Earthquakes)



Amplification Factor Dropped

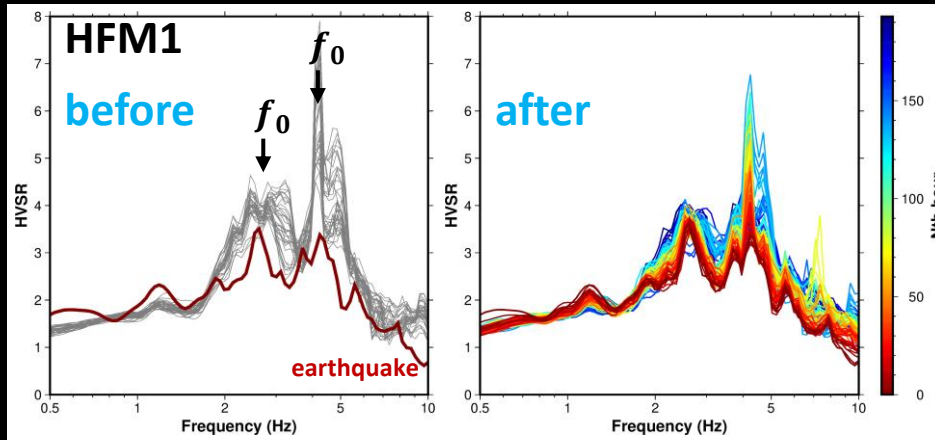


Nonlinear site effects!
Predominant frequency decreases, or
the amplification factor reduces.

When did it happen?
Multiple earthquakes happen
consecutively, and the peak ground
velocity exceeds 1 cm/s.

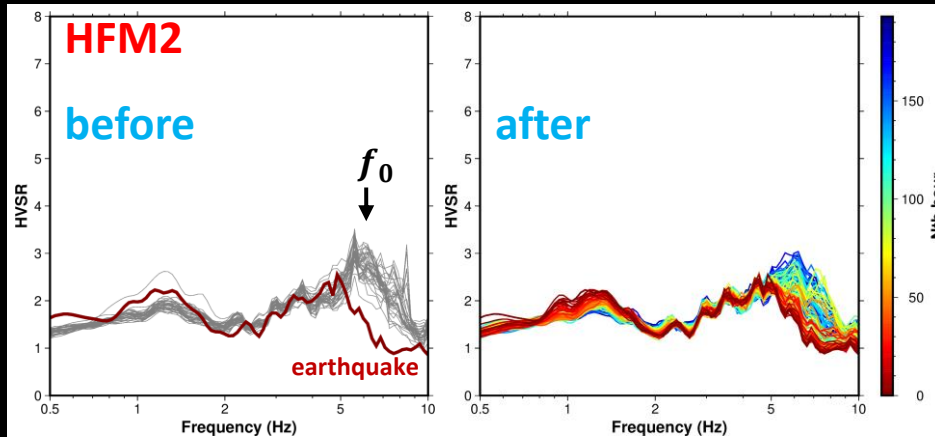
Temporary Variation of HVSRs (Earthquakes)

★ $M_L > 7$ ★ $M_L > 6$ ★ $M_L > 5$ ● $M_L > 4$



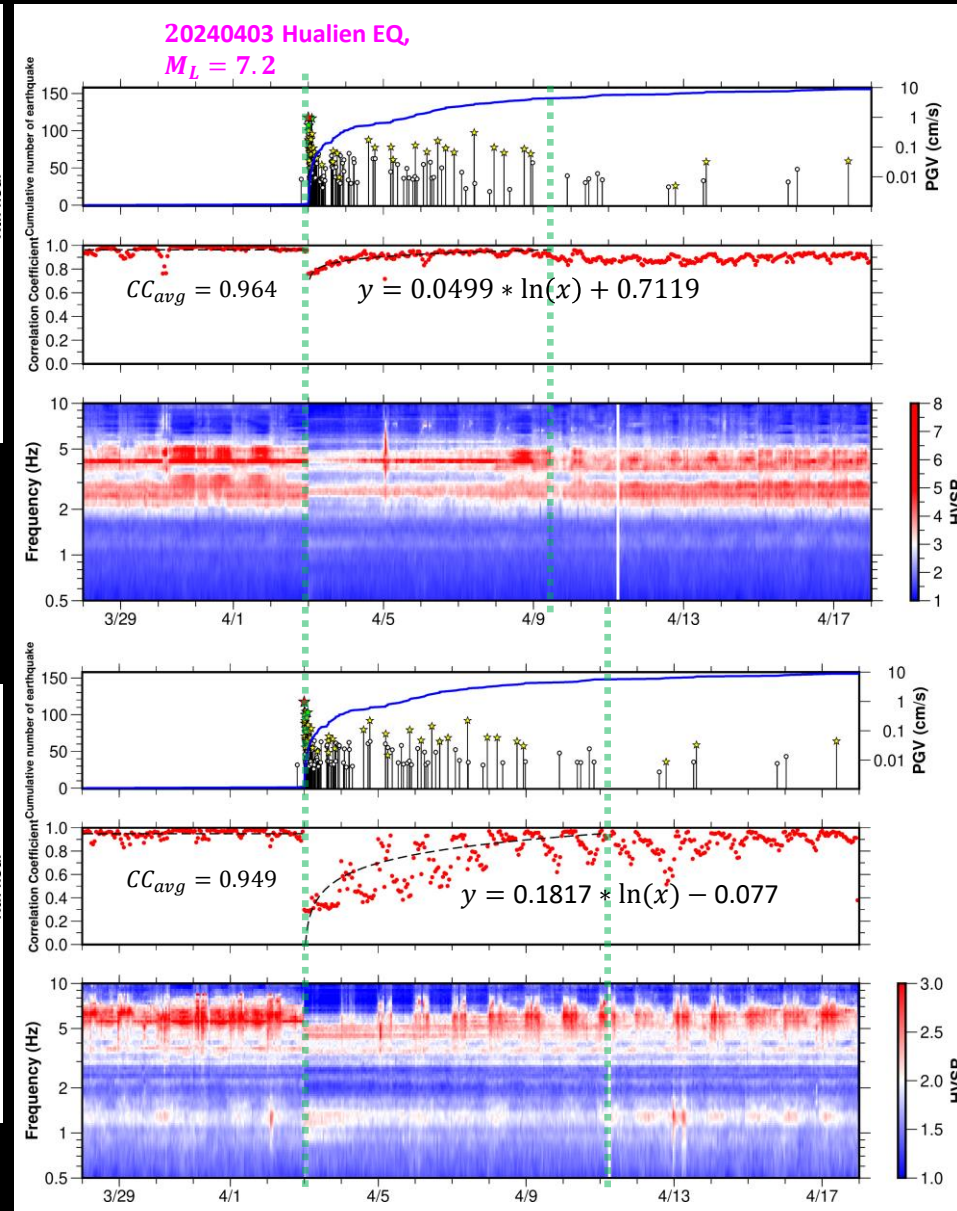
HFM1

1. A_0 : dropped 4 - 3.5 Hz
 f_0 : unchanged 2.5 Hz
2. A_1 : dropped 5 - 3.5 Hz
 f_1 : unchanged 4 Hz
3. Recovered in 6 days

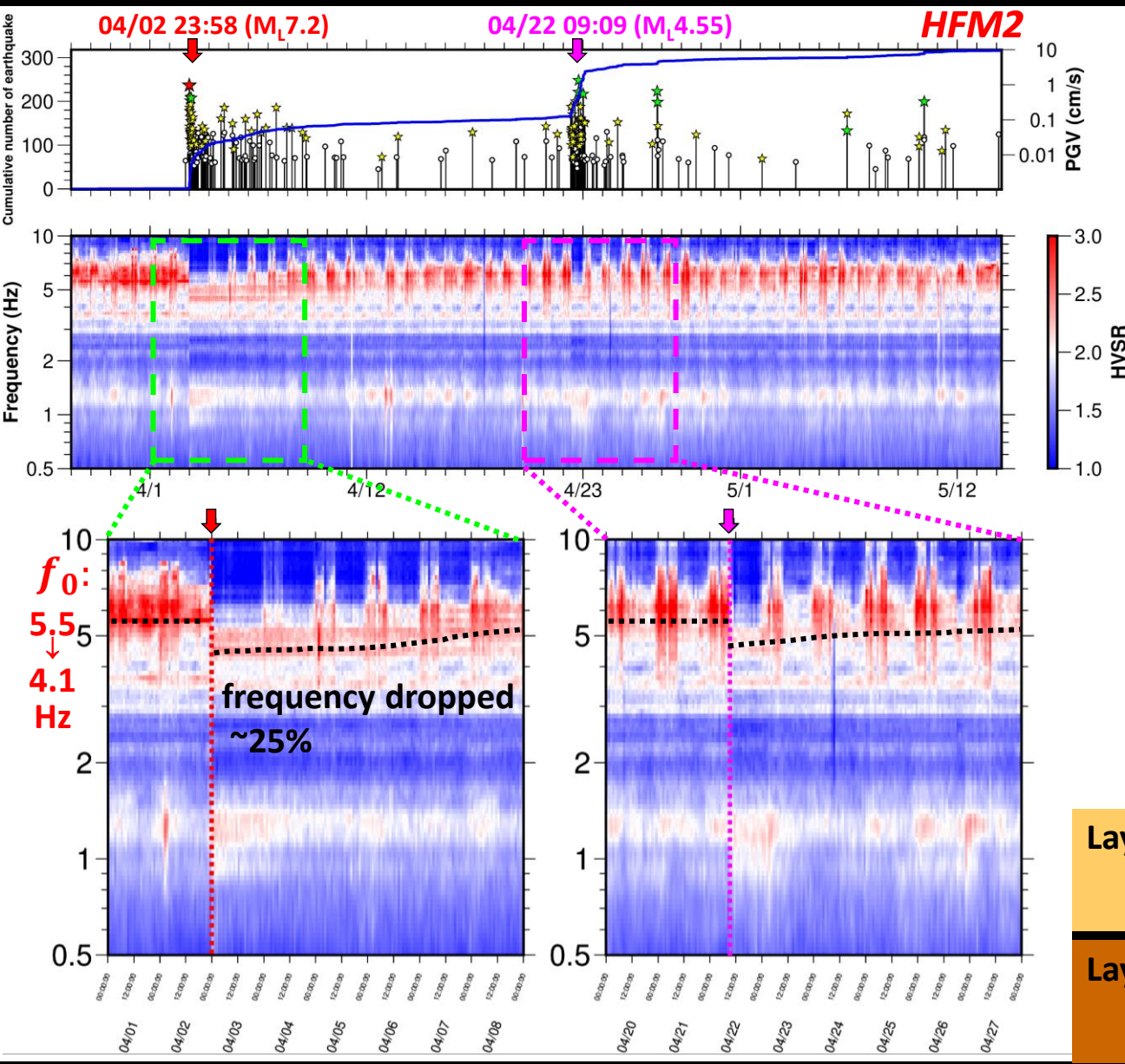


HFM2

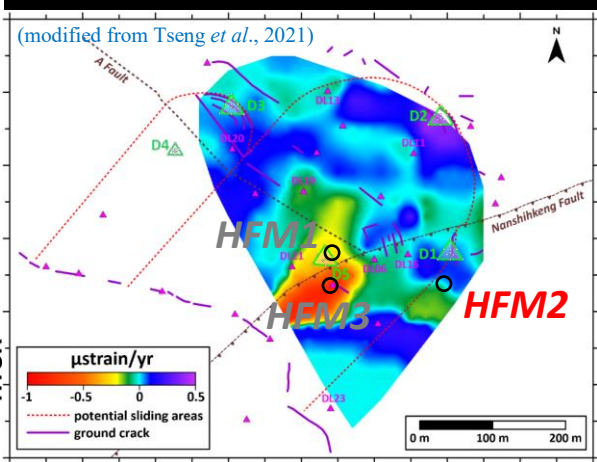
1. A_0 : dropped 3 - 2.5 Hz
 f_0 : dropped 6 - 5 Hz
2. Recovered in 8 days



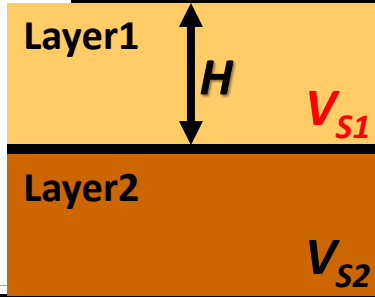
Temporary Variation of HVSRs (Earthquakes)



Frequency Dropped



Frequency changes after strong earthquakes are resulted from velocity decreases caused by the shaking-induced loosen soil at the shallow layers.



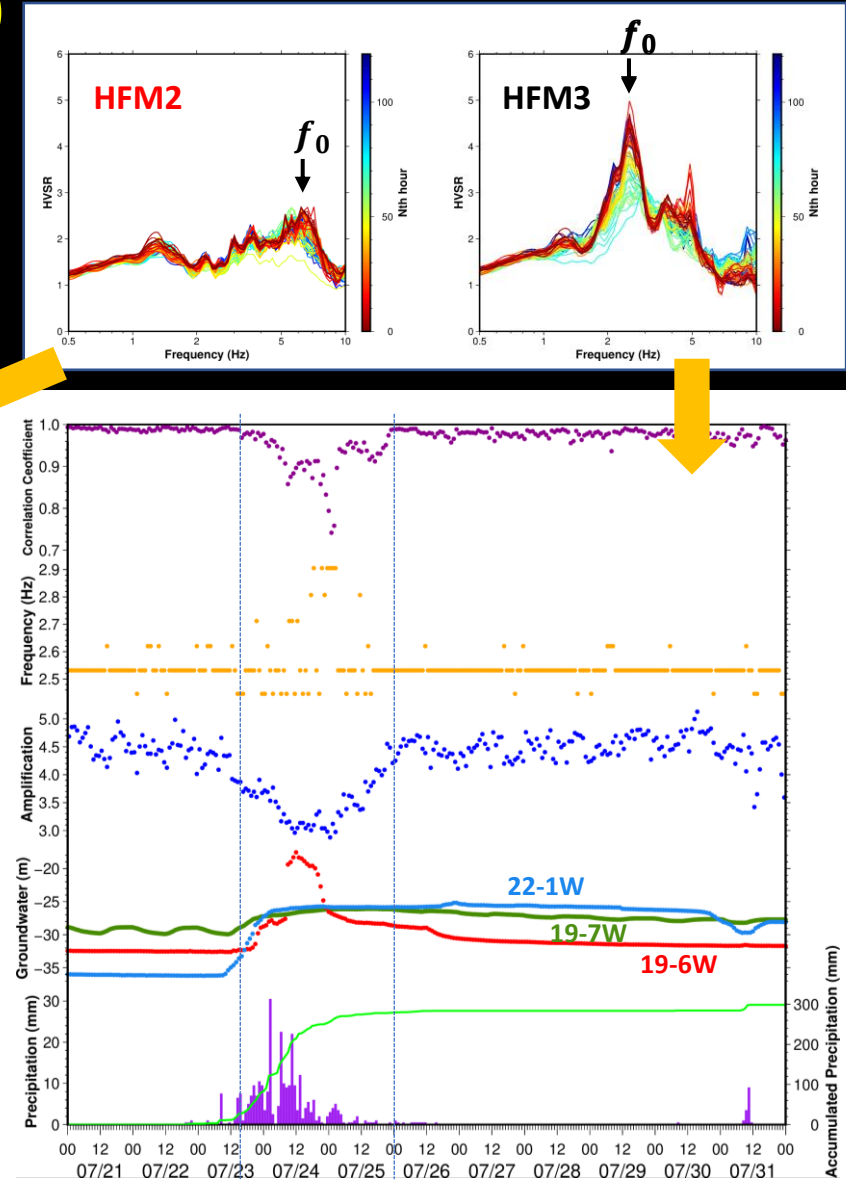
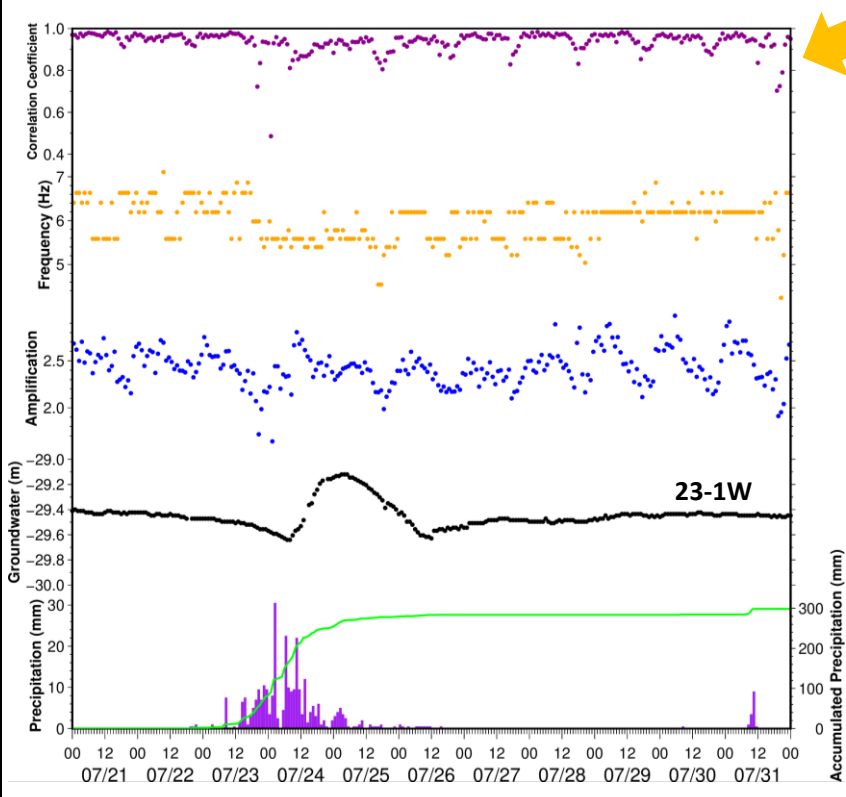
$$f_0 = \frac{V_{S1}}{4H}$$

$f_0 \downarrow$ $V_{S1} \downarrow$ ~25%

Peak frequency recovers to the initial value within a few days!

Temporary Variation of HVSRs (Rainfalls)

Frequency Dropped

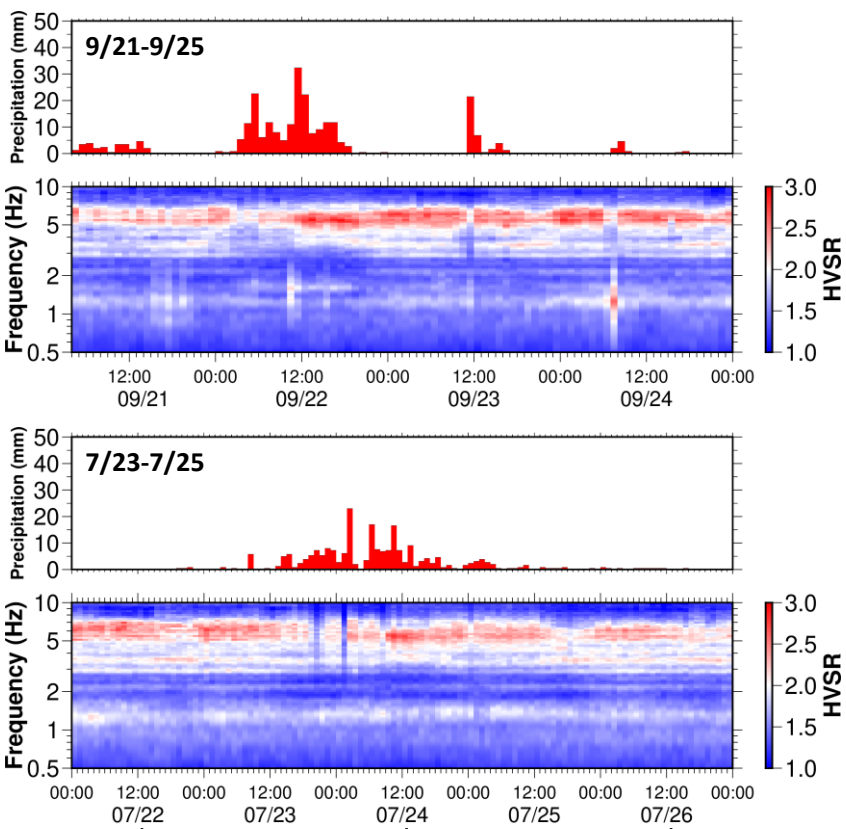


Frequency started to drop when the accumulated rainfall exceeds 30 mm

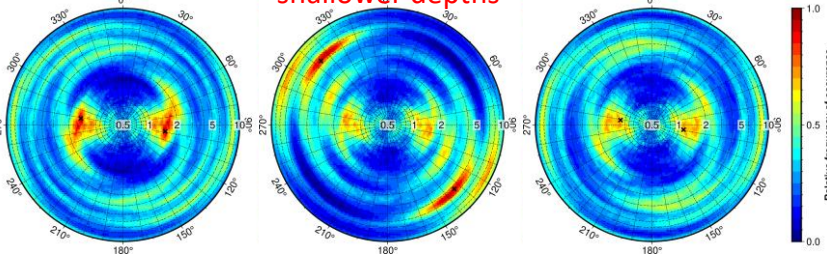
Temporary Variation of HVSRs (Rainfalls)

Frequency Dropped

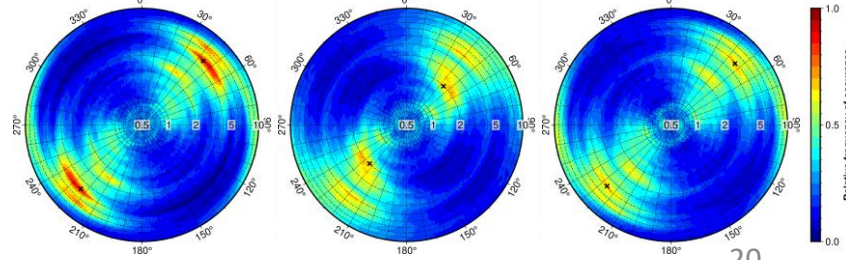
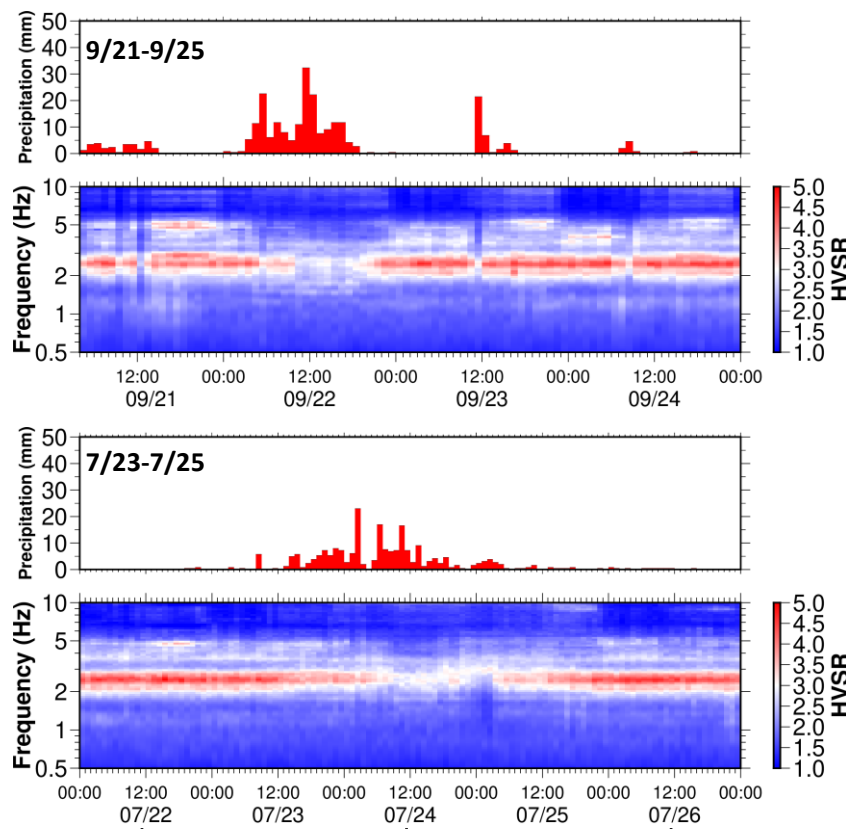
HFM2



Increase sliding at shallower depths



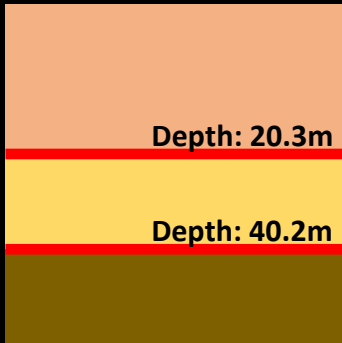
HFM3



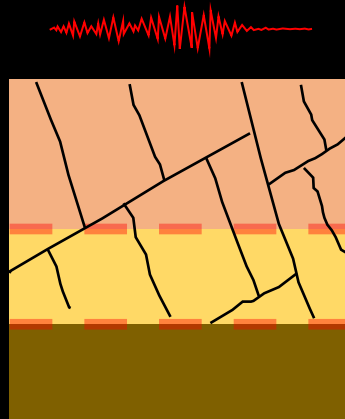
Temporary Variation of HVSRs (Earthquakes)

$$f_0 = \frac{V_s}{4H}, \text{ lower } V_s \text{ will decrease } f_0$$

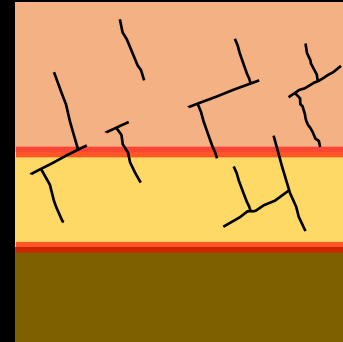
HFM1



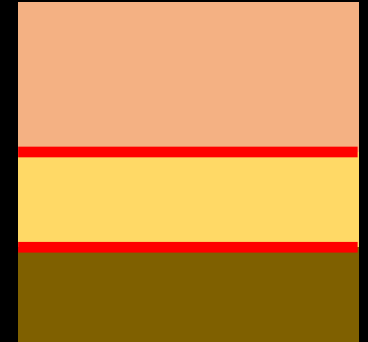
Two sliding interfaces



During shaking, fracture density increased, shear wave velocity and amplitude decreased

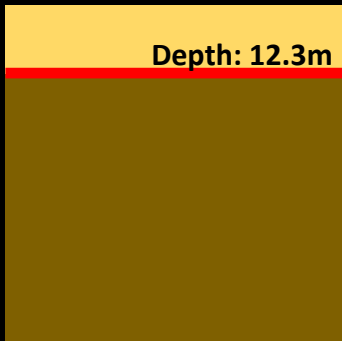


Postseismic period

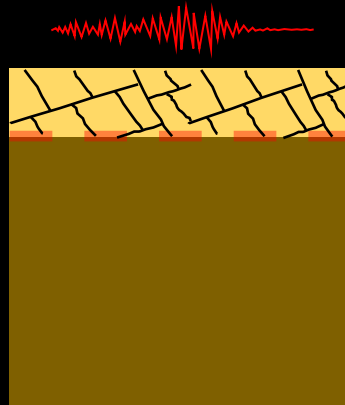


Returned to the initial stage in a few days

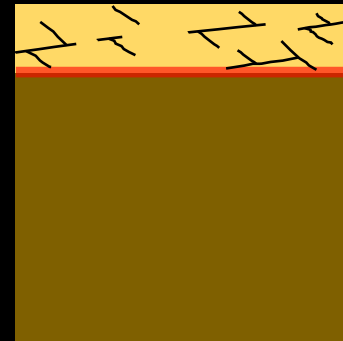
HFM2



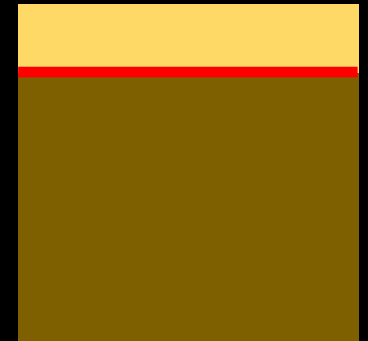
One shallower interface



During shaking, shear wave velocity and amplitude decreased. Frequency also decreased due to a shallower interface.



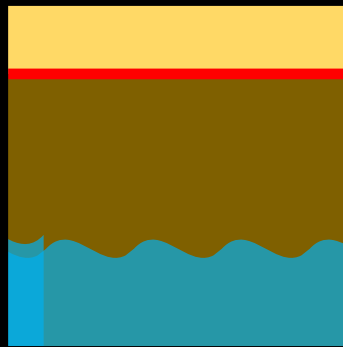
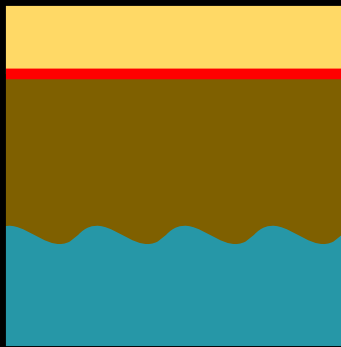
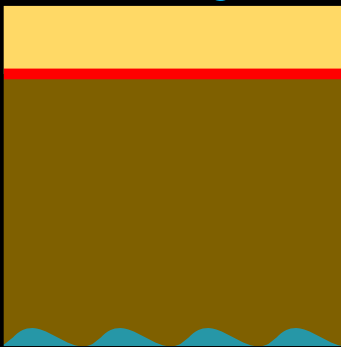
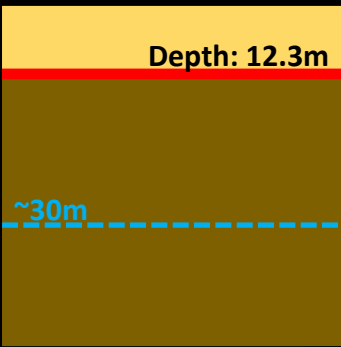
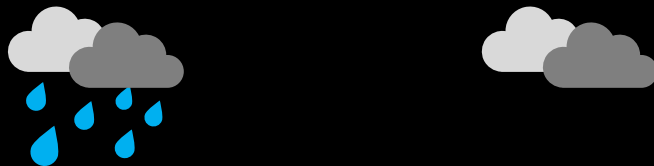
Postseismic period



Returned to the initial stage in a few days

Temporary Variation of HVSRs (Rainfalls)

HFM2

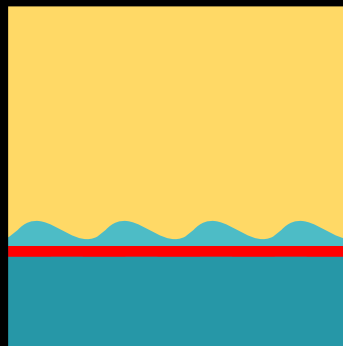
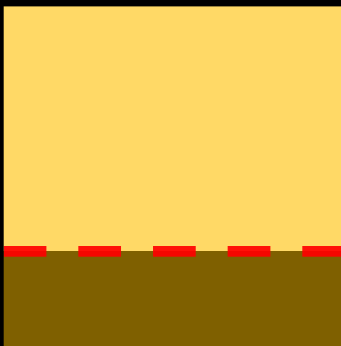
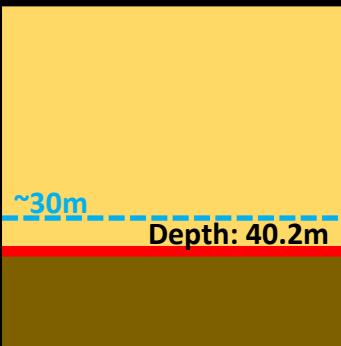
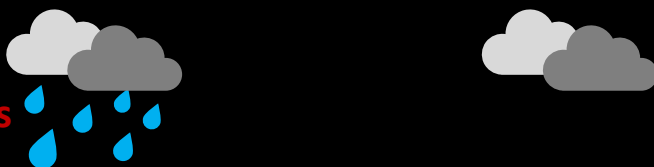


Groundwater level is lower than the sliding surface

Groundwater level increased, but did not reach the interface

HFM3

Groundwater level increases as rainfall starts



Groundwater level is higher than the sliding surface

Groundwater level increased and reached the interface. Lower the impedance contrast, and the amplitude decreases.

Summary

1. Microtremor analyses can be used to determine the geometry and depth to the sliding surface of a deep-seated landslide
2. Slope stability can be determined by the time frequency polarization analyses of microtremor signals
3. Continuous seismic recording reveals the mechanical properties of the slope for various periods of the earthquake and rainfall cycle

