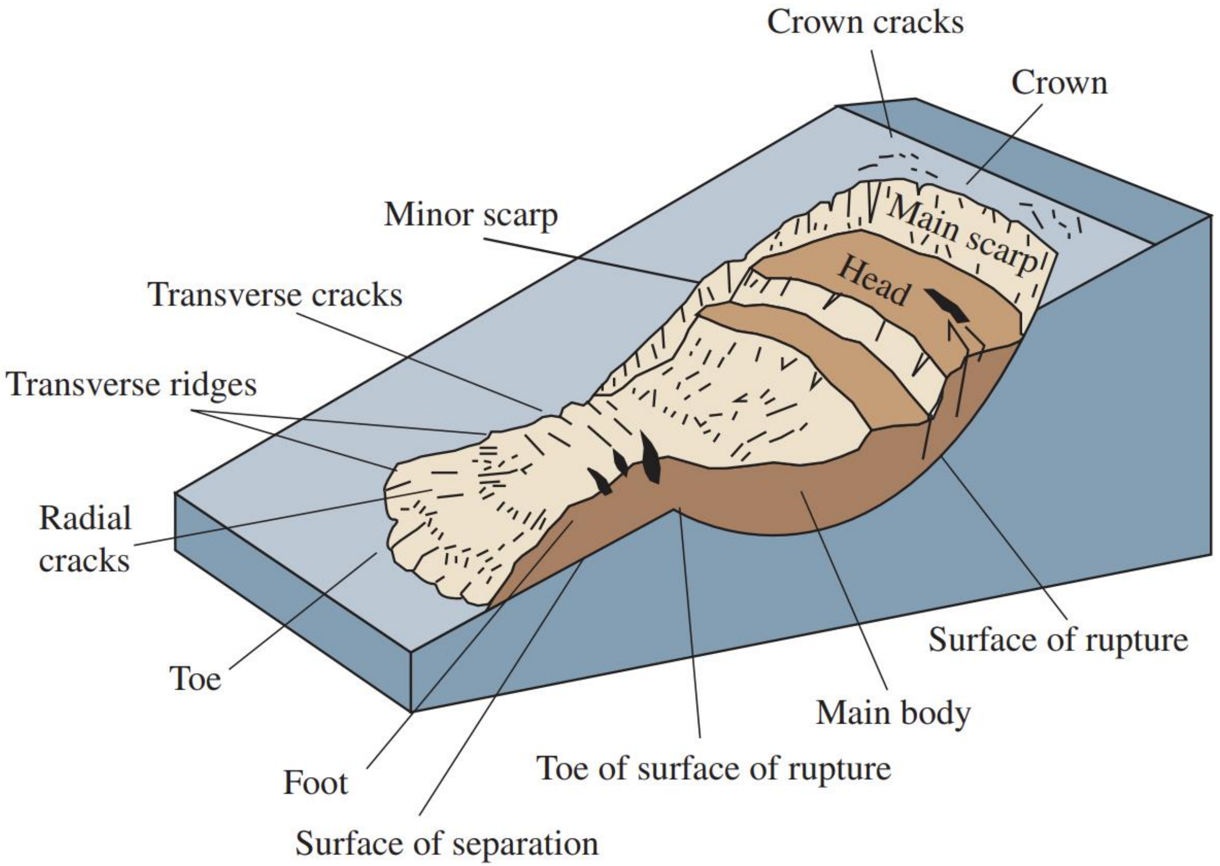
POLITECNICO DI MILANO

GEO-ENGINEERING TECHNIQUES FOR UNSTABLE SLOPES

Group 4 Presentation

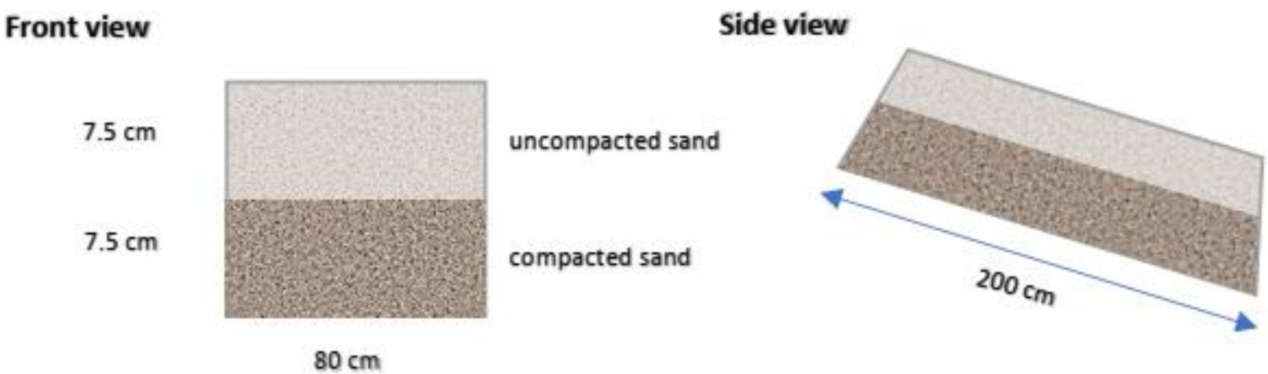
- What is a "Landslide"?
- Landslide Types
- Landslide Parts



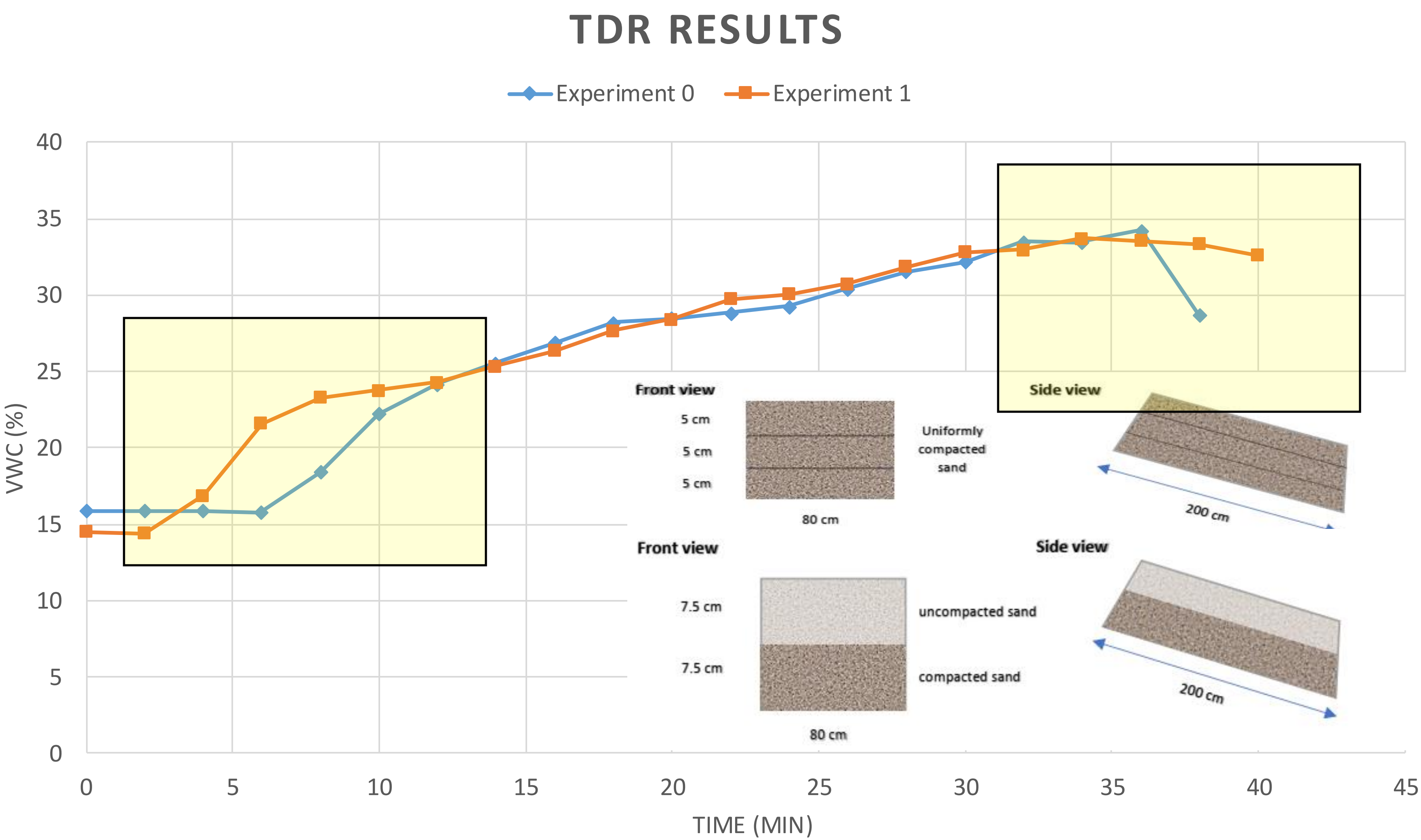
Comparison Between Experiment 0 and 1

- **Experiment 0**

- **Experiment 1**

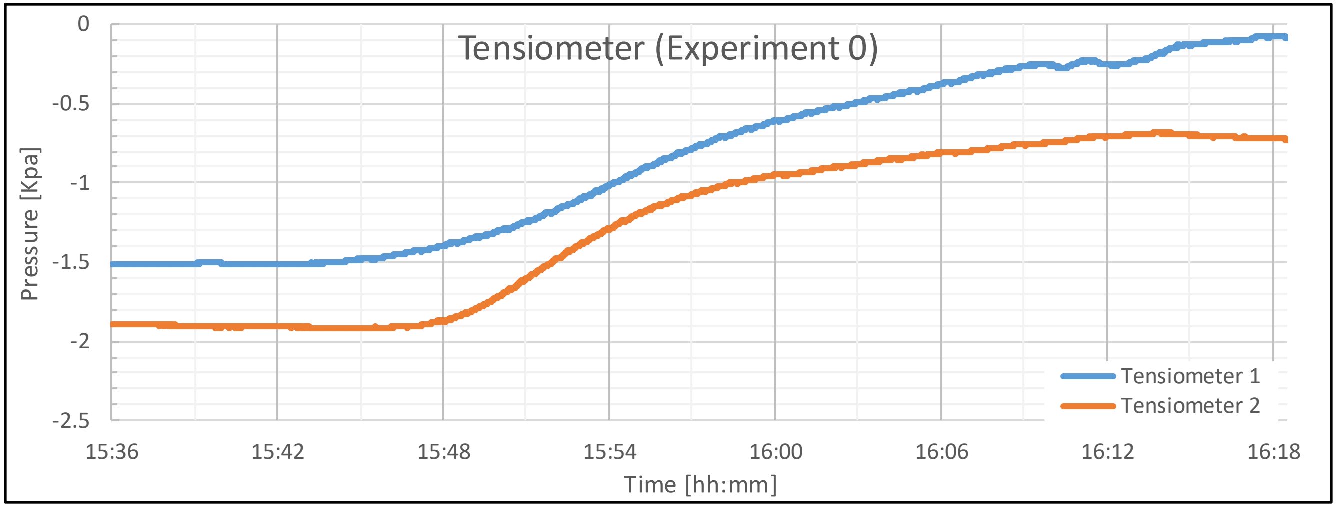


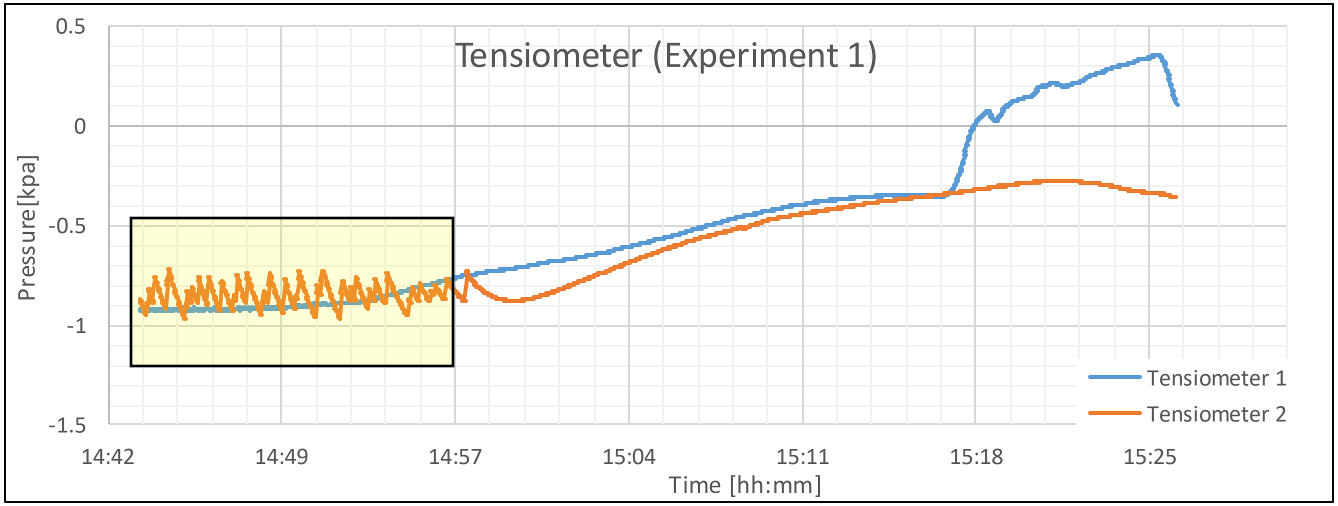
Comparison Between Experiment 0 and 1



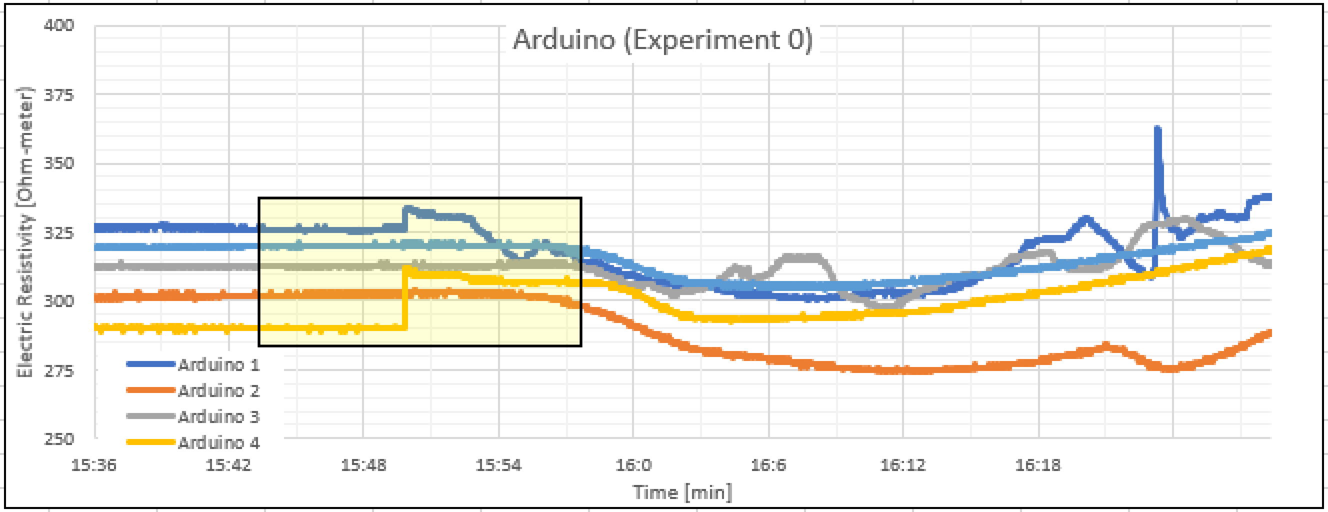
Author: Group 4

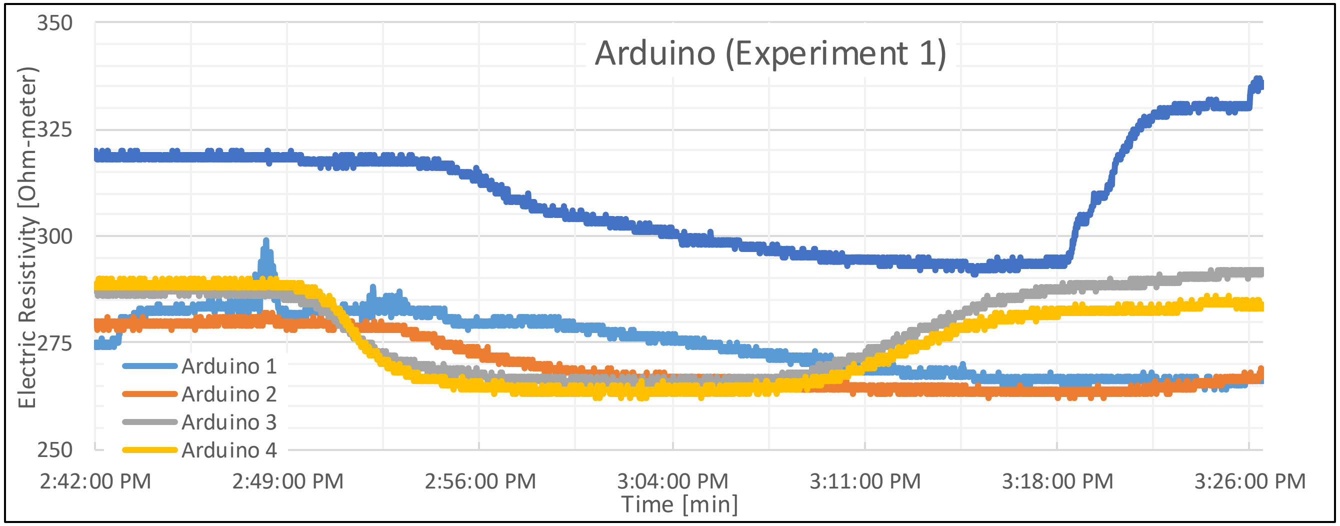
Comparison Between Experiment 0 and 1





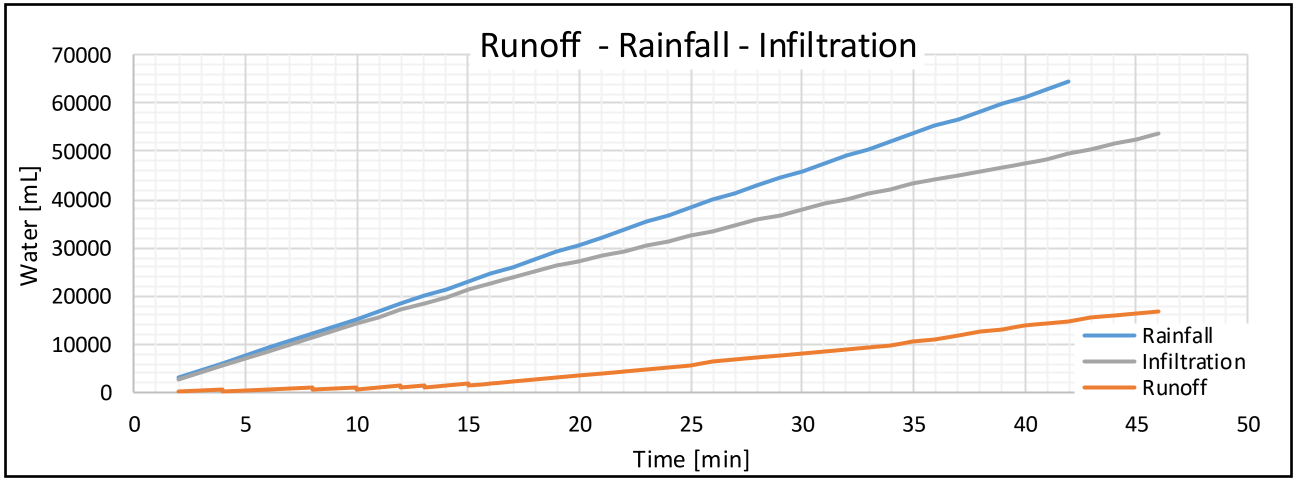
Comparison Between Experiment 0 and 1





Comparison Between Experiment 0 and 1

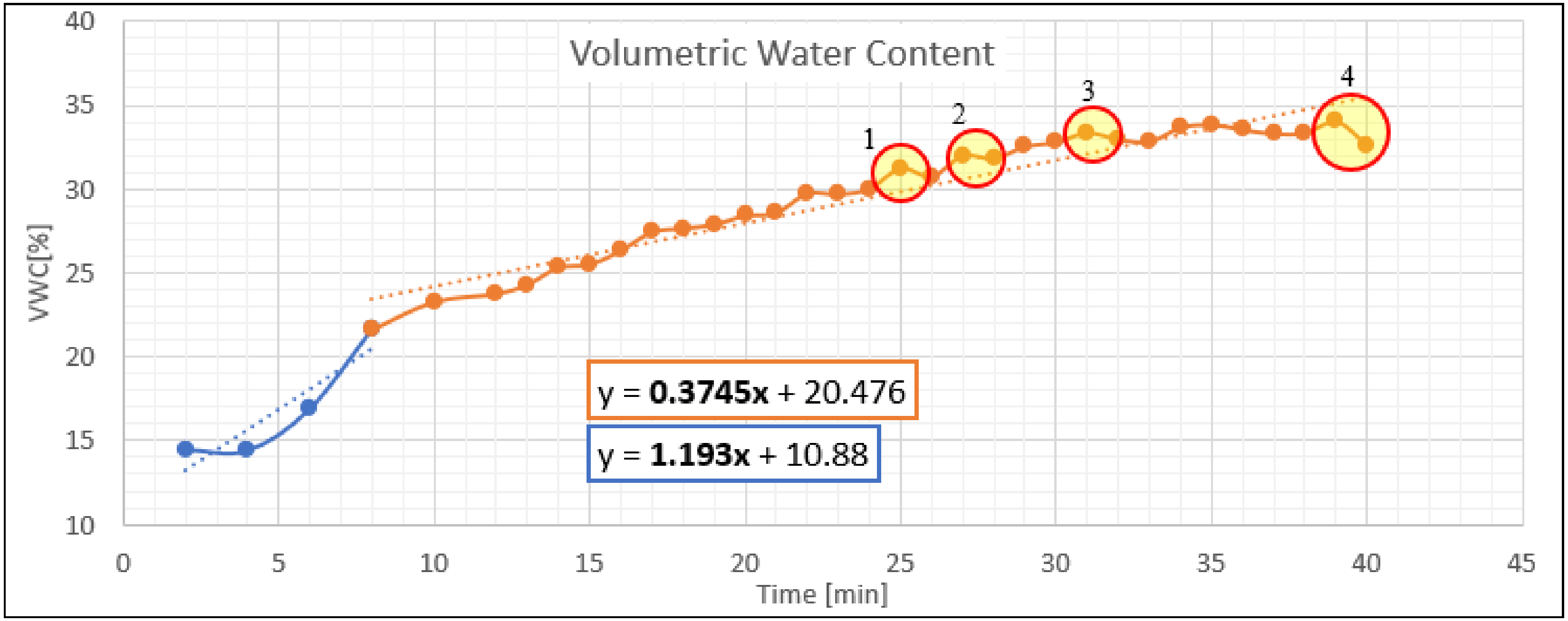
	Area [m^2]	1.6			
	N sprinklers	4	6	4	6
Pressure	Discharge	Intensity [mm/h]		Intensity [m/min]	
0.5	0.22	33.0	49.5	0.000549938	0.000824906
0.6	0.24	35.9	53.8	0.00059828	0.00089742
0.7	0.26	38.7	58.0	0.000644958	0.000967436
0.8	0.28	41.4	62.1	0.00068997	0.001034955
0.9	0.29	44.0	66.0	0.000733318	0.001099976
1	0.31	46.5	69.8	0.000775	0.0011625
1.1	0.33	48.9	73.4	0.000815018	0.001222526
1.2	0.34	51.2	76.8	0.00085337	0.001280055
1.3	0.36	53.4	80.1	0.000890058	0.001335086
1.4	0.37	55.5	83.3	0.00092508	0.00138762
1.5	0.38	57.5	86.3	0.000958438	0.001437656
1.6	0.40	59.4	89.1	0.00099013	0.001485195
1.7	0.41	61.2	91.8	0.001020158	0.001530236
1.8	0.42	62.9	94.4	0.00104852	0.00157278



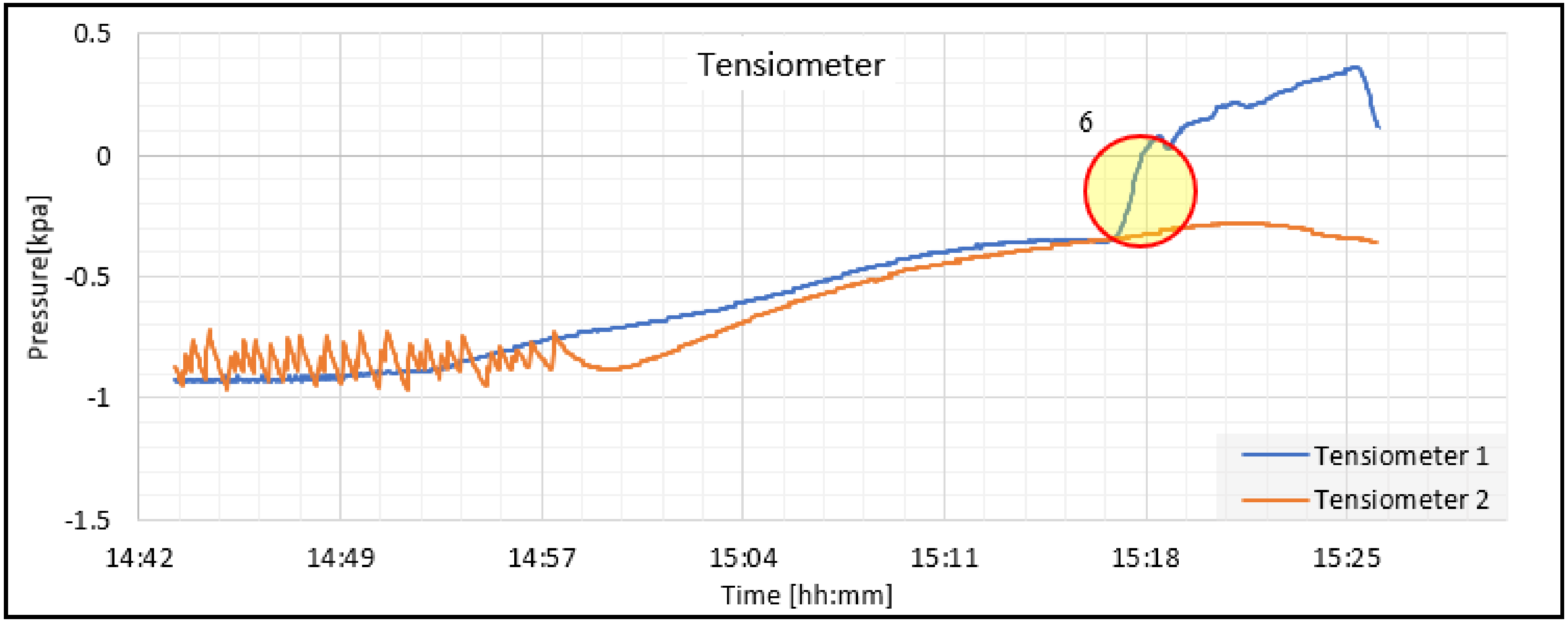
List of Anomalies

Table 3. List of Anomalies and Related Information

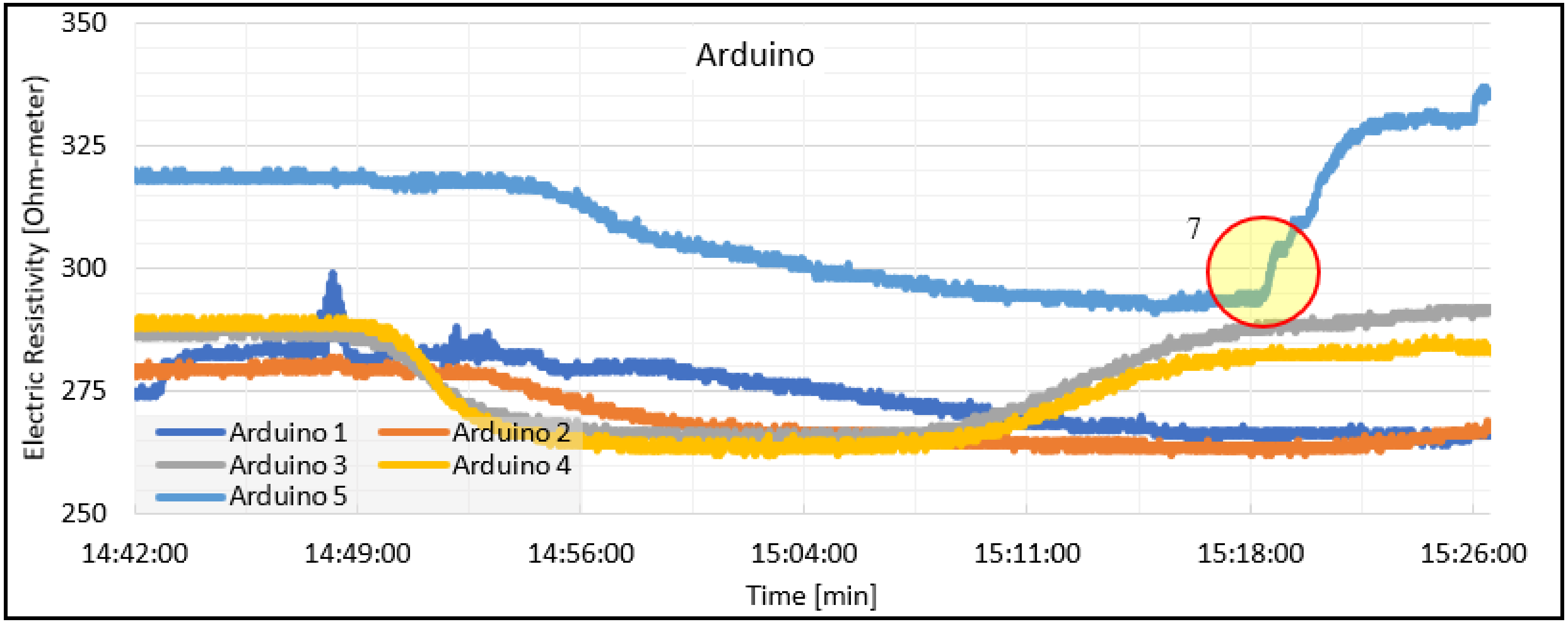
Geophysical Assessment			Photogrammetry Assessment		Geophysical Assessment	
Anomaly No.	Exp. Equipment	Time	Fracture ID	Time	Measurement ID	Time
1	TDR Exp.1	24-26	Fracture 2	24:10	T5 T6	22 27
2	TDR Exp.1	27-29	Fracture 3 Fracture 4 Fracture 5	27:09 27:50 28:20	T6	27
3	TDR Exp.1	31-33	Fracture 7 Fracture 8	31:00 30:50	T7	33
4	TDR Exp.1	38-40	Fracture 9 Fracture 10 Fracture 11 Fracture 12 Fracture 13 Fracture 14	38:10 37:00 37:30 38:00 39:30 30:45	T9 T10	37 39
5	TDR Exp.0	35			T6	33
6	Tensiometer Exp. 1	0.235	Same anomaly as No.4			
7	Arduino Exp. 1	15	Same anomaly as No. 4			


Volumetric Water Content
VWC[%]
Time [min]
y = **0.3745x** + 20.476
y = **1.193x** + 10.88
1
2
3
4
40
35
30
25
20
15
10
0
5
10
15
20
25
30
35
40
45

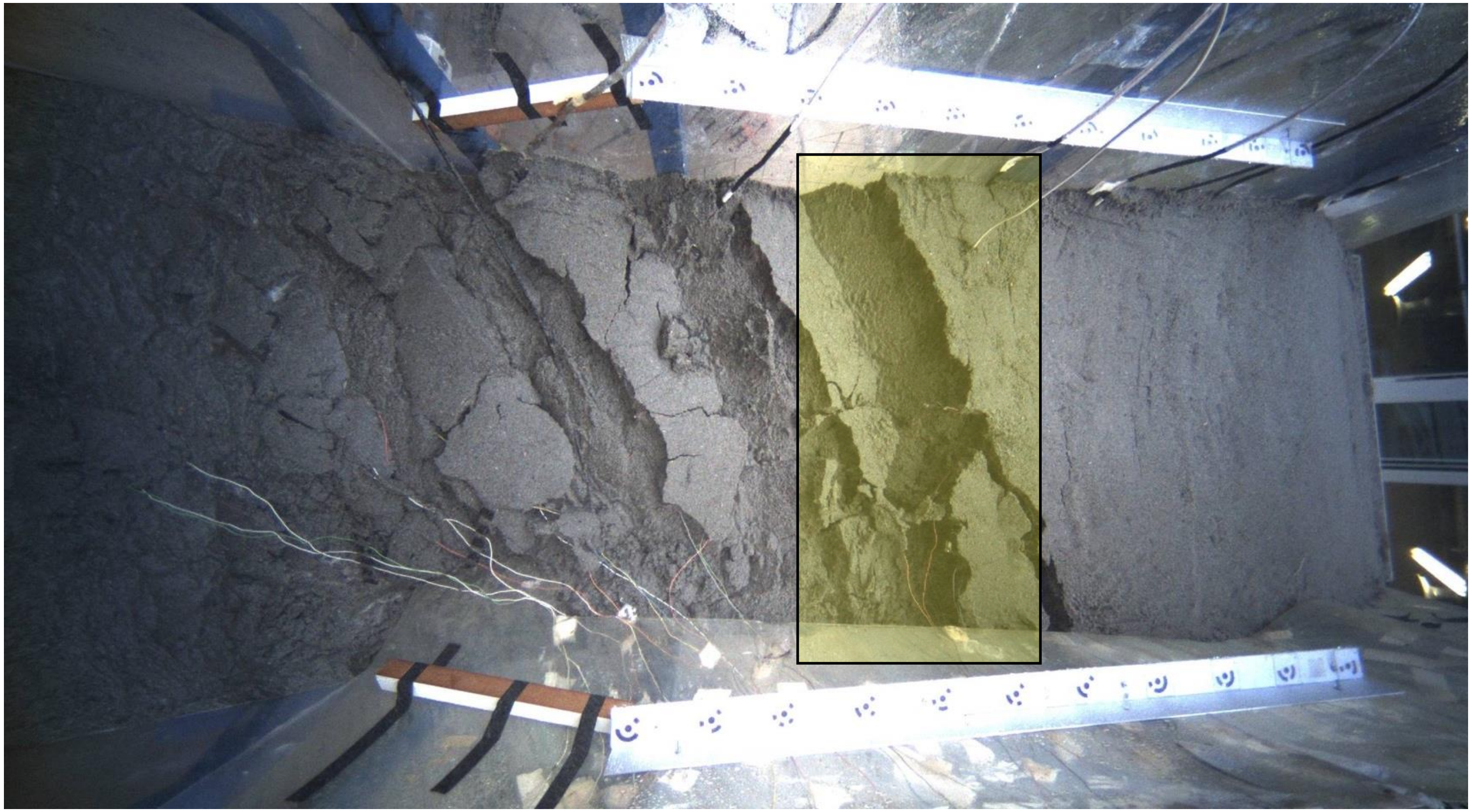
Anomaly 6, Geology



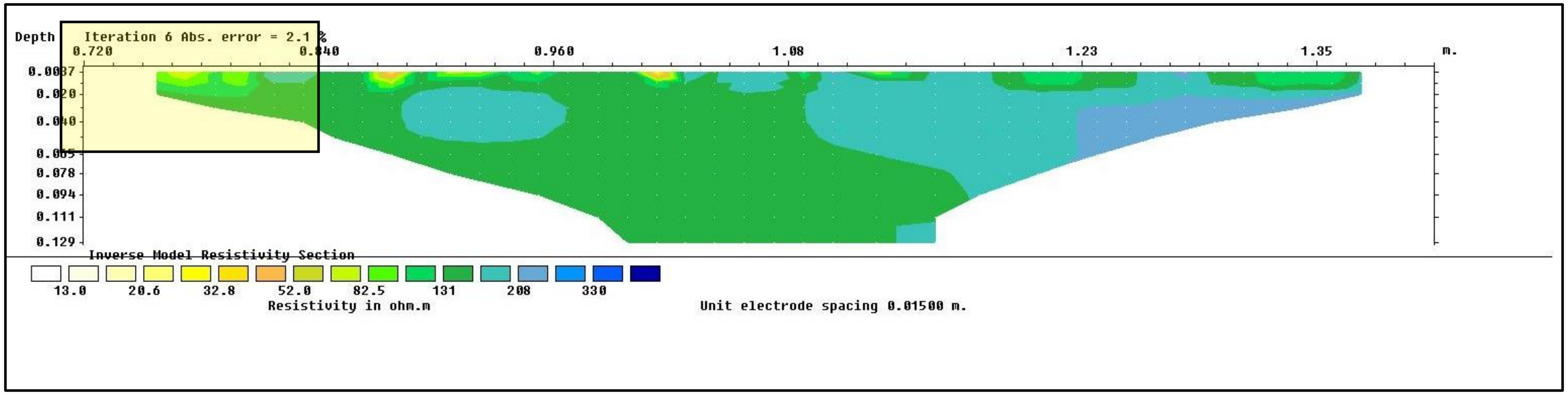
Anomaly 7, Geology

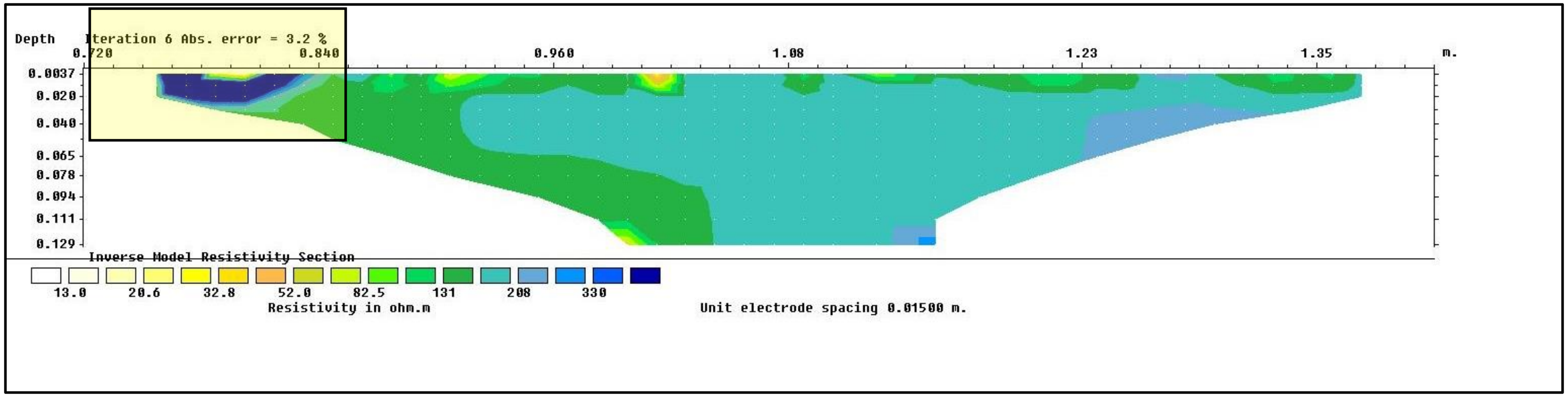


Anomaly 4, 6, & 7, Photogrammetry



Anomaly 4, 6, & 7, Geophysics



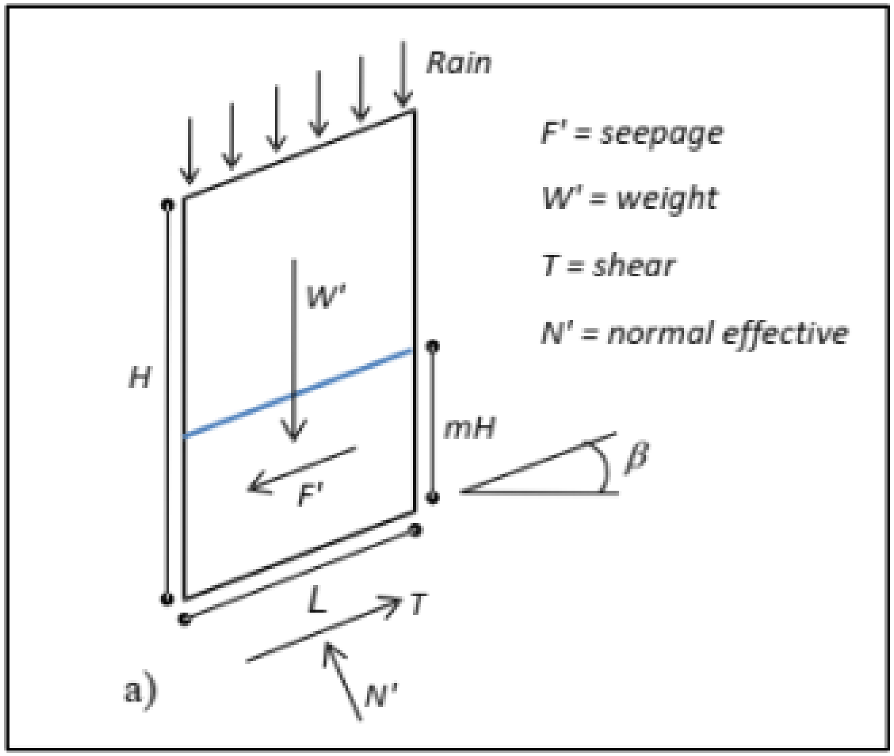


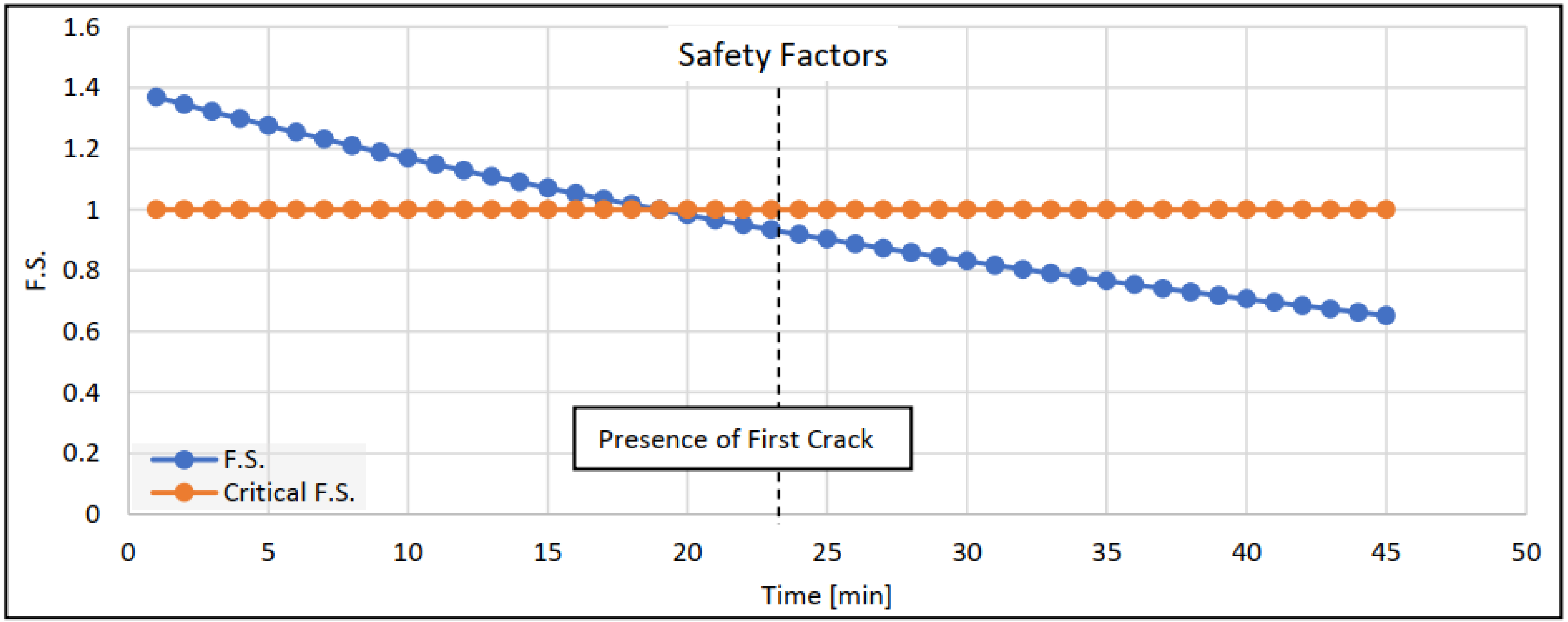
- **Statistical Models**
- **Physical Models**
- **SLIP model**
  - **Limit Equilibrium Method**
  - **2 sub-layers**

$$F_s = \frac{T_s}{T_d}$$

$$T_s = N' + tan\varphi' + C'$$

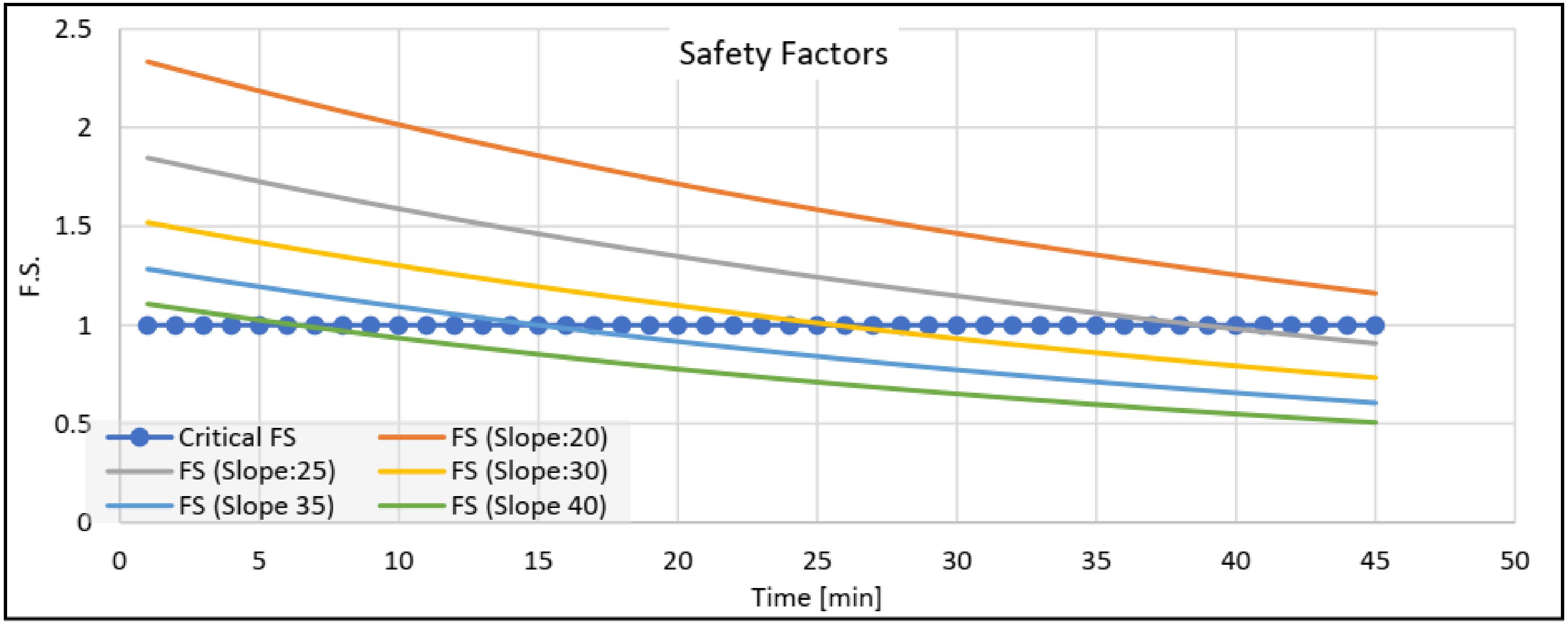
$$T_d = W'Sin\beta + F'$$



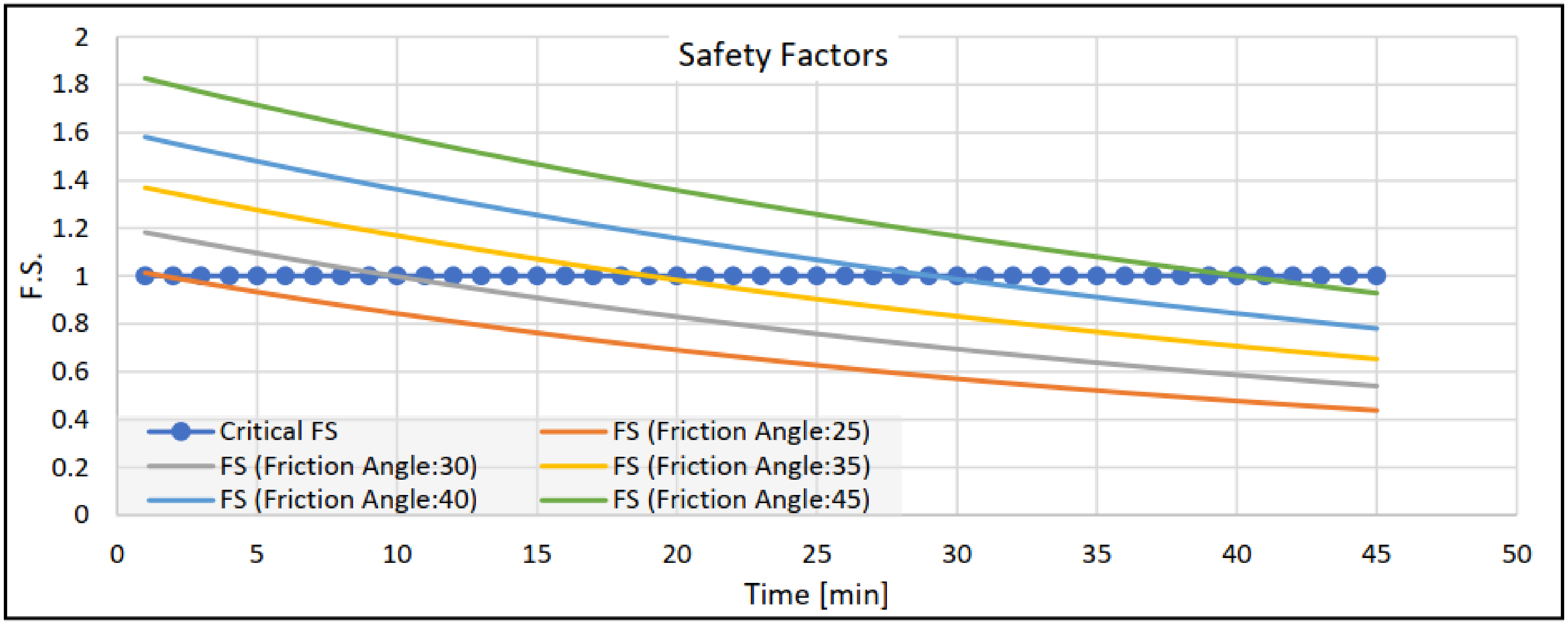


- **4-minute Inaccuracy due to Limitations**
  - **Neglecting the run-off water**
  - **Considering Uniform Layer**

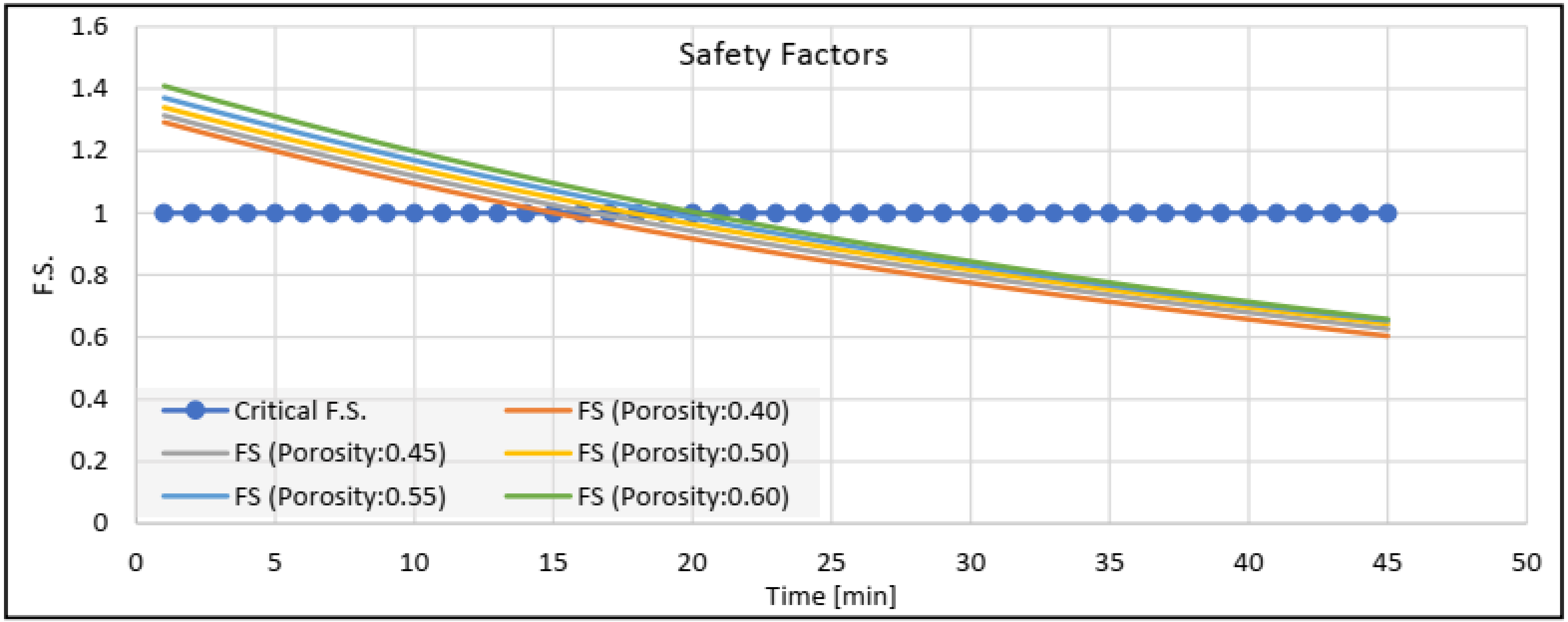
SLIP Model: Sensitivity to Slope



SLIP Model: Sensitivity to Friction Angle

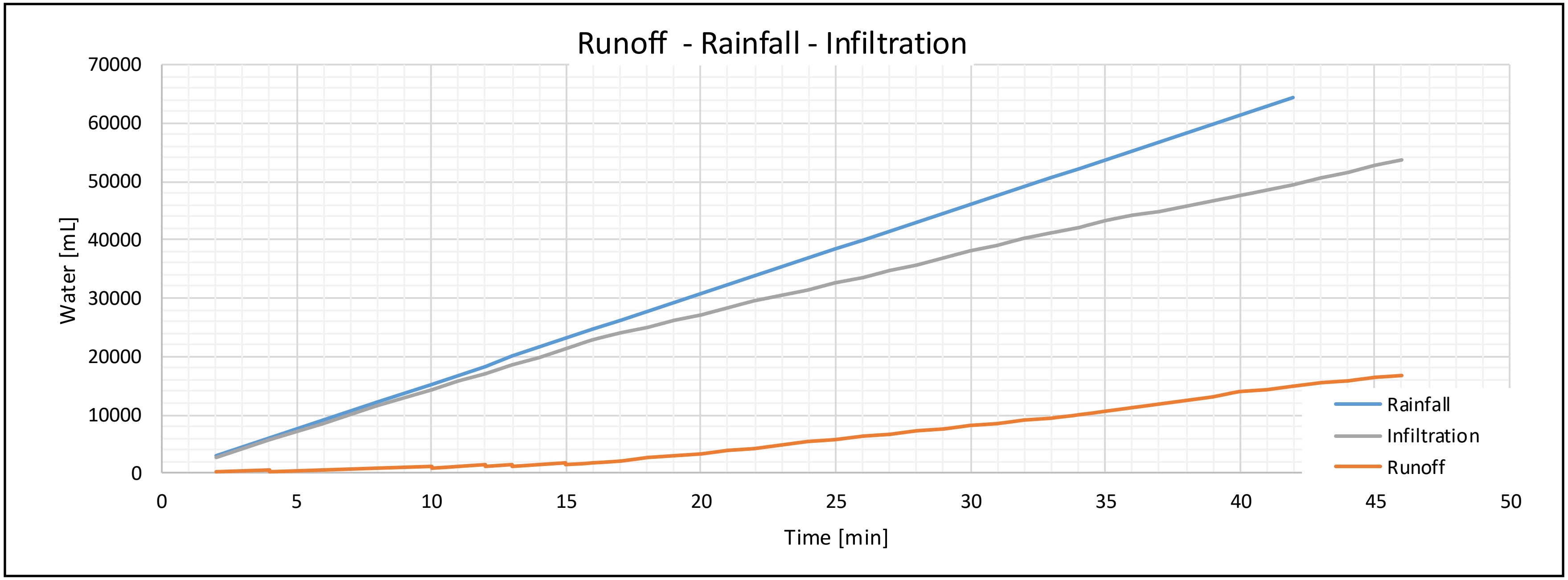


SLIP Model: Sensitivity to Porosity



SLIP Model Limitation (Run-off Water)

- **Sensitivity Analysis for Different Amounts of Run-off**
  - **75% Infiltration, 25% Run-off**
  - **Confirmed with Collected Run-off Water**



SLIP Model Limitation (Uniform Layer)

- **Default Limit Equilibrium Equation**

$$W' = cos\beta * H * \Delta s * \gamma_w[m(n-1) + cos(1-n) + nS_r(1-m)]$$

$$N' = cos^2\beta * H * \Delta s * \gamma_w[m(n-1) + cos(1-n) + nS_r(1-m)]$$

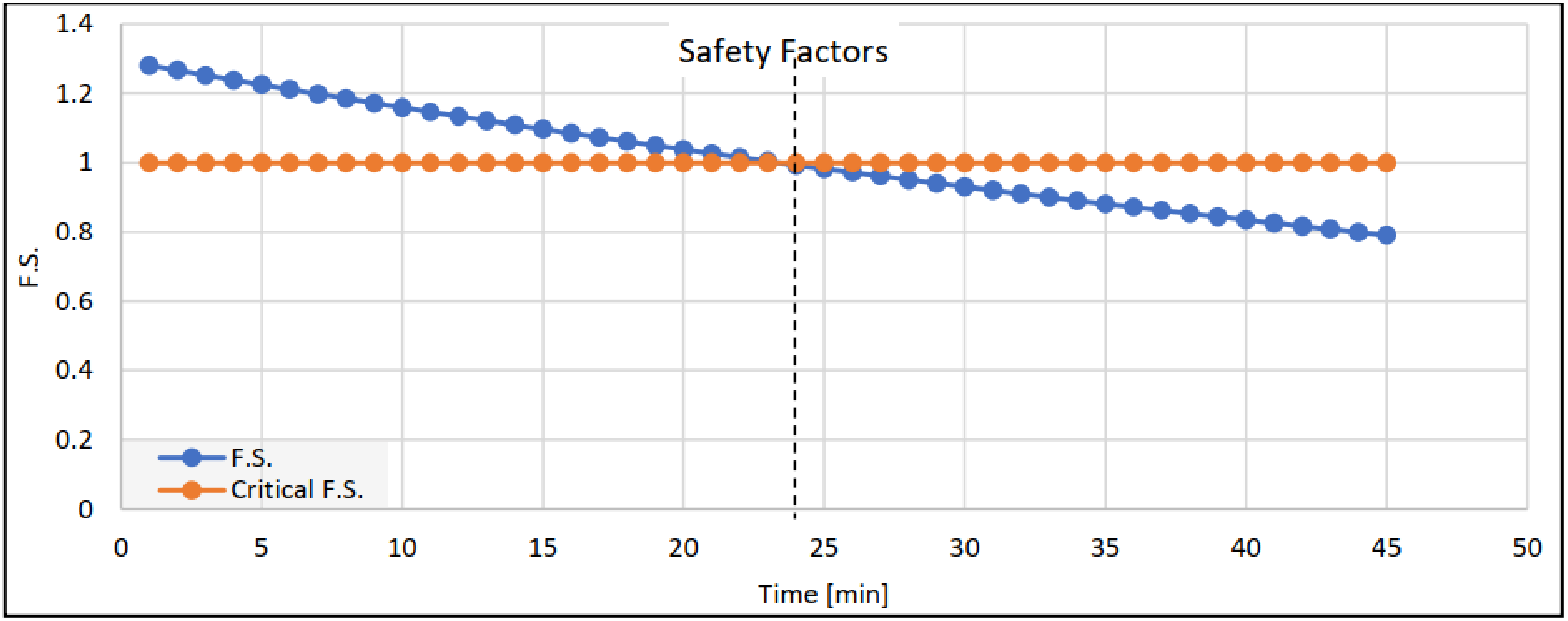
- **Modified Limit Equilibrium Equation**

$$W' = (cos\beta * 0.5 * H * \Delta s * \gamma_w[m(n-1) + cos(1-n) + nS_r(1-n)]) + (cos\beta * 0.5 * H * \Delta s * \gamma_w[m(0.85 * n - 1) + cos(1 - 0.85 * n) + 0.85 * nS_r(1-m)])$$

$$N` = (cos^2\beta * 0.5 * H * \Delta s * \gamma_w[m(n-1) + cos(1-n) + nS_r(1-n)]) +$$

$$(cos\text{^}2 * 0.5 * H * \Delta s * \gamma_w[m(0.85 * n - 1) + cos(1 - 0.85 * n) + 0.85 * nS_r(1-m)])$$

Modified SLIP Model Results

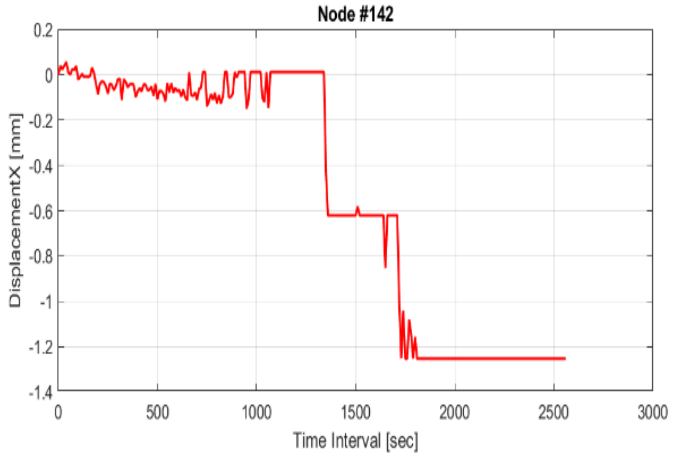


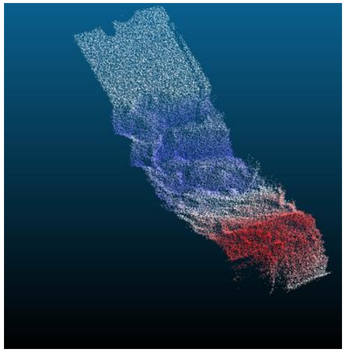
Suggestions for Better Experiment

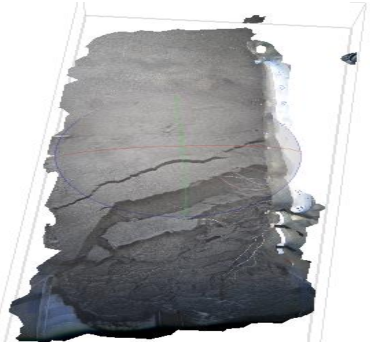
Photogrammetry

- **Definition of Photogrammetry**

- **Uses of Photogrammetry in Landslide Experiment**
  - **Spatial data of the fractures**







  - **Point cloud of the Landslide**

Techniques

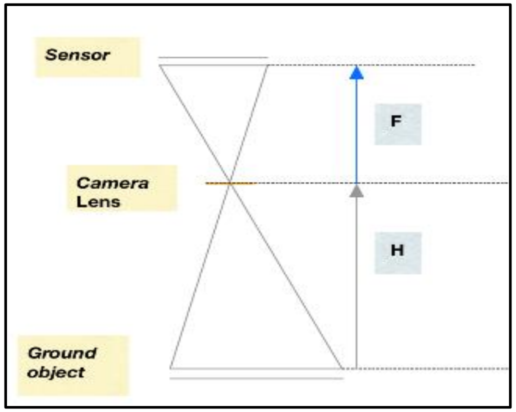
- **2-D Digital Image Correlation**

- **Structure for Motion**

- **Terrestrial Laser Scanner data**

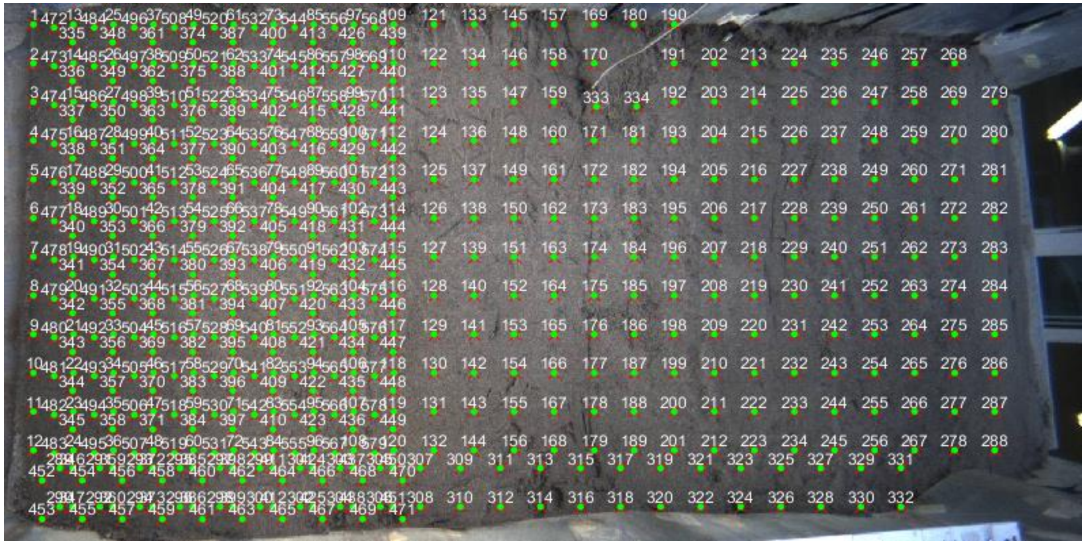
• 2D Digital Image Correlation

GSD PARAMETERS



GSD=*0.6325 [MM/PIX]*

GRID SELECTION



Experiment 1 Results

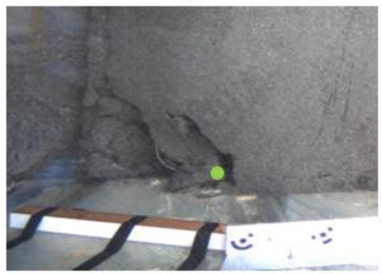
Front Camera, Fracture 1

Front Camera, Fracture 2

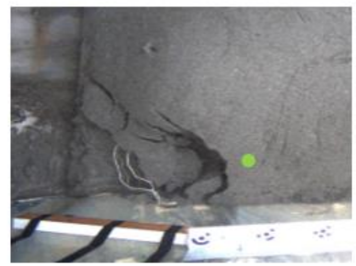
Front Camera, Fracture 3

Front Camera, Fracture 4,5,6

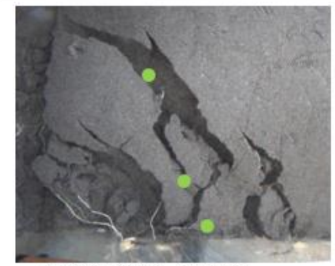
Camera 1#103, Fracture 1



Camera 1#148, Fracture 2



Camera 1#164, Fracture 3

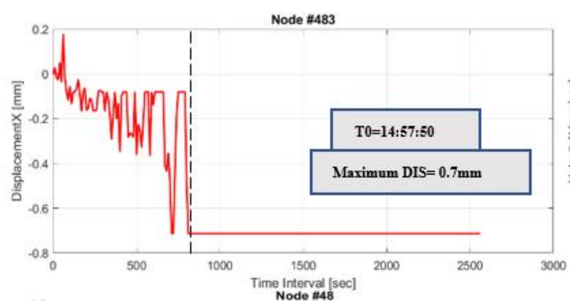


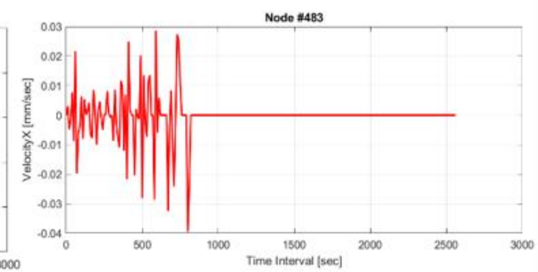
Camera 1#173, Fracture 4,5,6

Fracture 1

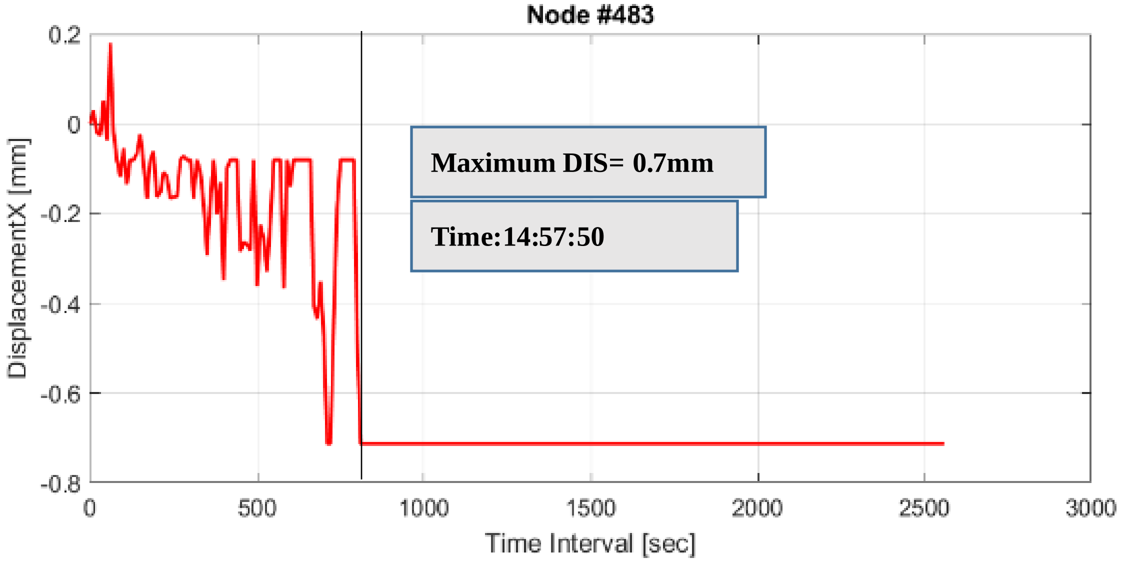
Coordinates of node 483(X=6.92, Y=9.84)

-Progressive Failure

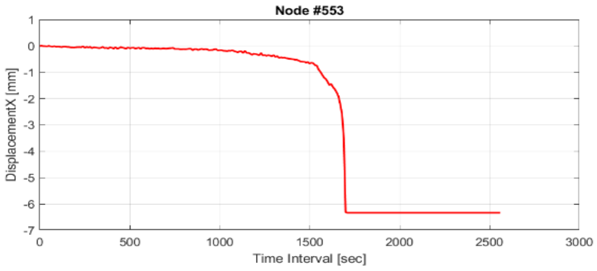




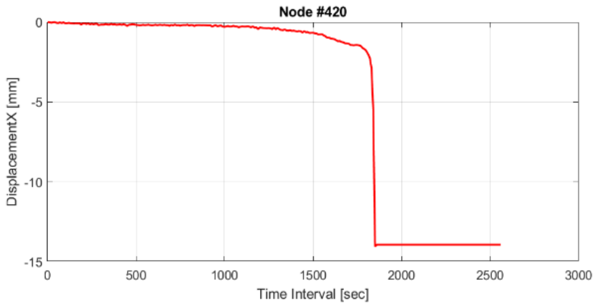
Displacement Results



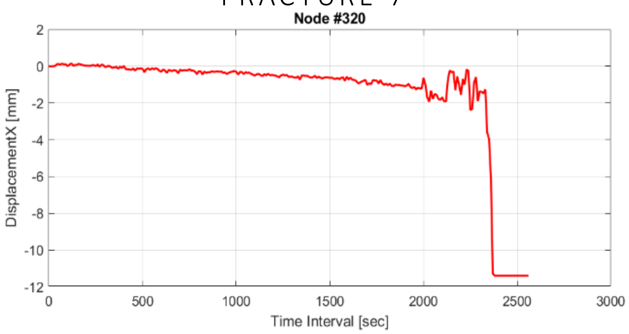
FRACTURE 1



FRACTURE 4

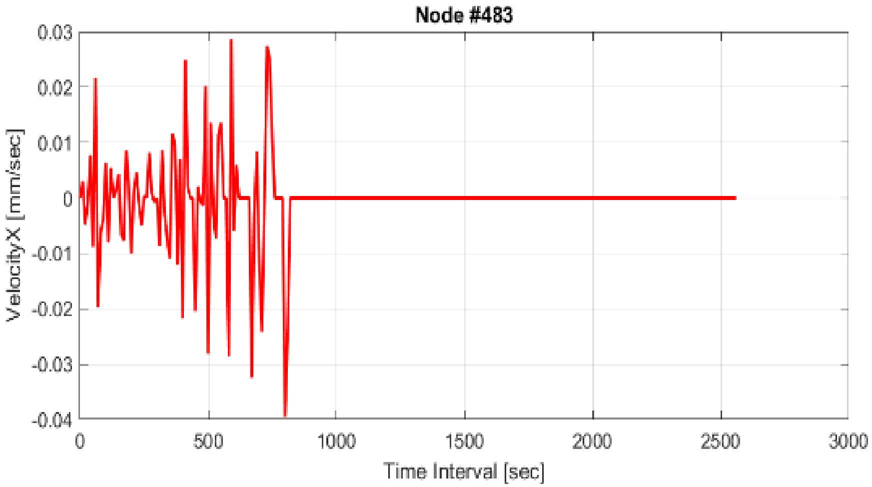


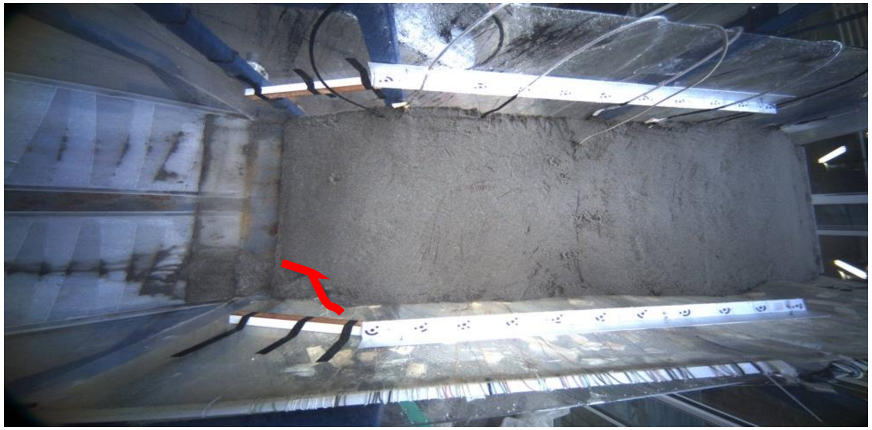
FRACTURE 7



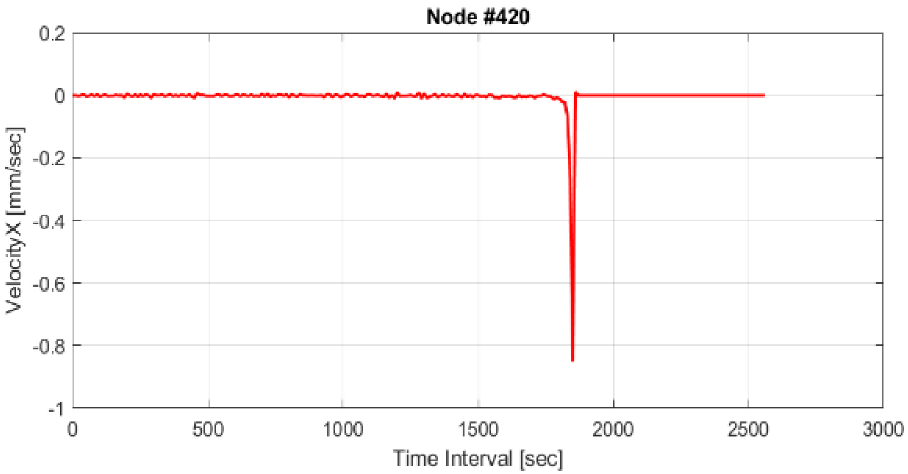
FRACTURE 13

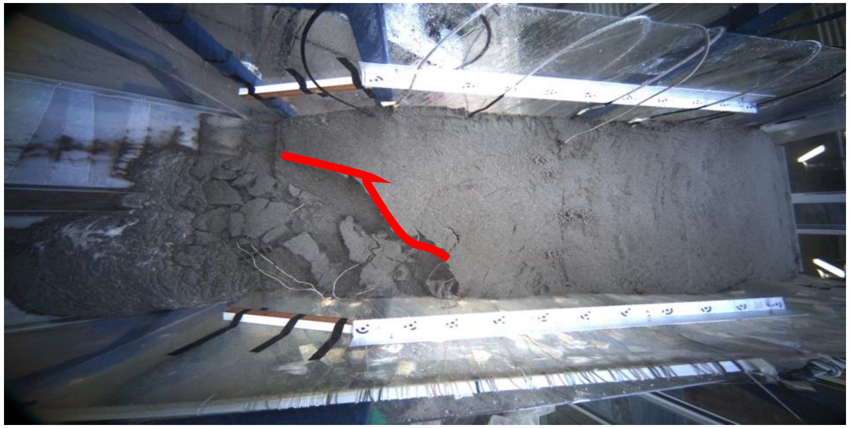
Velocity Results





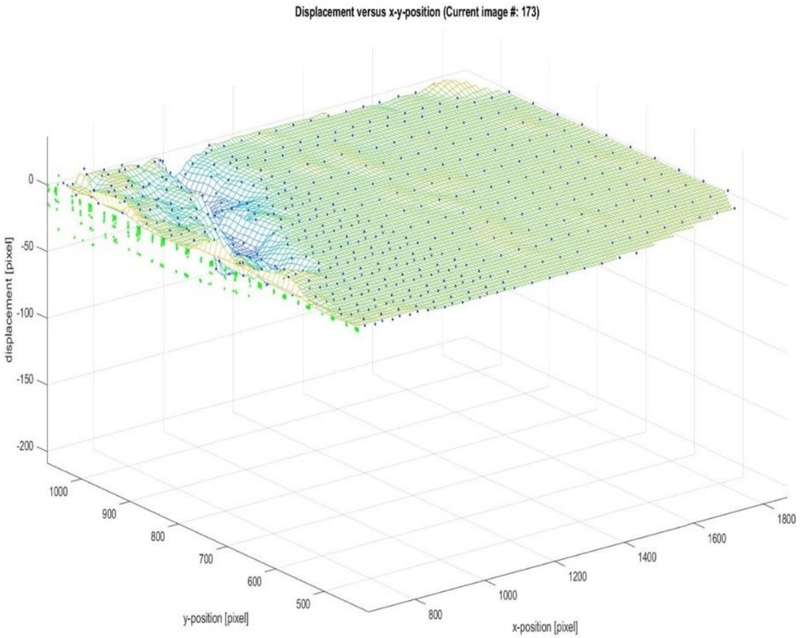
FRACTURE 1

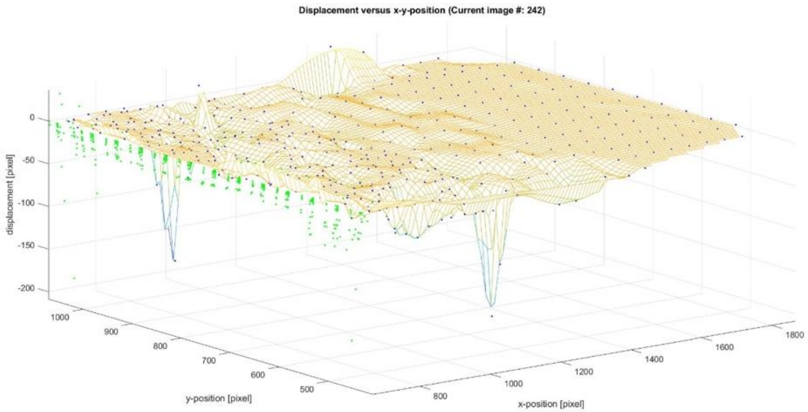




FRACTURE 7

3D Image Displacement





Failure Phases

TIME DIFFERENCE BETWEEN FRACTURE 1 AND 2

Time:14:57:50

Time:15:08:50

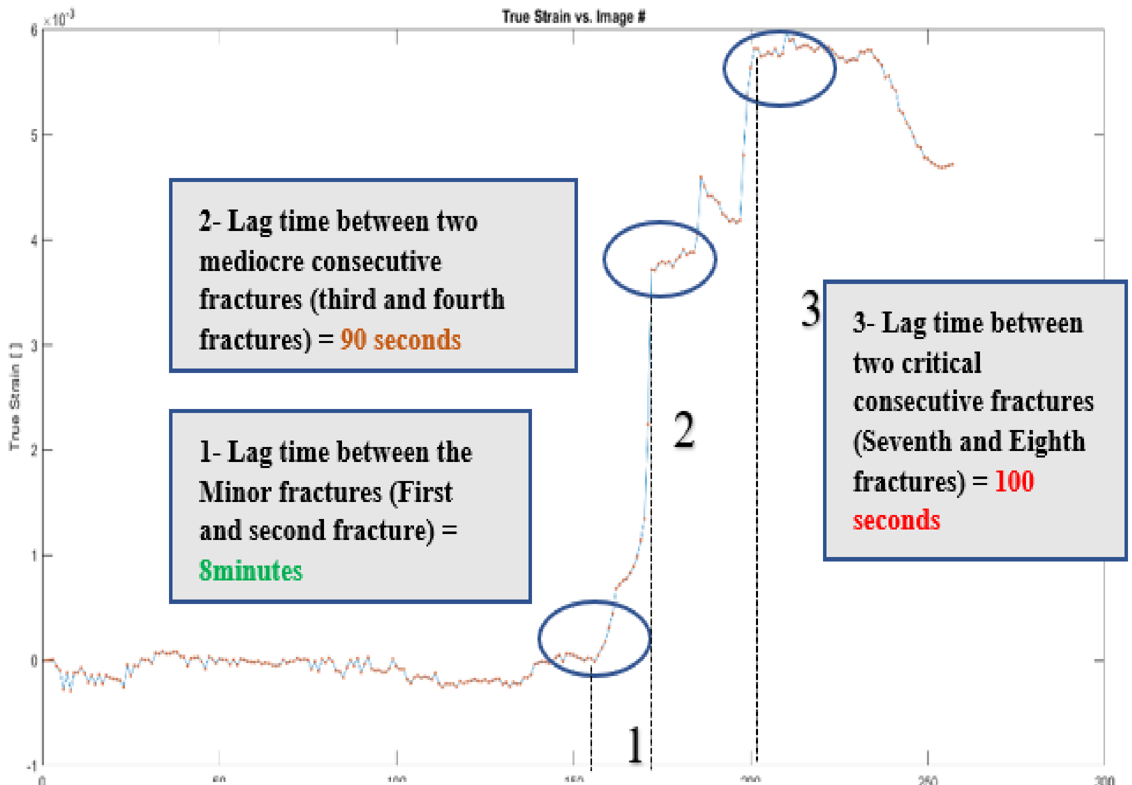
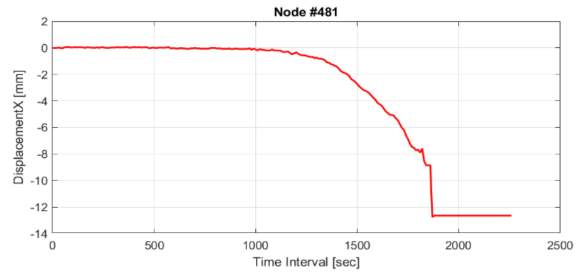
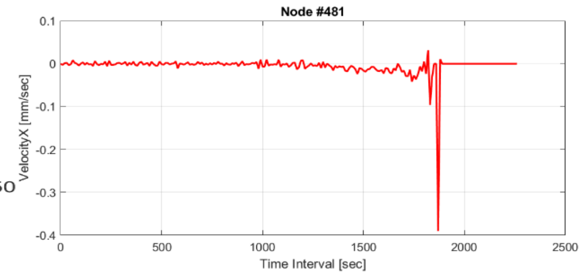


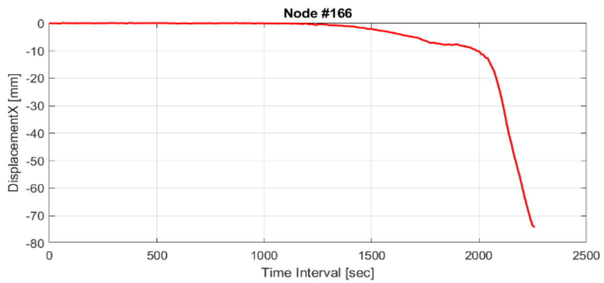
Fig.49. Exp1, True strain vs Image number

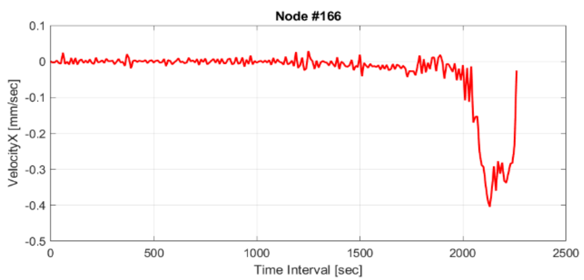
Fracture Number	Electrode Number	VWC (Geophysics)	VWC (Geology)
Fracture 2	1	0.36	0.2975
Fracture 3	3	0.45	0.3201
Fracture 4	24	0.31	0.3284

Experiment 0 vs Experiment 1









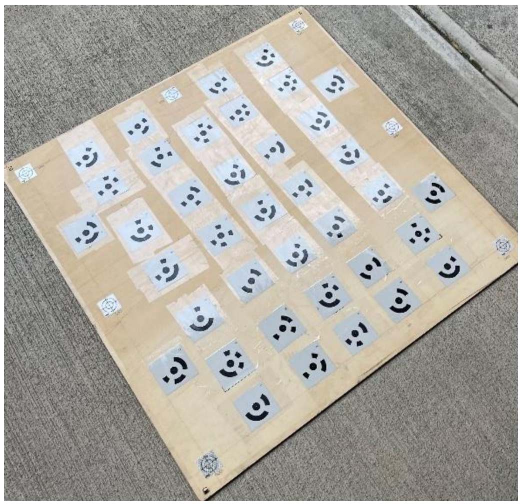
- **Experiment 0**

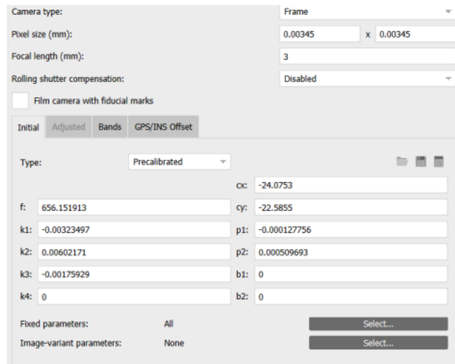
1- GRADUAL INCREASE FOLLOWED BY SUDDEN FAILURE

2- SMALL TIME DIFFERENCE BETWEEN DIFFERENT FRACTURES(MORE AGGRESSIVE)

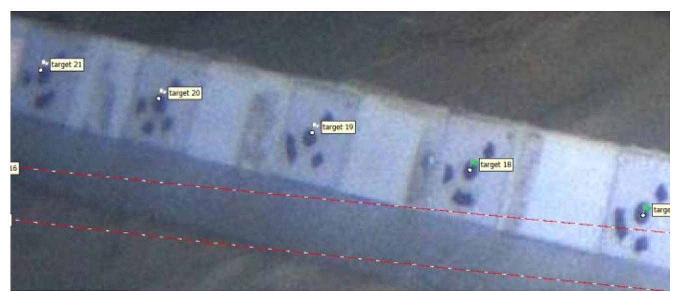
• 3D IMAGE GENERATION

• Cameras Calibration

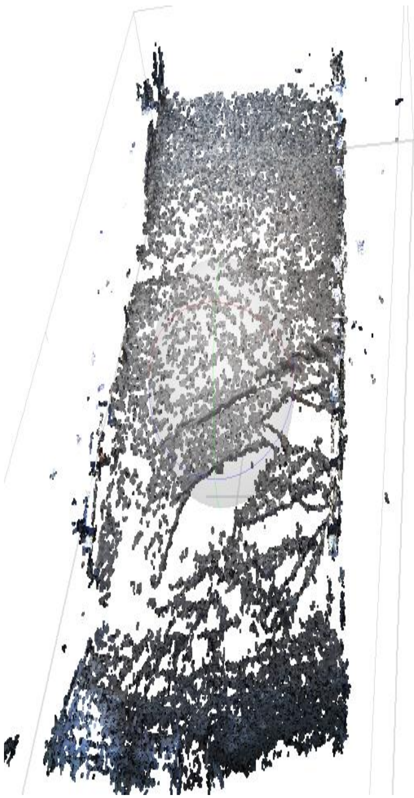


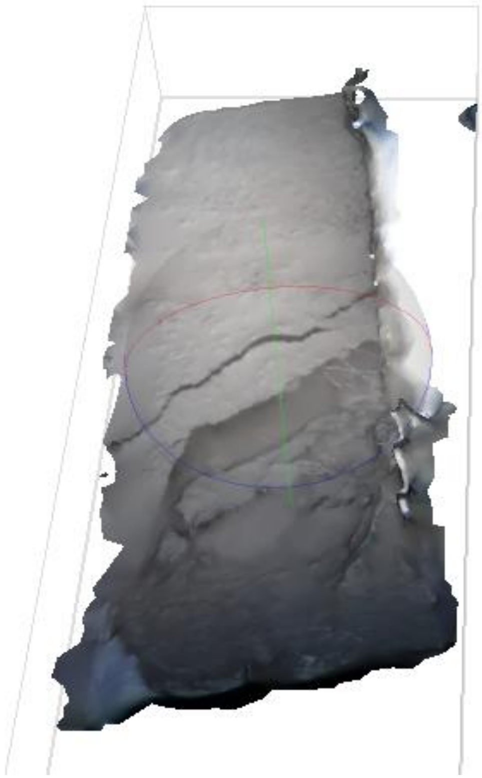


• Photo Alignments



3D Image for Fracture 8





Orthophotos for Fracture 7

- **Orthophotos**

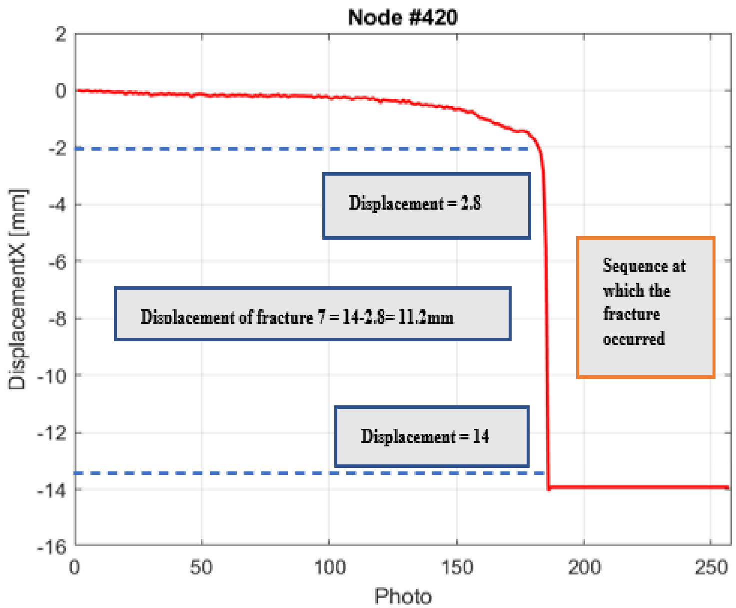
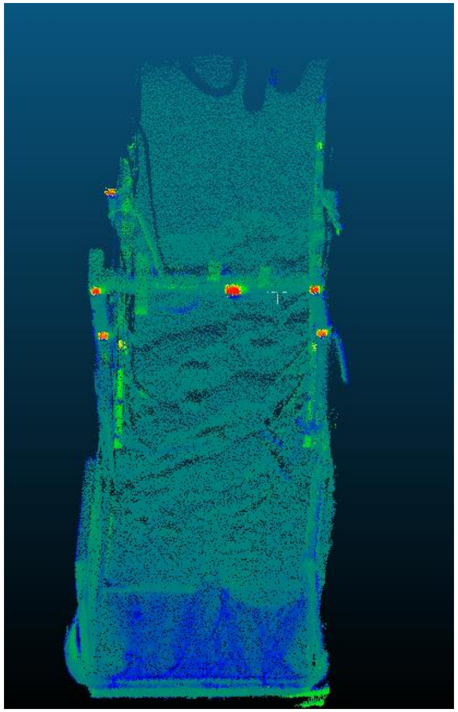


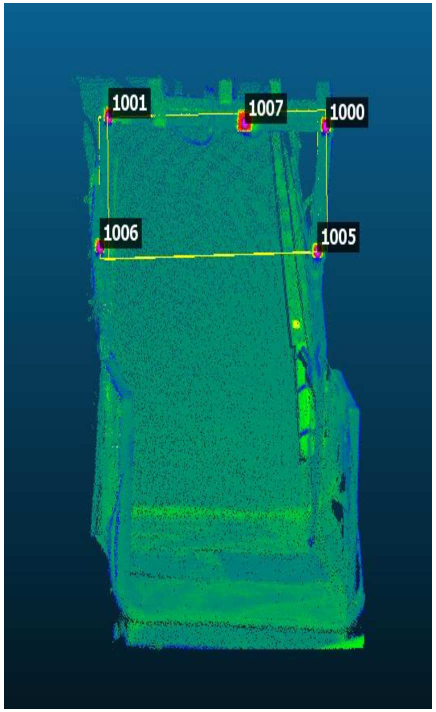
Fig.73. Displacement as measured for fracture 7 from 2D DIC

Laser Scanner Data

- **Filtering**

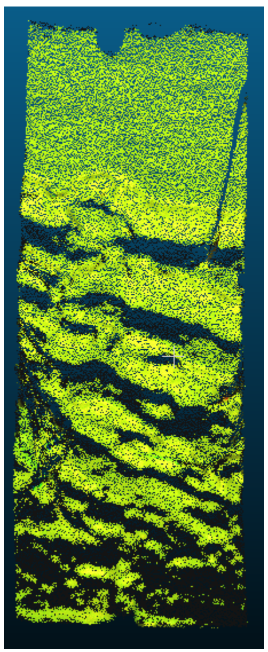


- **Geo-referencing**

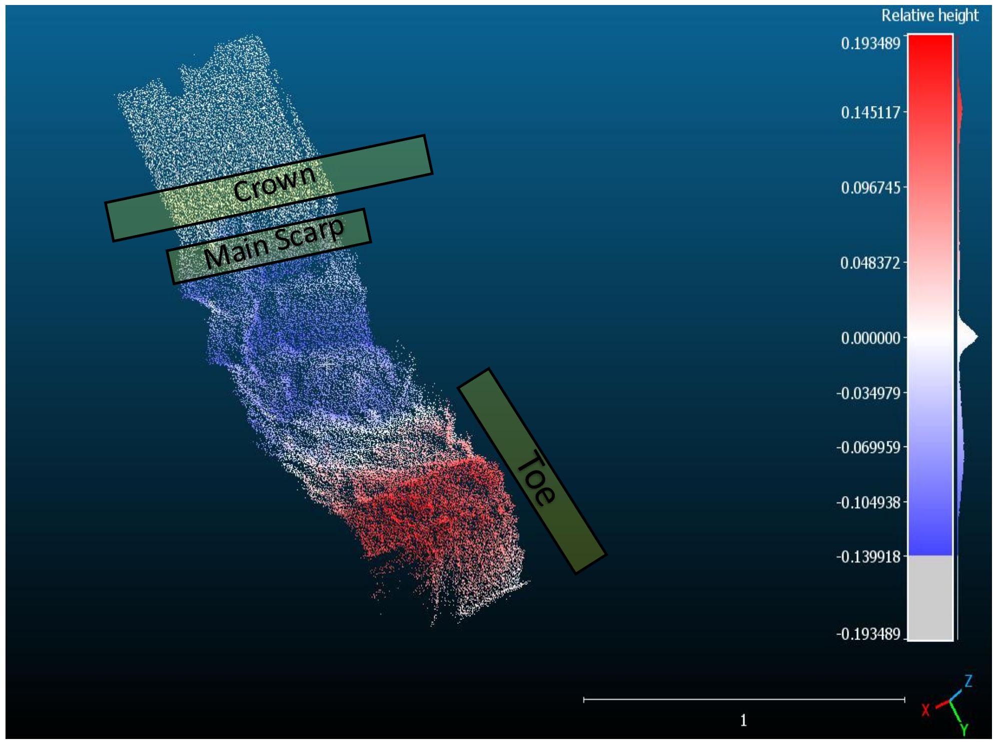


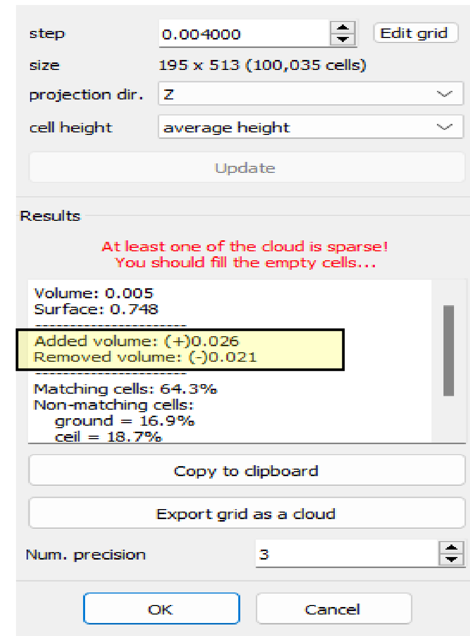
Volume Computation

- **Normal Vectors**

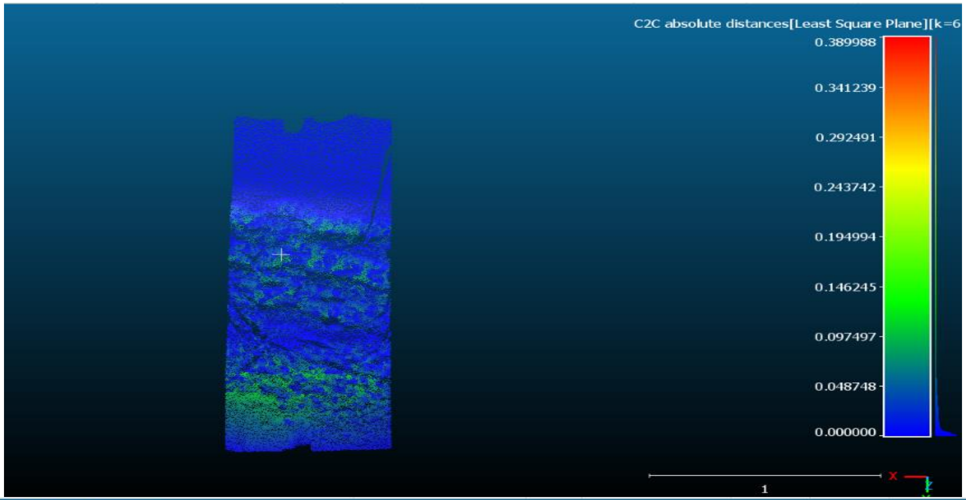


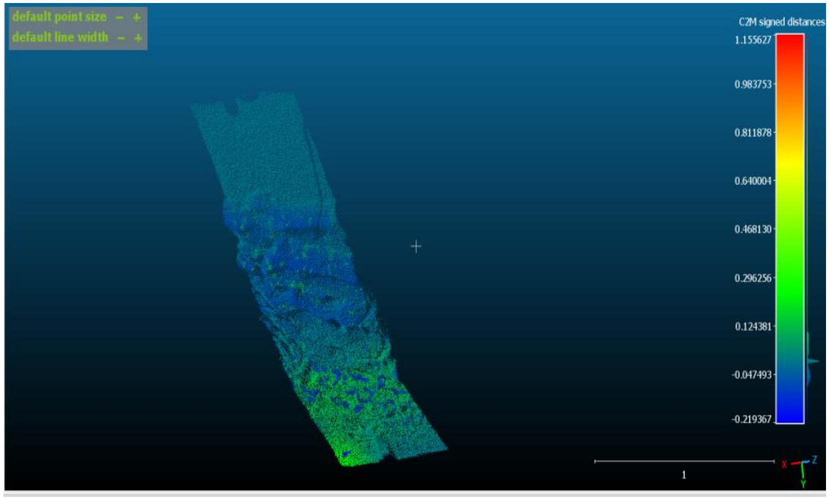
- **Volume Computation**

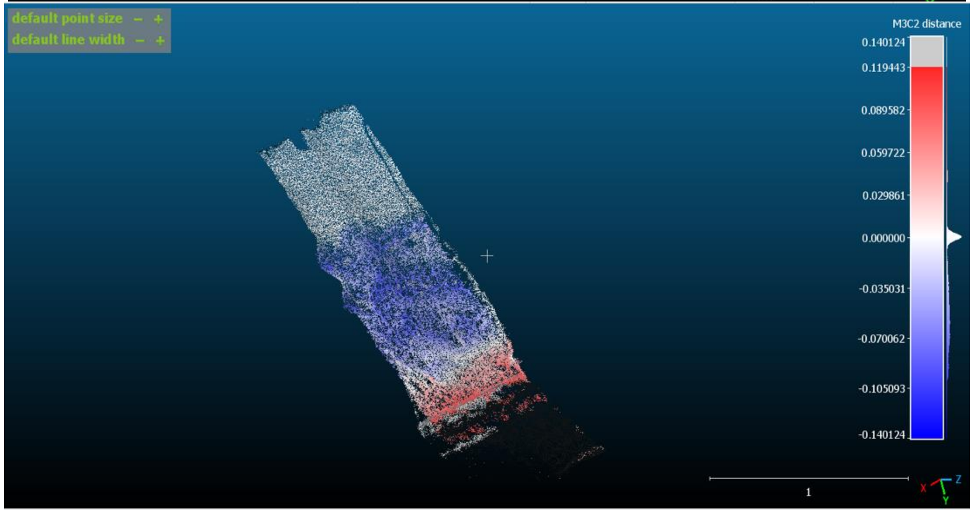




Distance Difference Computation

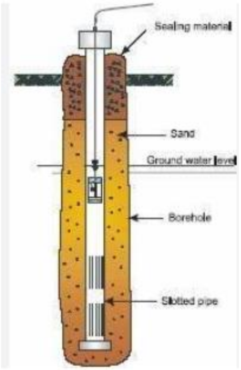






Early Warning System

Fracture Number	Electrode Number	VWC (Geophysics)	VWC (Geology)
Fracture 2	1	0.36	0.2975
Fracture 3	3	0.45	0.3201
Fracture 4	24	0.31	0.3284



VWV: 0.18

4 minutes in between

Lead Time: 5 Minutes before minor fractures

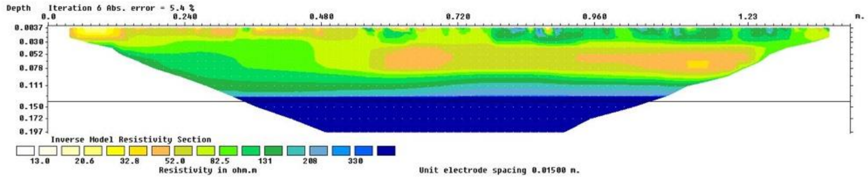
Lead Time: 9 Minutes before the more medicore fractures

Geophysics

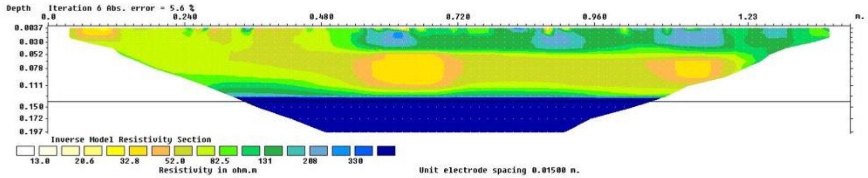
- DC resistivity method
- Electrical Resistivity Tomography(ERT)
- Wenner array

Resistivity Model in Experiment 1

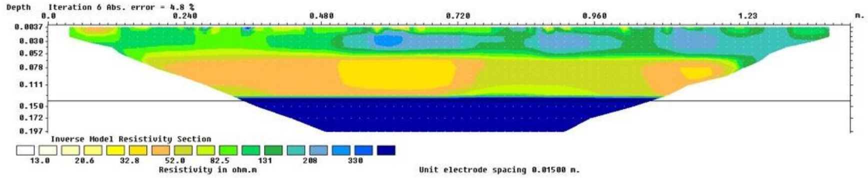
T2 at 6 min



T3 at 11 min



T4 at 17 min



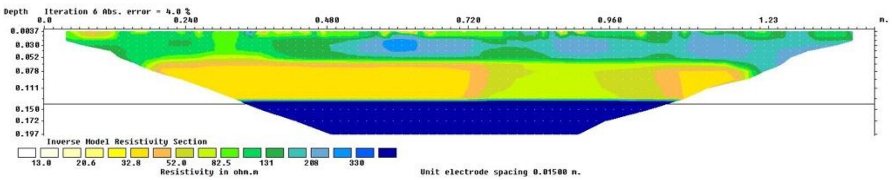
Phenomenon:

1.whole slope resistivity of soil is **decreasing**, especially the toe of the slope

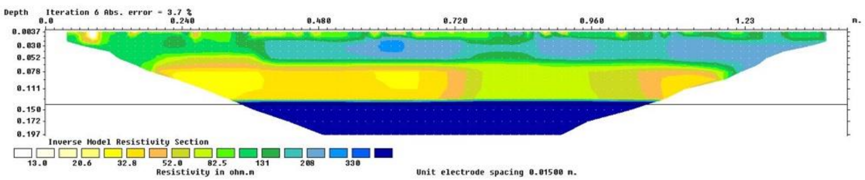
2.the decrease in soil resistivity **wasn’t in a smooth trend.**

Analysis for Resistivity Model of Software

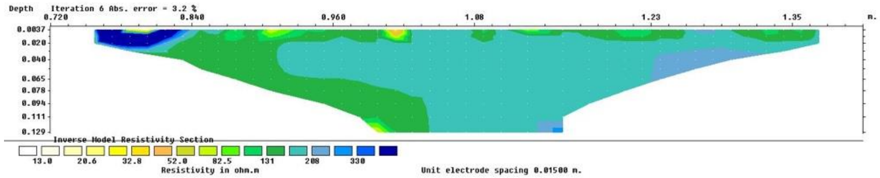
T5 at 22 min



T6 at 27 min



T10 at 39 min



Phenomenon：

1.the soil resistivity began to **increase in the crown part** meanwhile the **toe part kept decreasing.**

2.in the increasing part, the resistivity is still **smaller than 200Ωm**, we cannot consider it as the real crack but only the zones of different saturation.

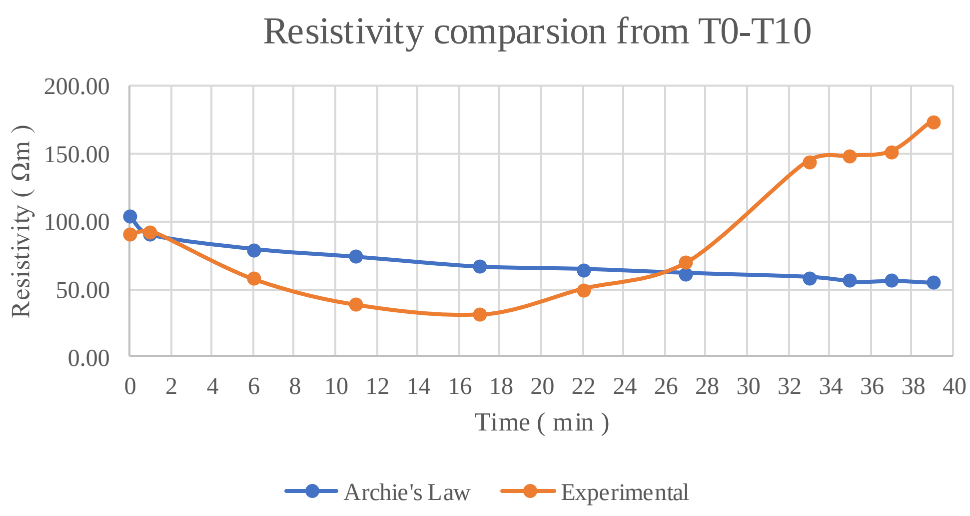
Mathematical Resistivity Model

-Archie's Law

$$\rho = F\, S_w^{-n} \rho_w$$

we can get the calibrated values for a, m, n:

a	m	n
0.5	1.3	1.2



relative difference is quite high.

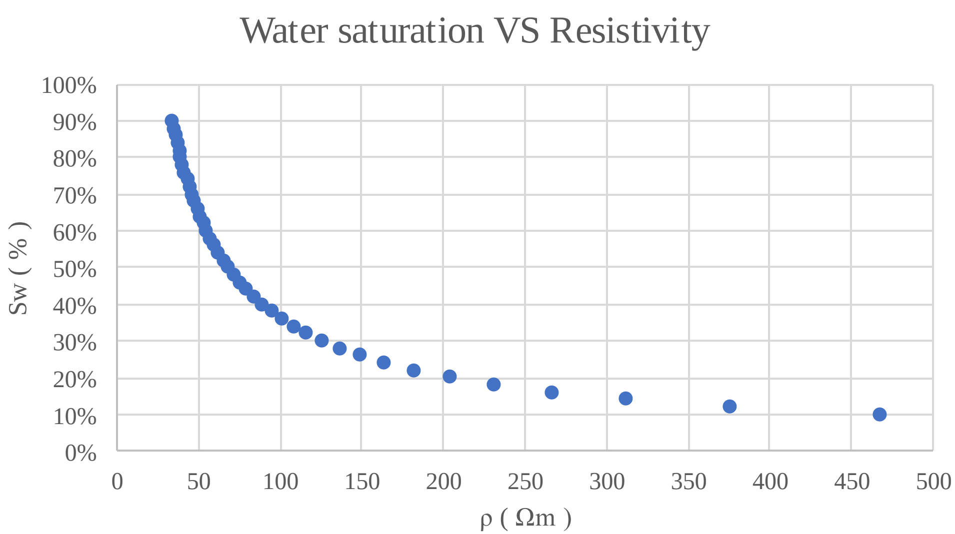
Why?

1. not uniformly compacted soil
2. the flaws that happened in this experiment is that the crack position is too far from electrodes.
3. during the experiment, the time when we tested the resistivity from the electrodes is not completely accurate compared with the time measuring porosity and volumetric water content for geology parts. Because the parts is operated by different people.

Water Saturation vs. Resistivity

As a result, we developed the following equation to obtain the water saturation of the landslide body from inverted resistivity data :

$$S_w = \left(\frac{29.43}{\rho}\right)^{0.83}$$



dry sand to the water saturation of about 30%-40%, the resistivity values **rapidly decrease** from 500Ωm to 100Ωm approximately .

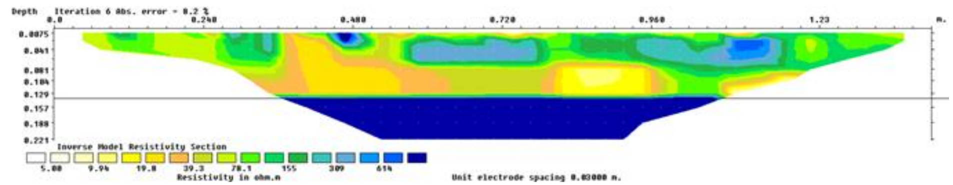
when water saturation beyond about 40%, the resistivity **decreases softly and gently**.

Until the soil is almost **full of water**, the **resistivity is getting closer to zero.**

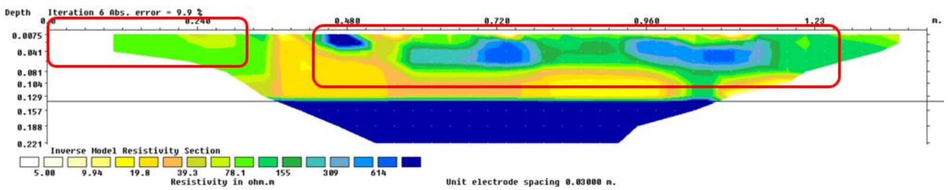
From the graph we can easily observe that **resistivity is always decrease while the water saturation increasing**, but the relationship between the two isn't linear.

Resistivity Model in Experiment 0

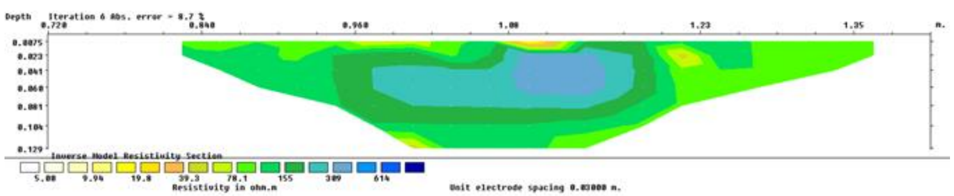
T5 at 28 min

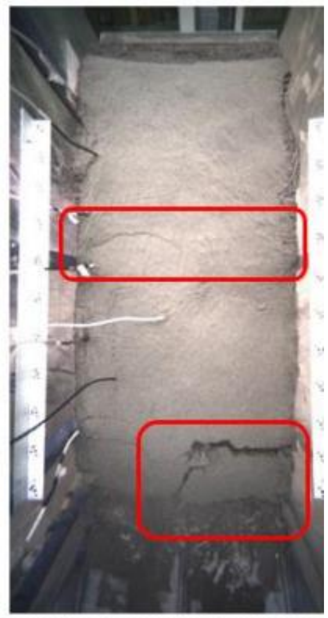


T6 at 33 min



T7 at 38 min





T6

Phenomenon:

other parts resisitivity is decreasing ,while in T6 we can easily find that resistivity is increasing and over 200Ωm

To conclude, it's obvious that the results obtained from geology, photogrammetry and geophysics were supplementary to each other.

Figure 3. Family 2

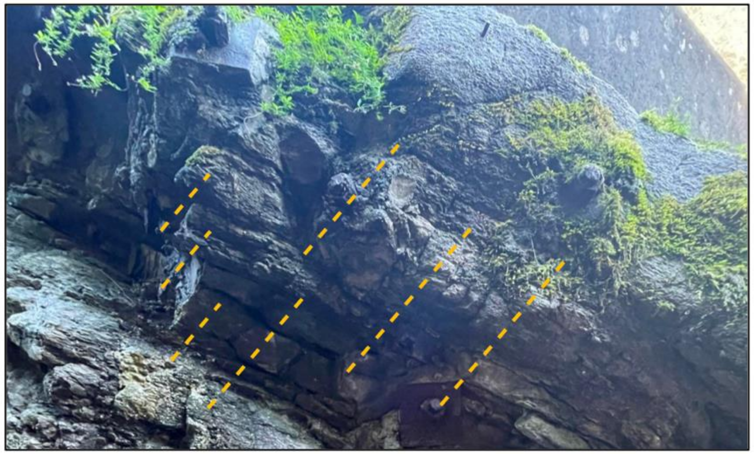


Figure 4. Family 3

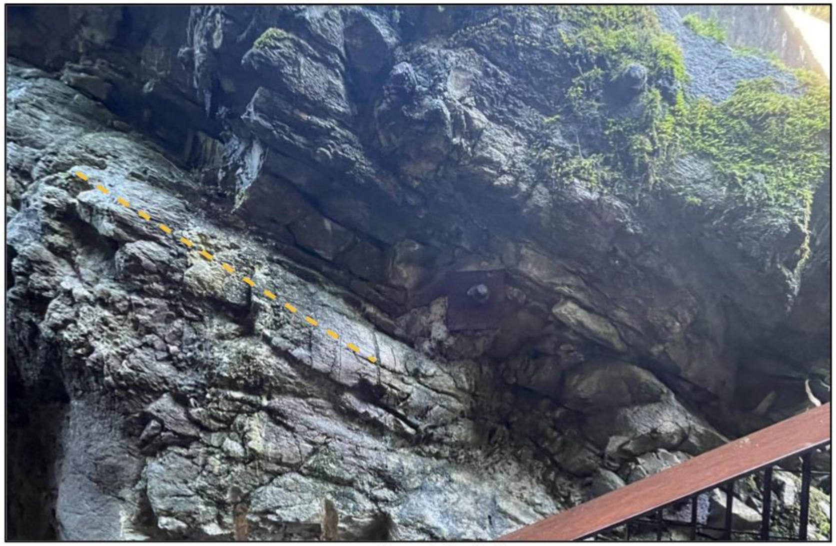
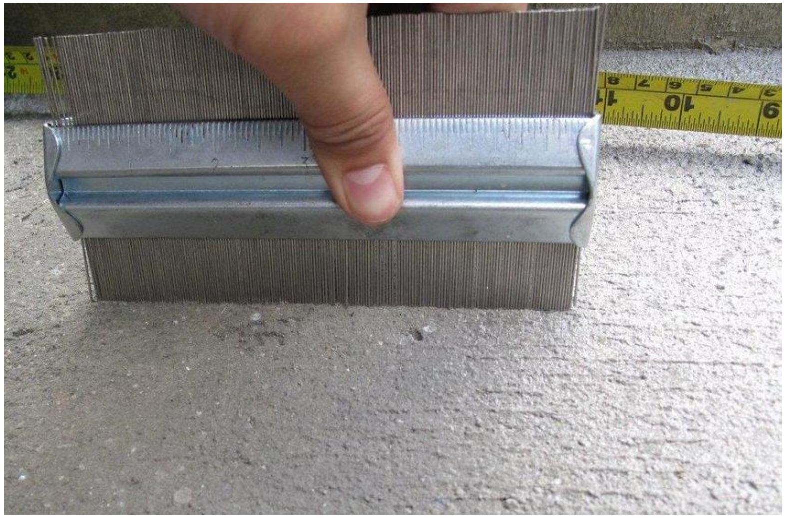
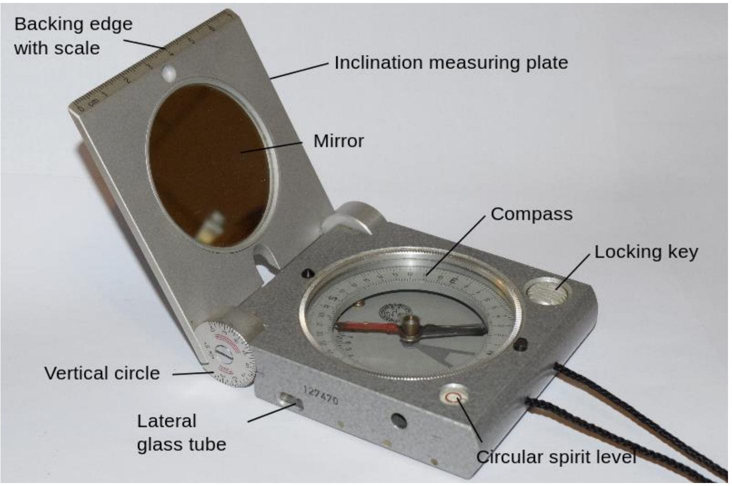


Figure 2. Family 1


proceq
50 years of know-how you can measure




Backing edge
with scale
Inclination measuring plate
Mirror
Compass
Locking key
Vertical circle
Lateral
glass tube
Circular spirit level


FieldMove Clino
Project 1
55° 51' 46" N, -4° 15' 17" W
285°
Fold Axis
Locality 1
Add rock unit
Petroleum Experts

Rockmass Characterizations

- Joint Orientation and Data Processing
- Joint Spacing
- Intercept
- Water presence
- Infill
- Persistence
- Weathering
- Estimation of the Joint Roughness Coefficient (JRC).
- Joint Compressive Strength (JCS)
- Rock Quality Designation (RQD)
- Aperture

Aperture

Aperture is the perpendicular distance separating the adjacent rock walls of an open discontinuity, in which the intervening space is air or water filled. A classification of aperture is shown in table [5.]. Moreover, the measure of aperture between discontinuities of all 3 families demonstrate very wide or open as it shown in the table [6.].

Table 1. Classification of the separation of joints (ISRM, 1978).
Table 2. Aperture of joint sets

Term	Separation
Very tight	<0.1 mm
Tight	0.1 – 0.5 mm
Moderately	0.5 – 2.5 mm
Open	2.5 – 10 mm
Very open	10 – 25 mm
Wide	>10 mm
Very wide	1 – 10 cm
Extremely wide	10 – 100 cm
Cavernous	>1 m

Joint set	Aperture	Classification
K1	<1 mm	Very tight
K2	<1 mm	Very tight
K3	<1 mm	Very tight

Joint Families

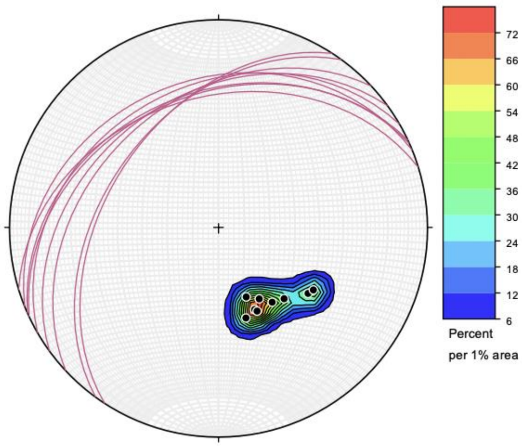


Figure 9. Family 1

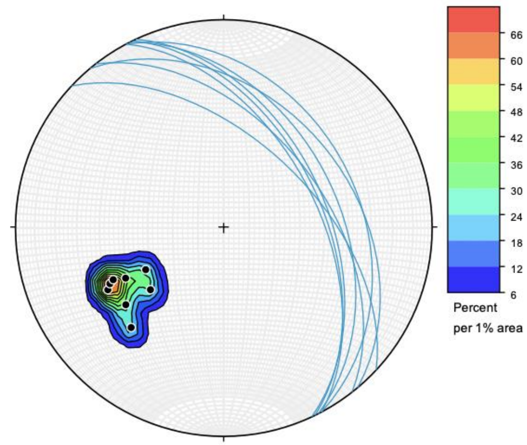


Figure 10. Family 2

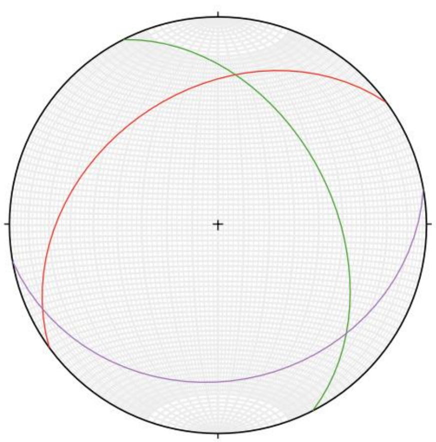


Figure 12. Family Mean Vector

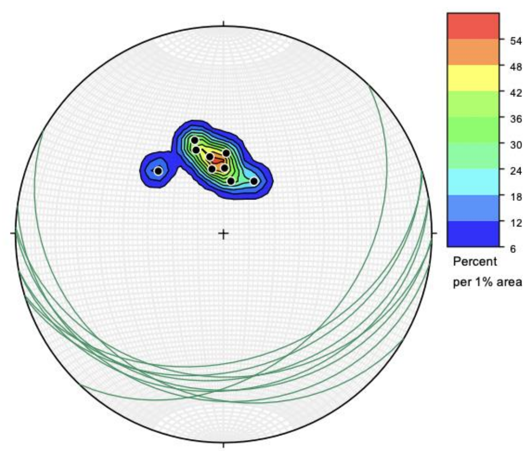


Figure 11. Family 3

Kinematic analysis: Circular and Planar Failure

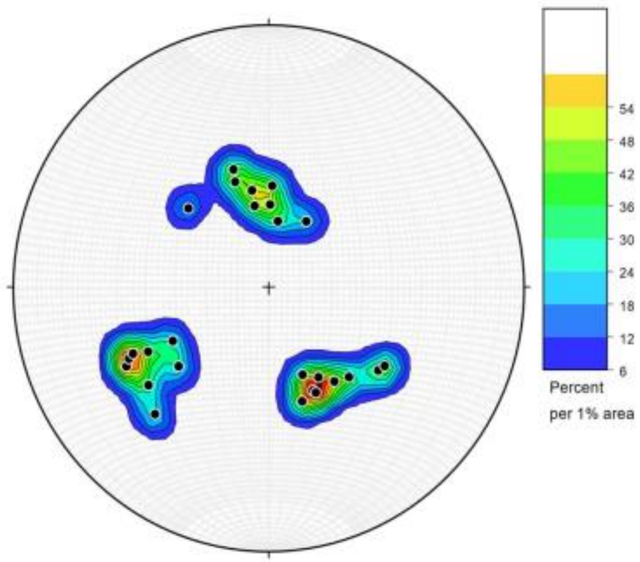


Figure 18. Poles of All Joint Sets

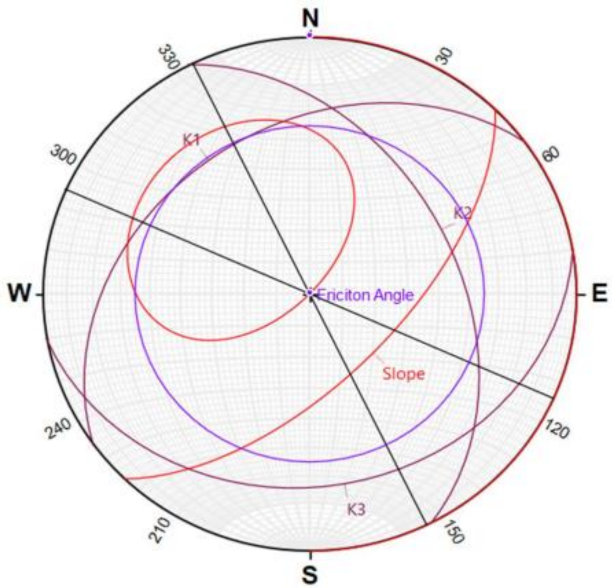


Figure 19. Mean orientation of joint sets, slope and friction angle in Stereonet

K1	36	324
K2	44	63
K3	26	170
slope	63	134
Friction angle	35	

Planar failure	K1	K2	K3
Condition 1	yes	yes	yes
Condition 2	no	no	no
Condition 3	yes	yes	no
Condition 4	yes	no	no

Kinematic analysis: wedge failure and Toppling

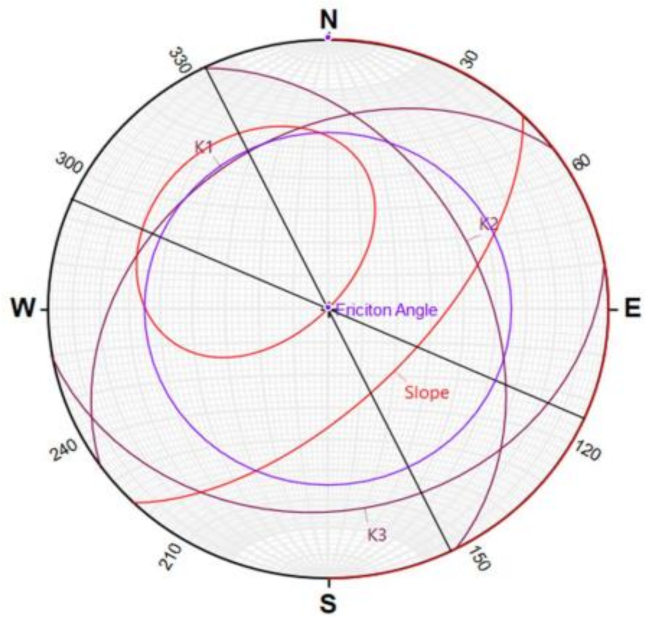


Figure 19. Mean orientation of joint sets, slope and friction angle in Stereonet

Wedge failure	K1 & K2	K2 & K3	K1 & K3
Intersection line/ dip	29	21	8
Condition 1	yes	yes	yes
Condition 2	no	no	no
Condition 3	no	no	no

Toppling	K1	K2	K3
Condition 1	no	no	no
Condition 2	no	yes	no

Block volume estimation

Persistence Reduction:

$$V\,b = \frac{S1 \times S2 \times S3}{sin\gamma1 \times sin\gamma2 \times sin\gamma3 \sqrt{p1 \times p2 \times p3}}$$

$$V\,b\text{ average} = \frac{S1 \times S2 \times S3}{sin\gamma \times sin\gamma2 \times sin\gamma3}$$ → V b = 756,898 cm3 ~ 0.757 dm3

V b = 5.236,36 cm3 ~ 0.0052 dm3

$$V\,b\text{ Minimum} = \frac{S1 \times S2 \times S3}{sin\gamma1 \times sin\gamma \times sin\gamma3}$$ → V b = 61 cm3 ~ 0.06 dm3

V b = 436,36 cm3 ~ 0.436 dm3

$$V\,b\text{ Maximum} = \frac{S1 \times S2 \times S3}{sin\gamma \times sin\gamma2 \times sin\gamma}$$ → V b = 3932 cm3 ~ 3.932 dm3

V b = 27.927 cm3 ~ 0.027 dm3

Rock volume categorization	
Very small	$V_b = 10 – 200\ cm^3$
Small	$V_b = 0.2– 10\ dm^3$
Moderate	$V_b = 10\text{-}200\ dm^3$
Large	$V_b = 0.2 – 10\ m^3$
Very large	$V_b > 10\ m^3$

Table 22. Classification of block volume suggested by Palmstrom (1995)

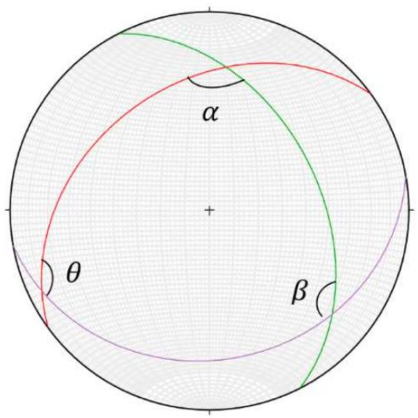


Figure 20. Representation of angles between discontinuities

Safety distance evaluation of rockfall

$$Ra = 9.98\ Vb^{0.33}$$

We have considered the safety distance for three block volume:

Size	Volume (cm3)	Safety distance (Ra) (cm)
Average	759.89	88.9
Minimum	61	38.72
Maximum	3932	153

Table 23. Safety Distance of Blocks

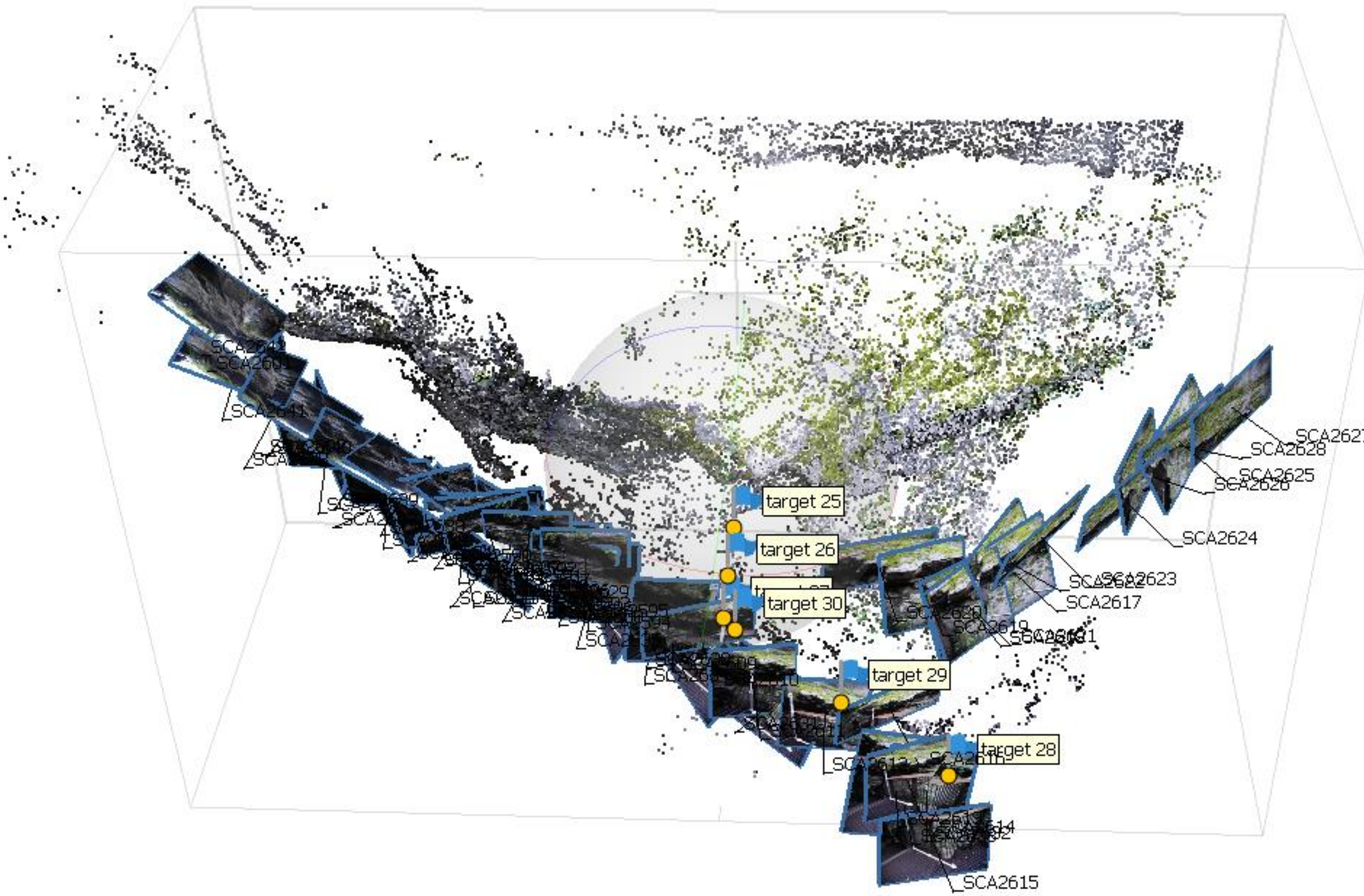
Additionally, we have calculated the X distance (the reachable distance of the block from the position of its detachment) for the three values of the Vb, while considering an assumption of an average height of 1m for the elevation of the rock.

$$Log\ (x) = Log\ (H) - 0.664 + 0.1529\ Log\ (V)$$

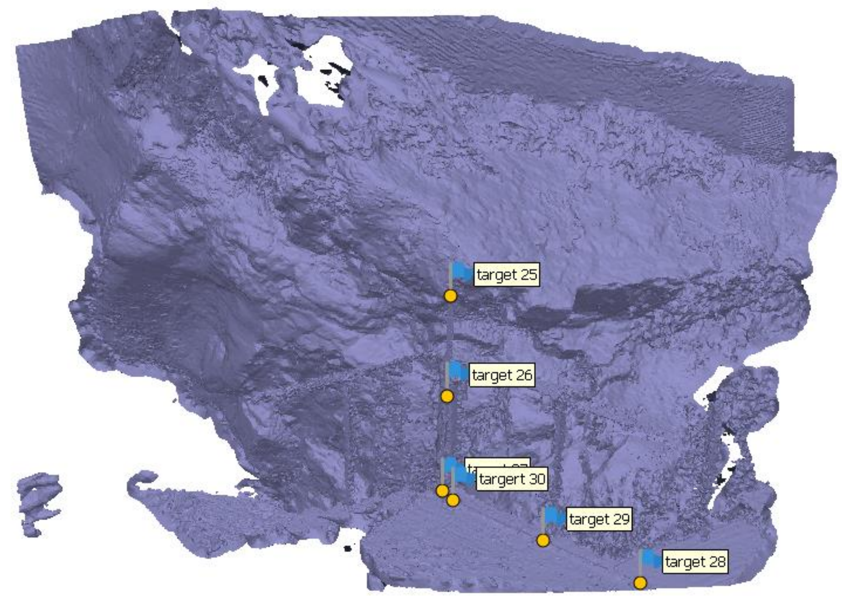
Vb(Size)	X(cm)	Ra(cm)
Average	59	88.9
Minimum	40	38.60
Maximum	76.84	153

Table 24. Safety Distance of Blocks

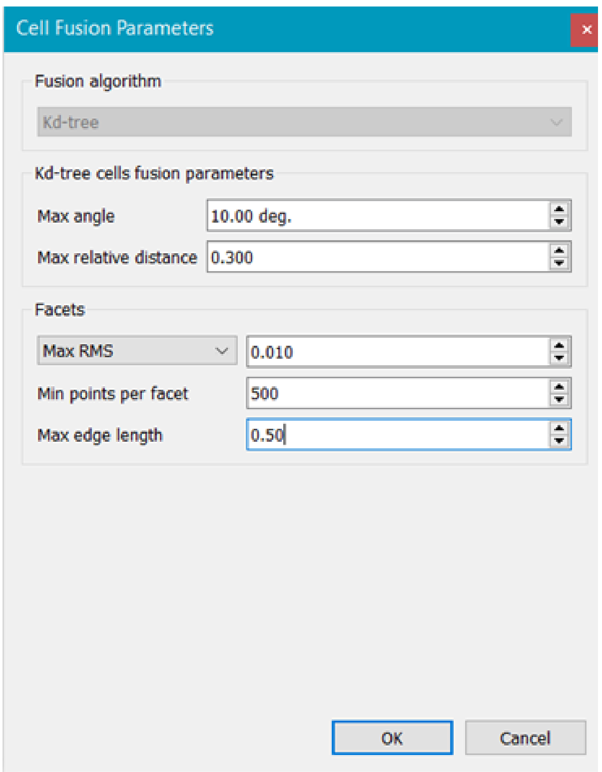
Field Trip Photogrammetry

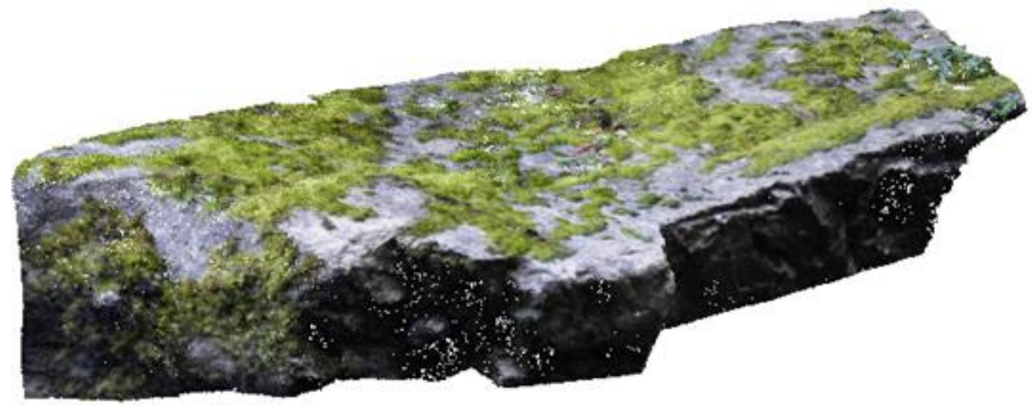


3D models of the Rock Surface



Families Location

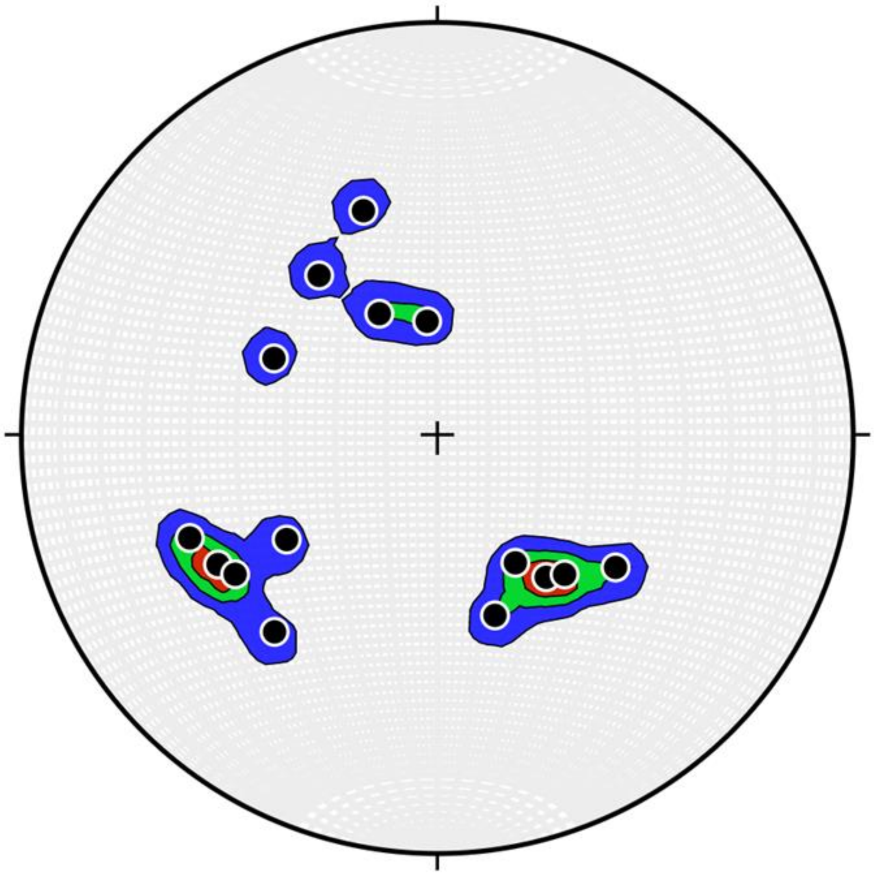




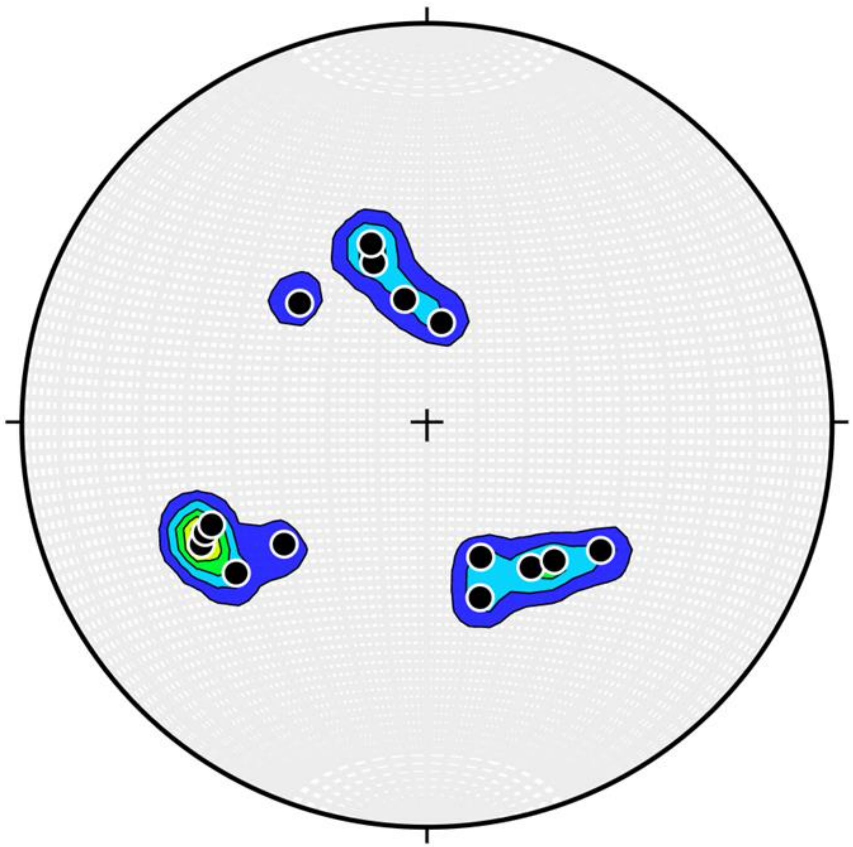
The dip and dip direction Software and In-situ

	In-Situ		Software		Difference		Average	
Family	dip	dip direction	dip	dip direction	dip	dip direction	dip	dip direction
Family 1	29	338	29	328	0	10	0,4	2,6
	37	343	37	342	0	1		
	36	324	35	322	1	2		
	38	317	37	317	1	0		
	44	306	44	306	0	0		
Family 2	53	62	54	68	1	6	0,6	7,4
	38	50	36	56	2	6		
	51	64	51	60	0	4		
	50	52	51	40	1	12		
	49	65	49	56	0	9		
Family 3	21	188	23	175	0	12	1,2	5,2
	26	170	27	155	1	10		
	35	162	40	144	3	4		
	39	163	48	162	1	0		
	36	134	36	116	1	0		

Stereograms of Software and In-situ Results

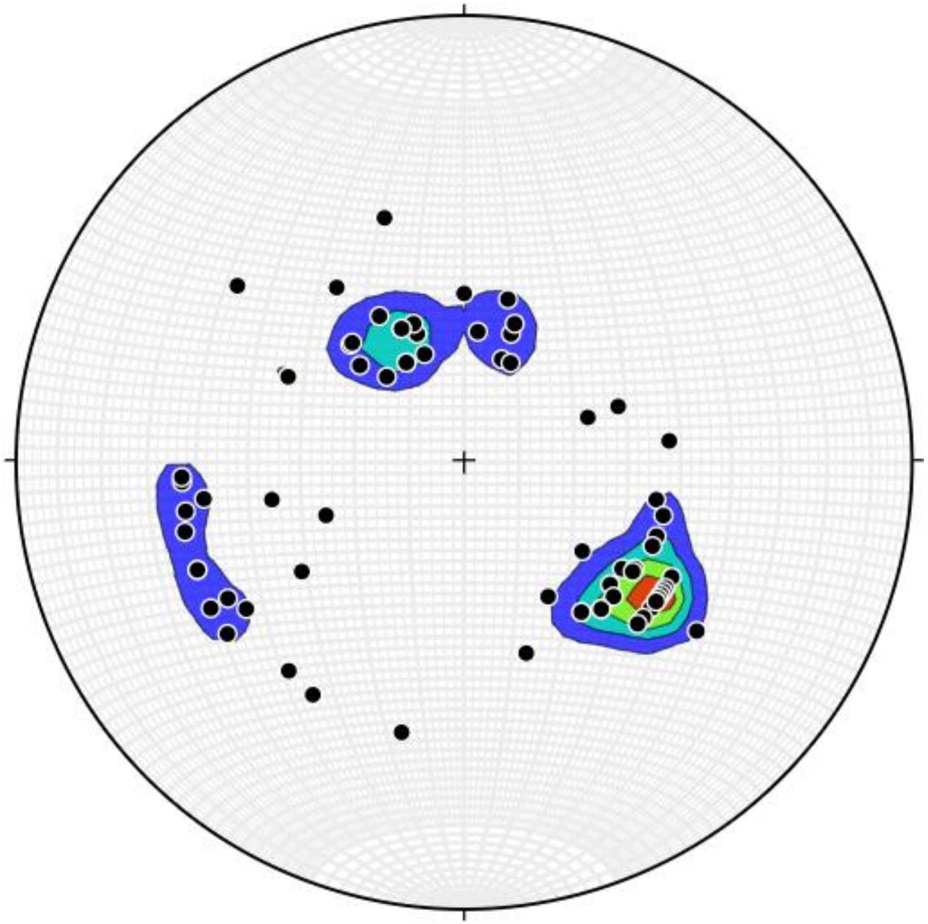


The Cloud Compare Results



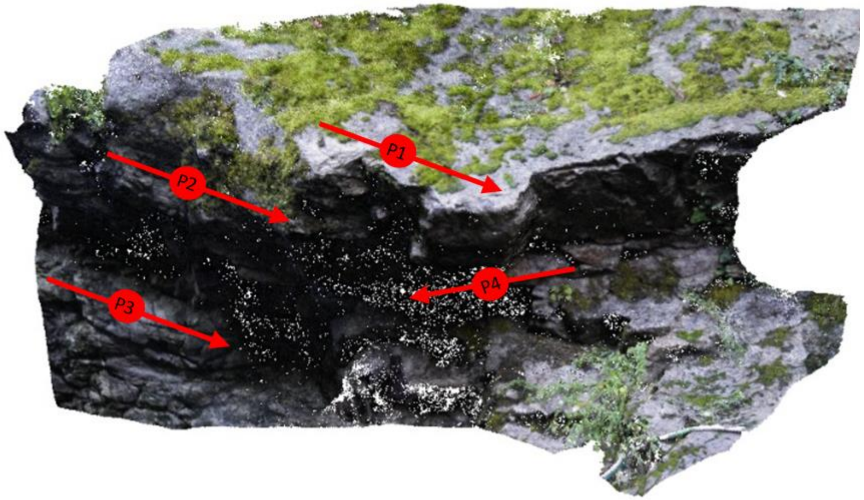
The In-Situ Results

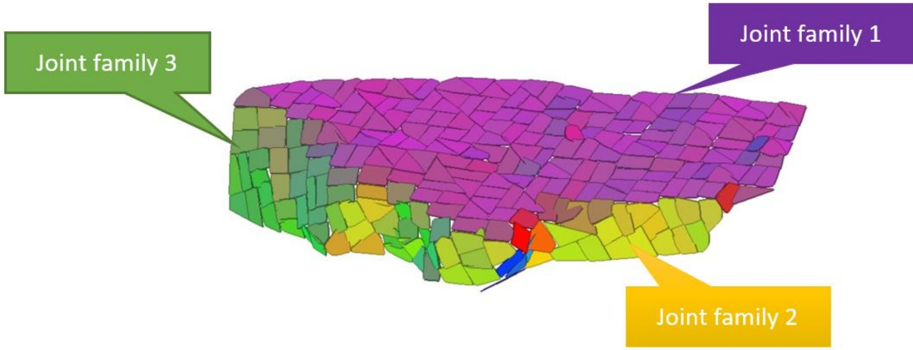
Stereograms of Global Results



All Results from Software and In-Situ

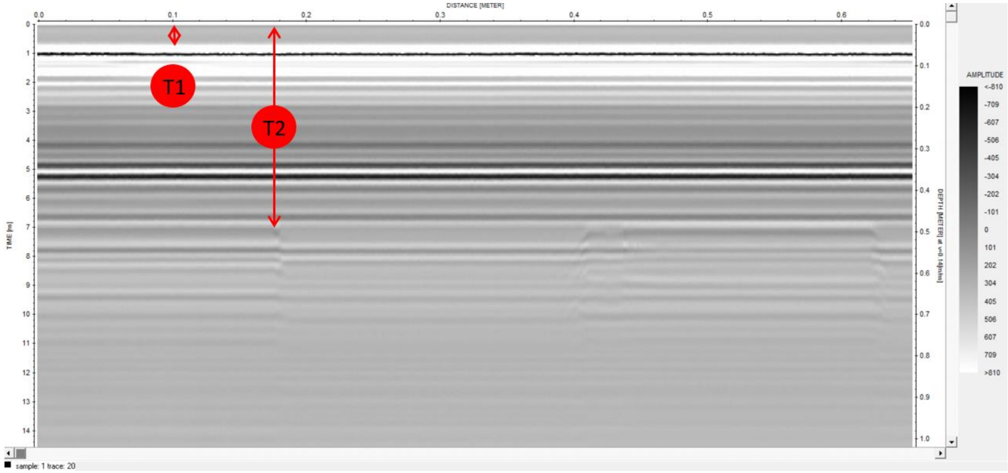
- Ground-penetrating radar(GPR)
- IDS (3GHz) GeoRadar





Velocity test

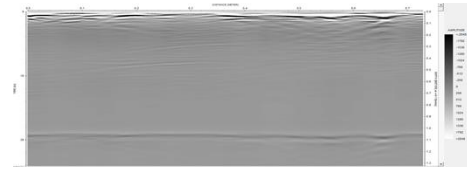
Velocity is estimate using distance over time, during this process, we main use the metal shield to create the reflection with opposite polarity



Data processing

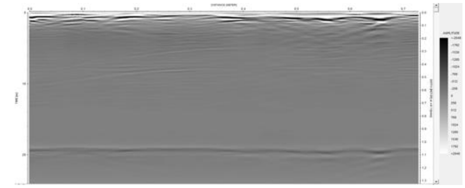
Time calibration

To calibrate the time scale so the time open the transmitting antennas is equal to 0



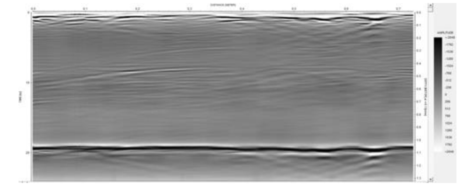
Bandpass filter

limit having sparse information ,select the range of frequencies



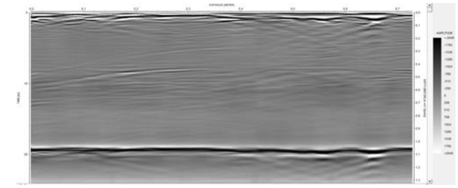
Gain

to amplify the defraction, to make the signal visible with the same amplitude with the background signal.



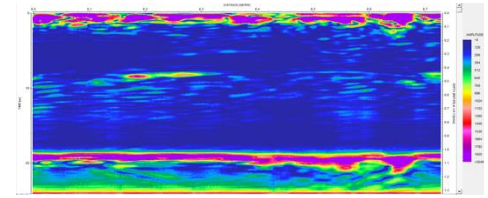
Background removal

Highlight the shallow signal which mask by background signal.

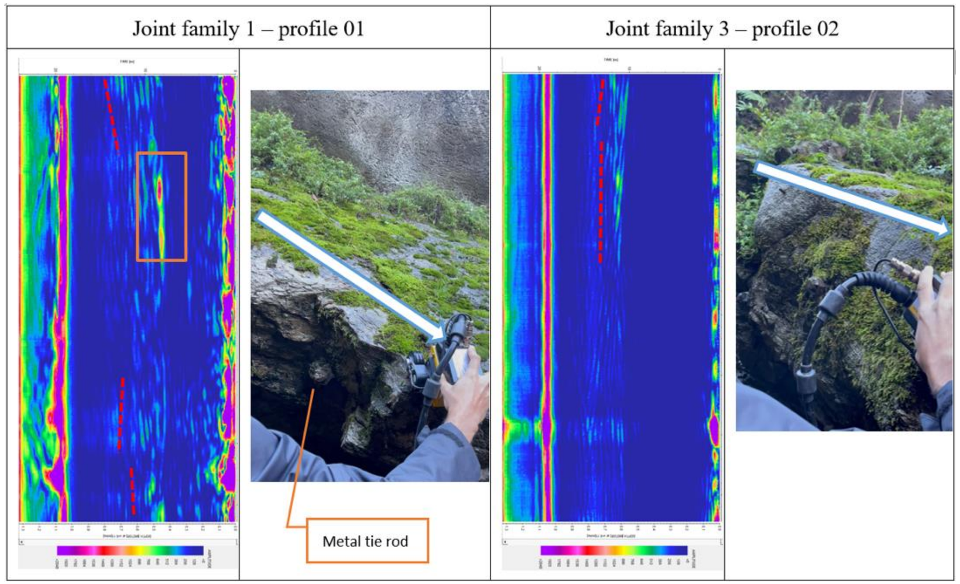


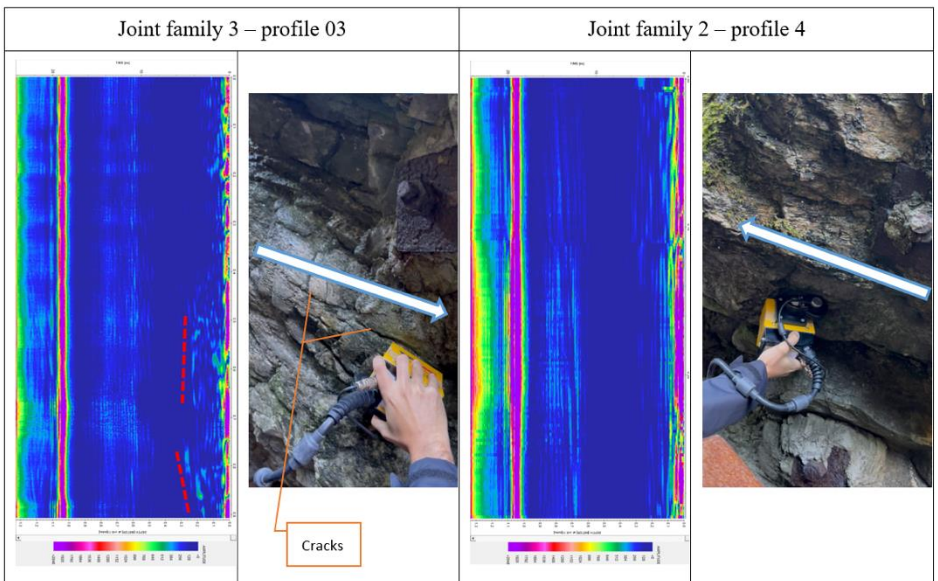
Envelope

remove the negative amplitudes from the profile by transforming waves with negative and positive oscillations into positive signals,



Result





Profile 01 – family 1

1.Strong signal in depth 50cm shows a metal tie rod.

2.moderate joint-persistency, as discontinuities are quite far from each other.

Profile 02,03 – family 3

1.Not so strong signal in depth 15cm,maybe a metal or inner fracture.

2.a moderate joint-persistency, since discontinuities are short and far from each other

Profile 04 – family 2

1.signal is more horizontal and in low value because located in a less exposed place.

2.a low joint-persistency, since no evident discontinuity inside the rock.

Result

A joint-persistency factor p is used for estimating our joint families:

$$p = \frac{L_j}{L_j + L_r}, L_j\text{: joint length}, L_r\text{: gap between joints}$$

Joint family	Estimated joint-Persistancy (%)	Average joint-spacing (cm)
JF1	66%	5
JF3	68%	10

This parameter tells us the possibility of forming a line of crack inside the structure.
Just moderate joint-persistency.

In this project, a combination of various techniques and finally we finish our field trip.

Thank you!