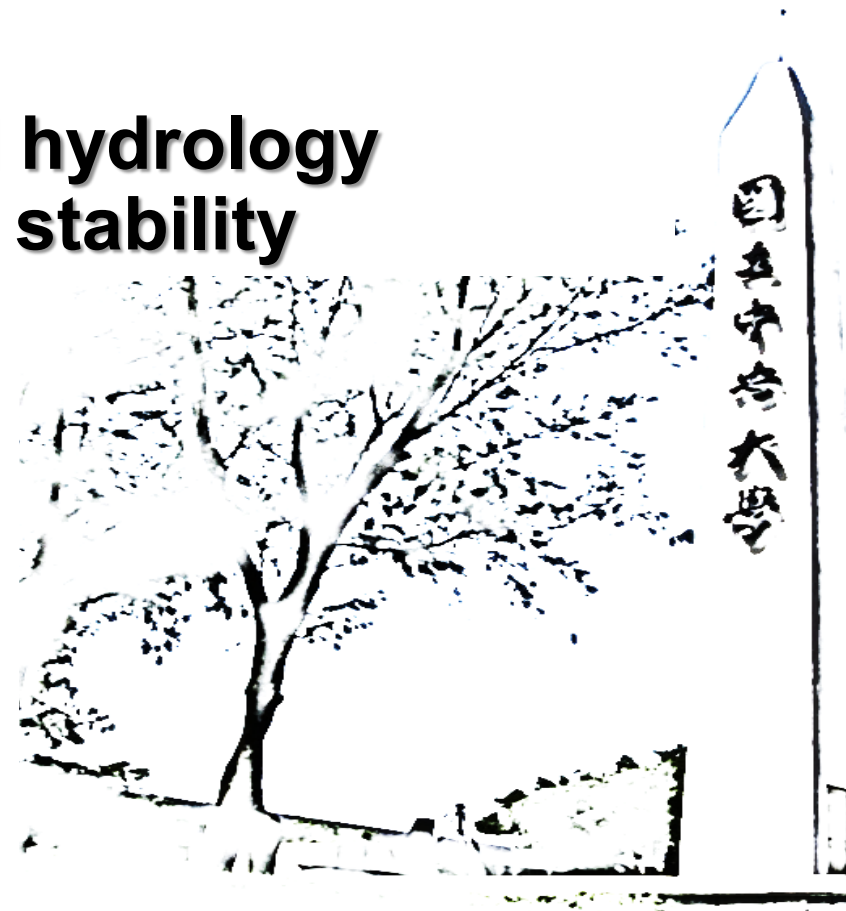


土壤介電行為與水文特性於淺層崩塌穩定 應用探討

**Investigation of soil dielectric and hydrology
properties on shallow landslide stability**

鐘志忠

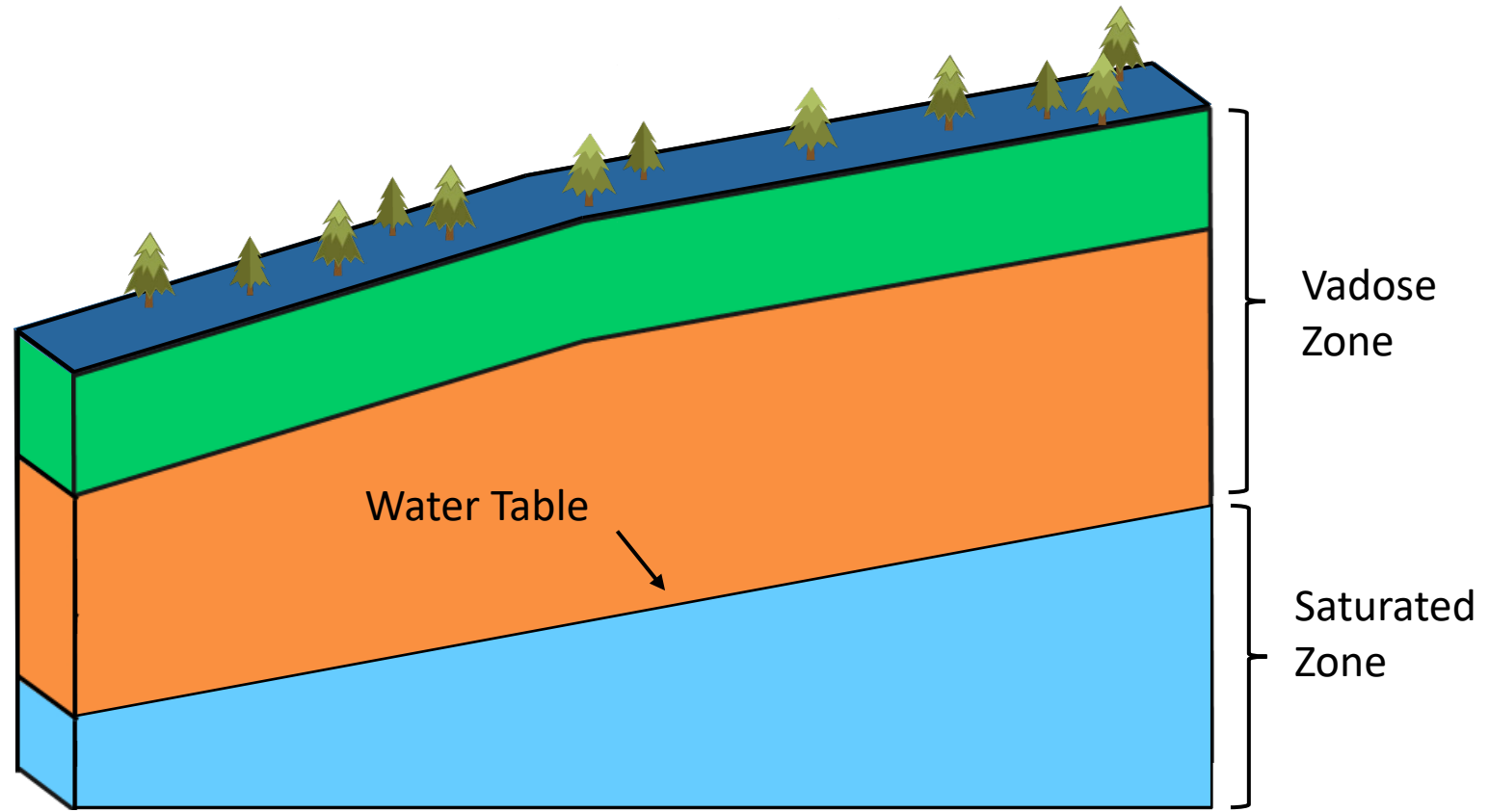
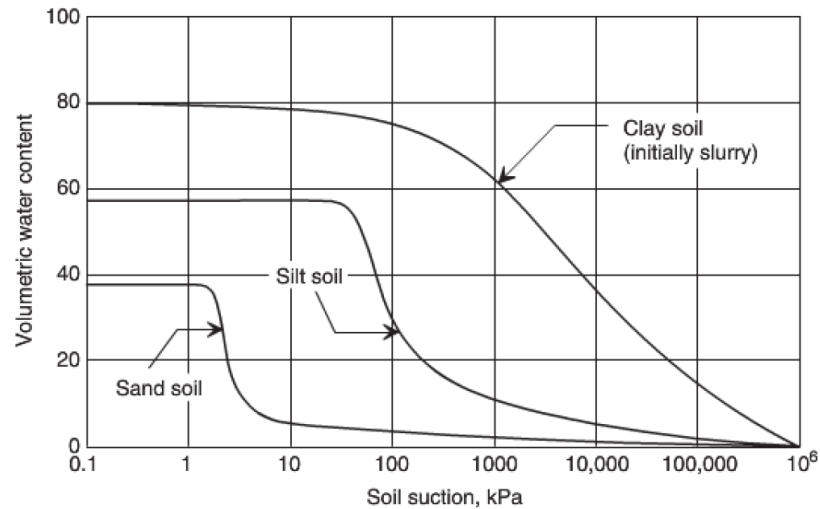
2023/10/24



Introduction

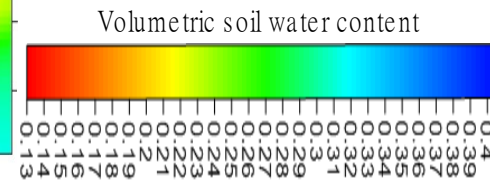
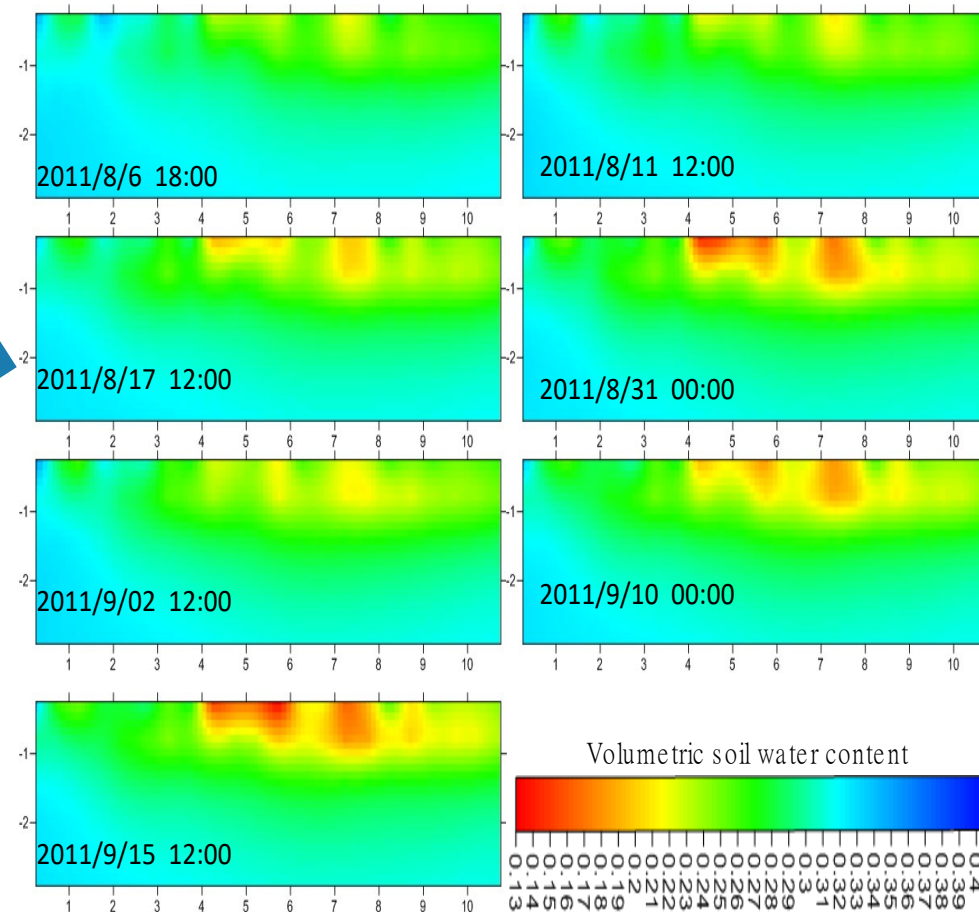
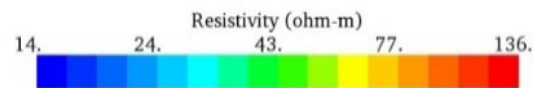
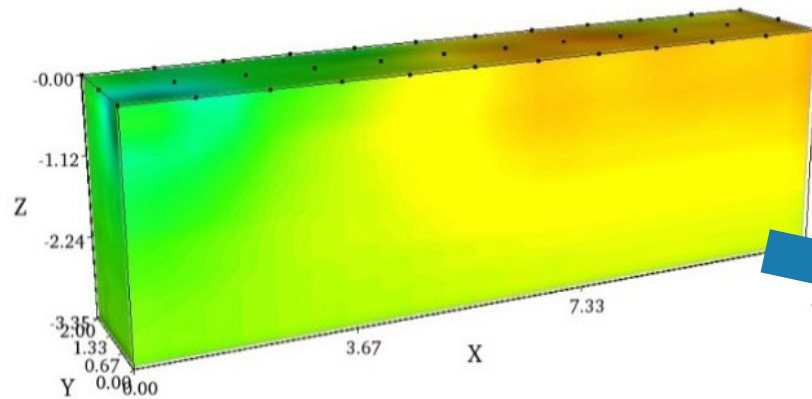
Vanapalli et al., (1996)

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \left[(\tan \phi') \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right]$$

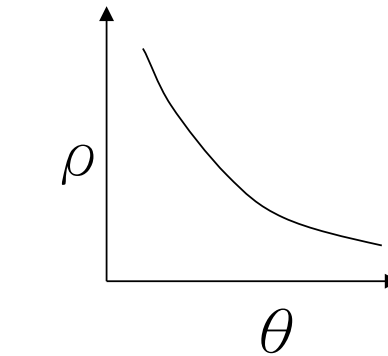
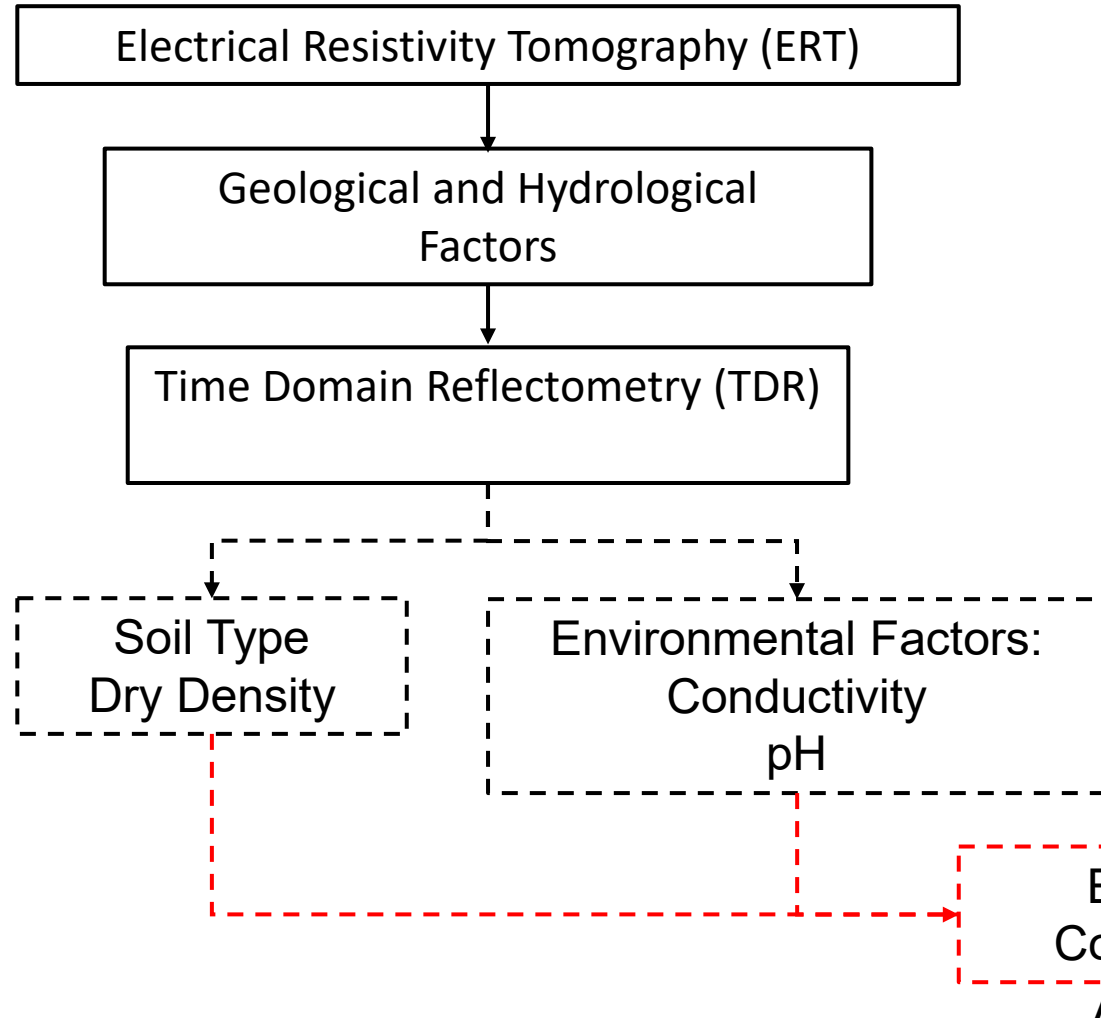




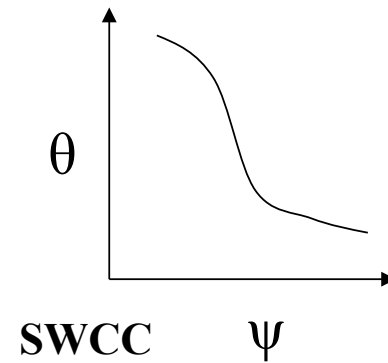
ERT vs Soil water content



Objectives

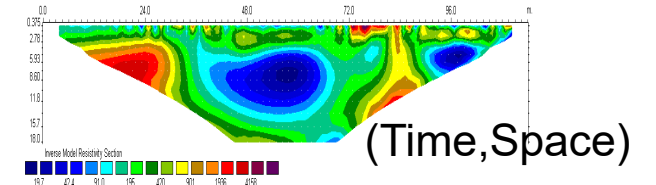


Archie's Law



SWCC

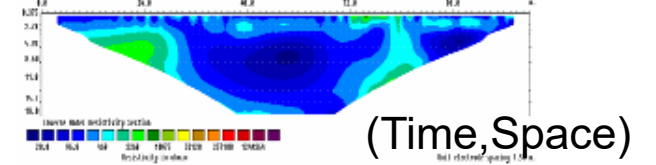
Resistivity section



(Time,Space)

θ v.s ρ

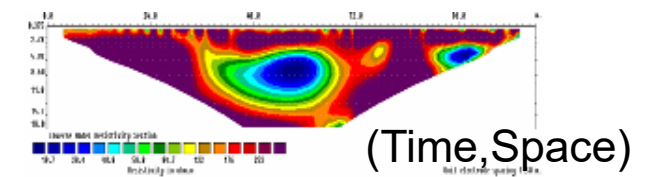
Water Content section



(Time,Space)

ψ v.s θ

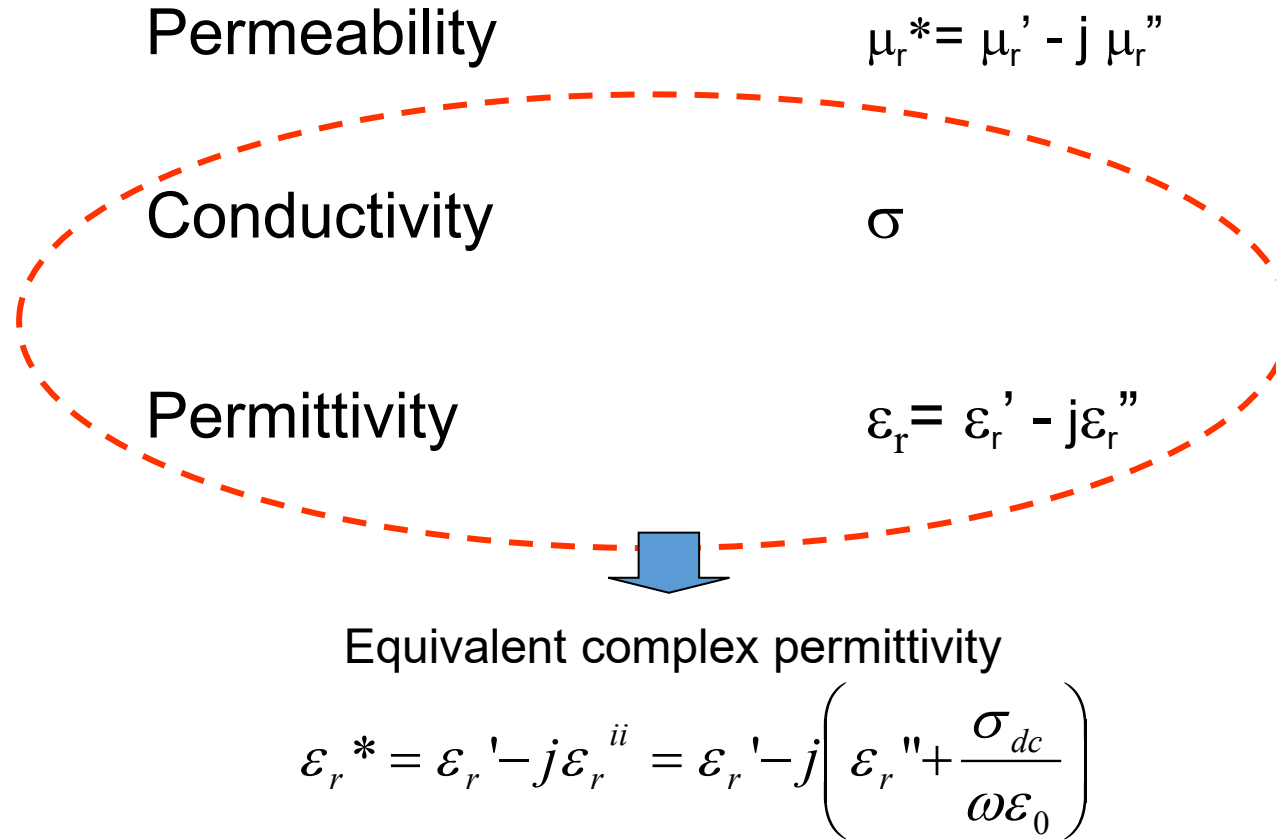
Matric suction section



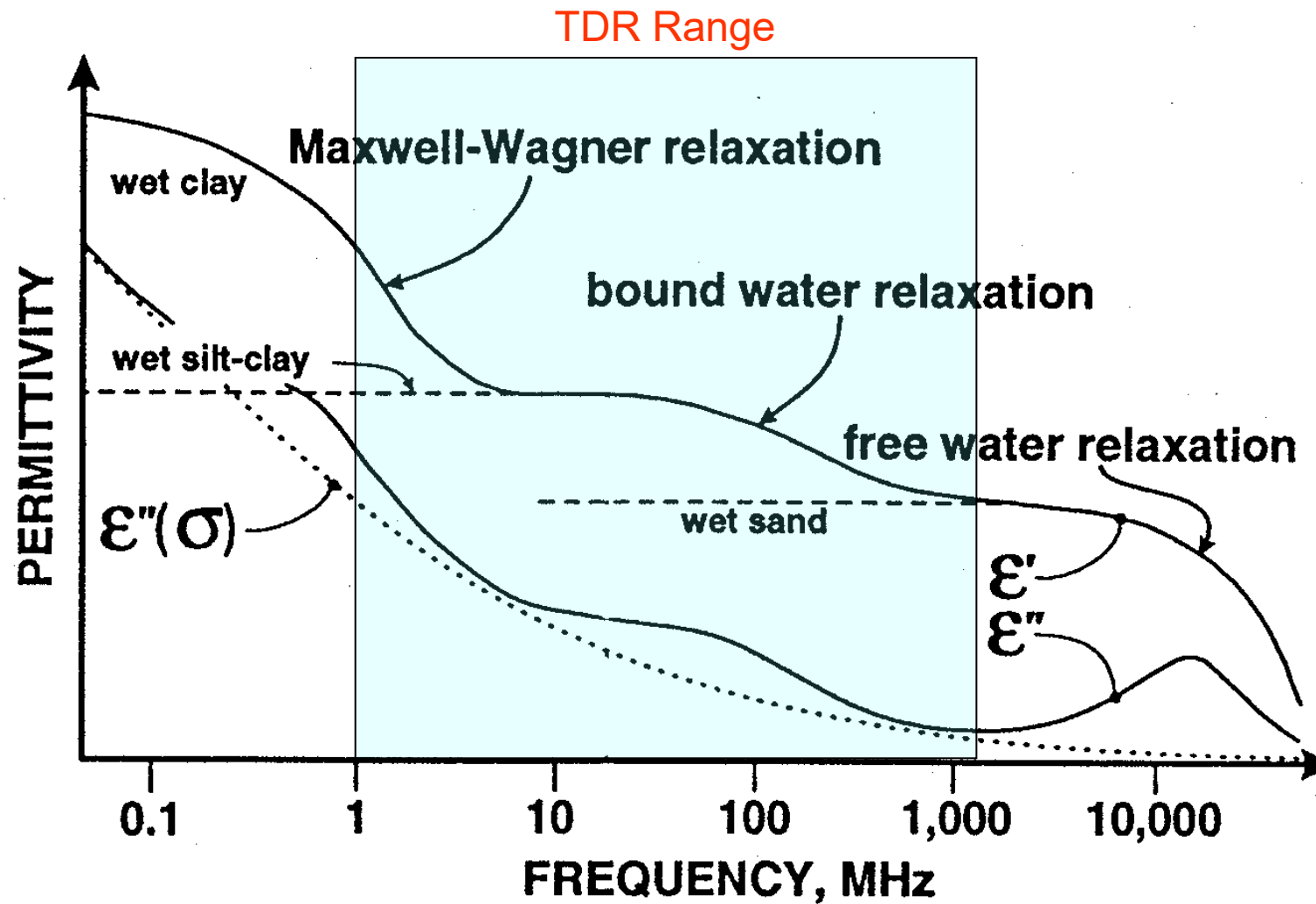
(Time,Space)

Reviews

Electromagnetic Properties of Materials

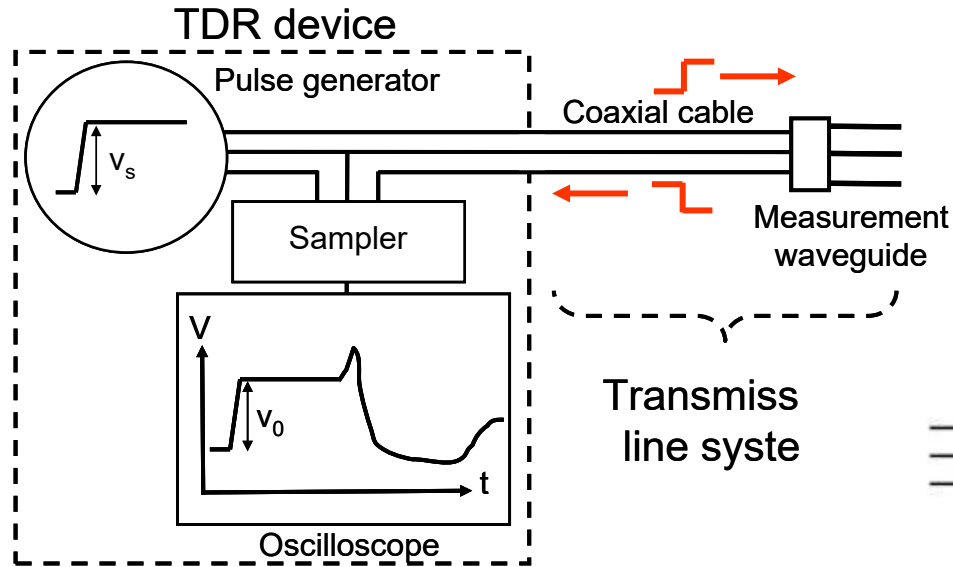


Dielectric Permittivity

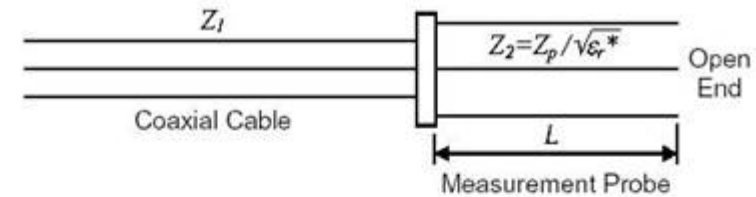


Hilhorst and Dirkson (1994)

Basic of TDR



1D radar

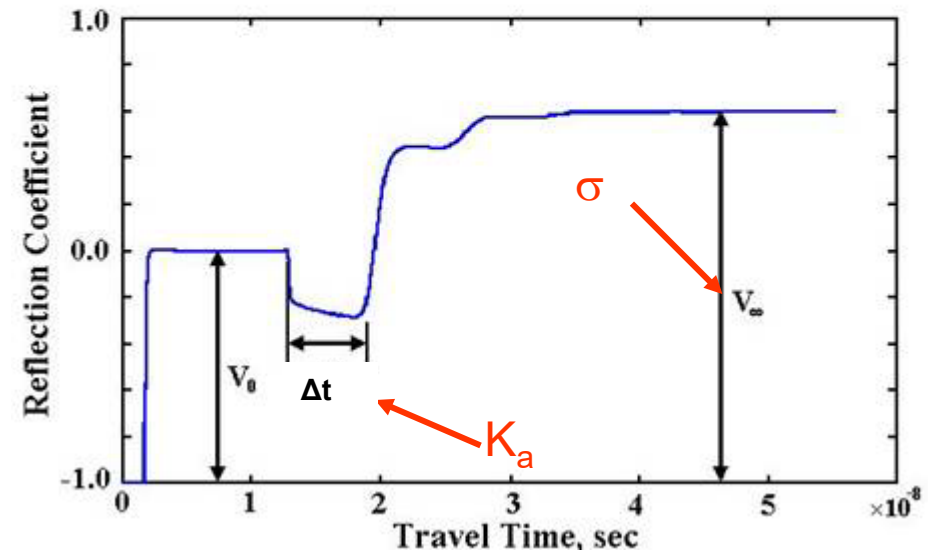


Propagation constant

$$\gamma = \frac{j2\pi f}{c} \sqrt{\epsilon_r^*} = \alpha + j\beta$$

Characteristic impedance

$$Z_c = \frac{\ln(b/a)}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{1}{\sqrt{\epsilon_r^*}} = \frac{Z_p}{\sqrt{\epsilon_r^*}}$$



TDR Travel Time Analysis and Applications

Phase velocity

$$V(\omega) = \frac{\omega}{\beta} = \frac{c}{\sqrt{\frac{\epsilon'(\omega)}{2} \left[1 + \sqrt{1 + \left(\frac{\epsilon''(\omega)}{\epsilon'(\omega)} \right)^2} \right]}}$$

Apparent dielectric constant, K_a

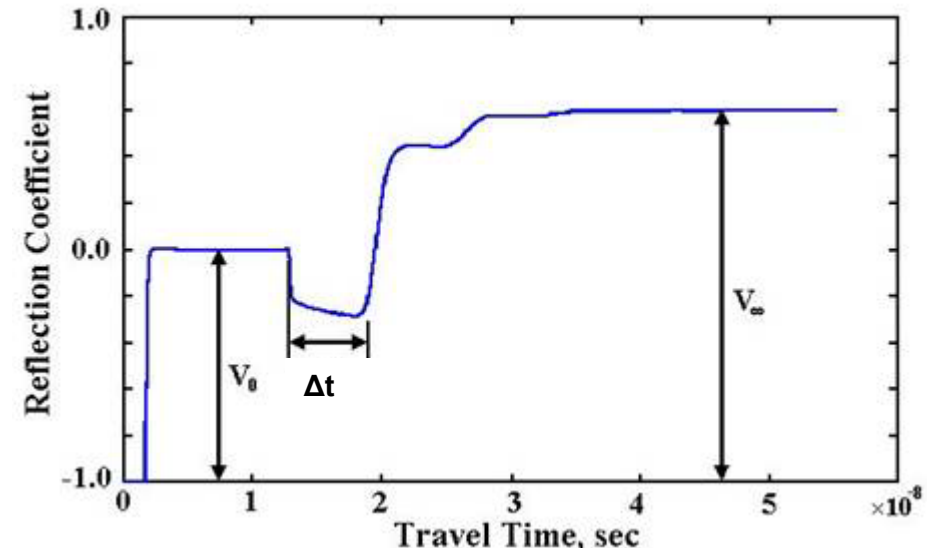
$$V_a = \frac{c}{\sqrt{K_a}}$$

$$K_a = \left(\frac{c\Delta t}{2L} \right)^2$$



$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$$

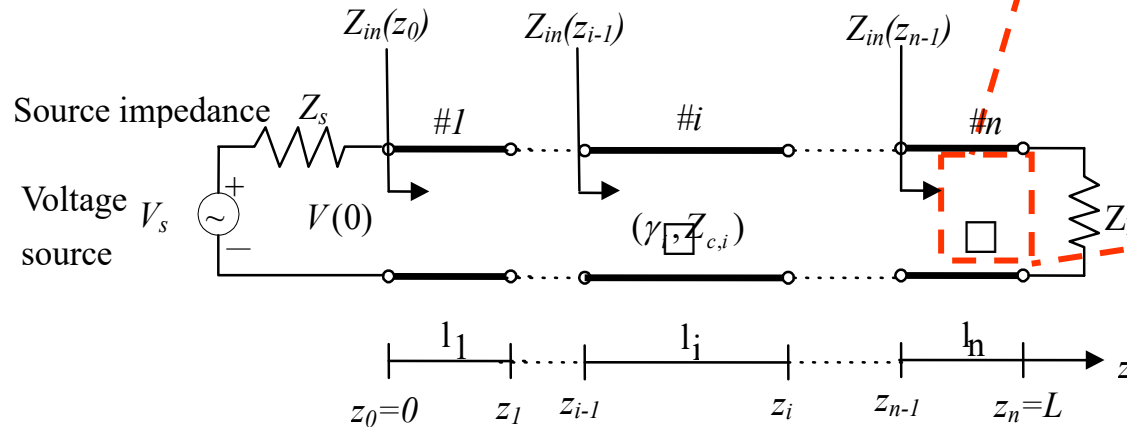
θ = volumetric soil water content



Topp et al. (1980)

TDR Modeling

Input impedance method
for multi-section system



$$\begin{cases} Z'_c = \frac{Z_p}{\sqrt{\epsilon_r^*}} * A \\ \gamma' = \frac{j2\pi f}{c} \sqrt{\epsilon_r^*} * A \end{cases}$$

resistance correction factor

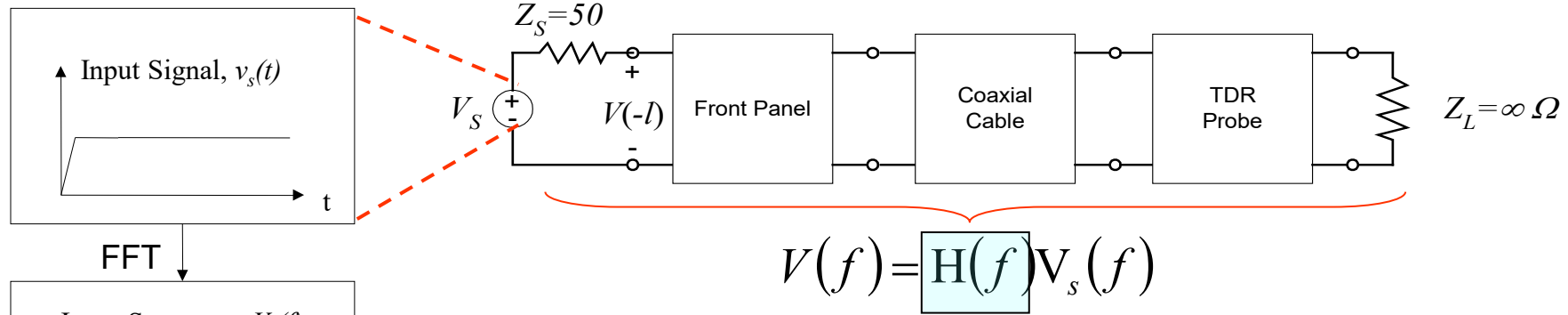
$$A = \sqrt{1 + (1 - j) \left(\frac{\eta_0}{Z_p} \right) \frac{\alpha_R}{\sqrt{f}}}$$

$$V(0) = \frac{Z_{in}(0)}{Z_{in}(0) + Z_s} V_s = H V_s \quad H = \frac{1 + S_{11}}{2}$$

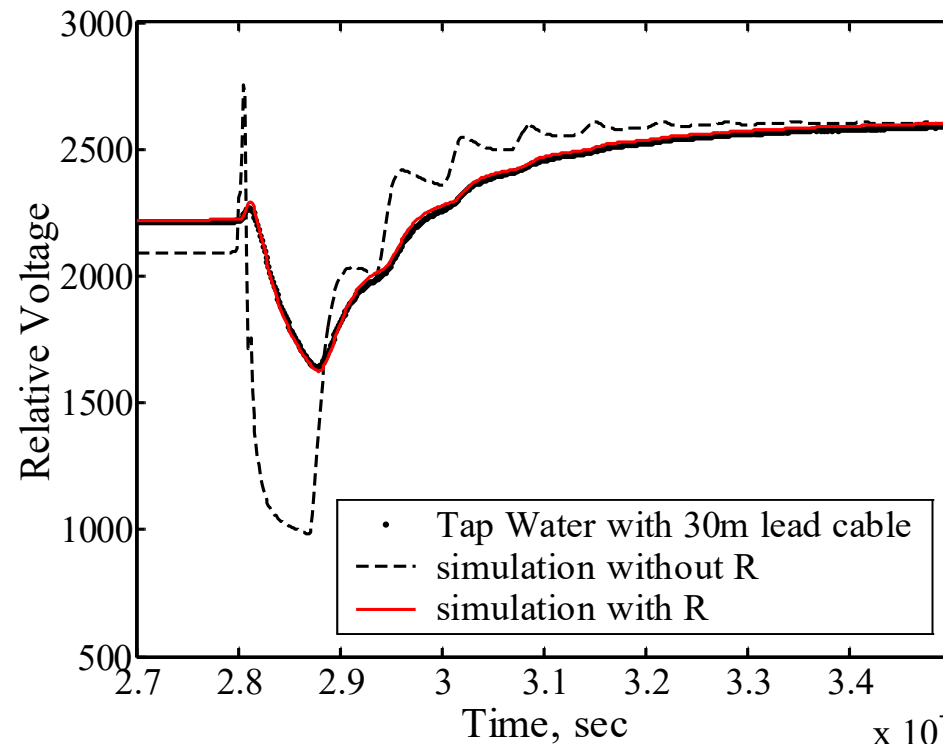
Lin (2003)

Lin and Tang (2007)

TDR Modeling

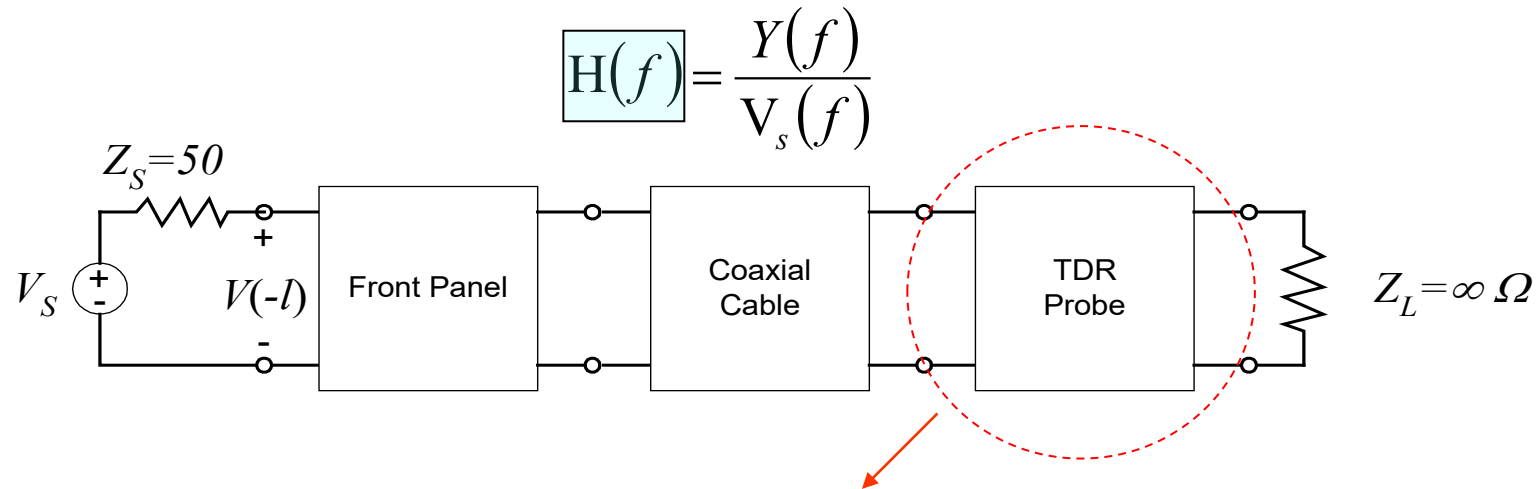


modified from Lin (1999)

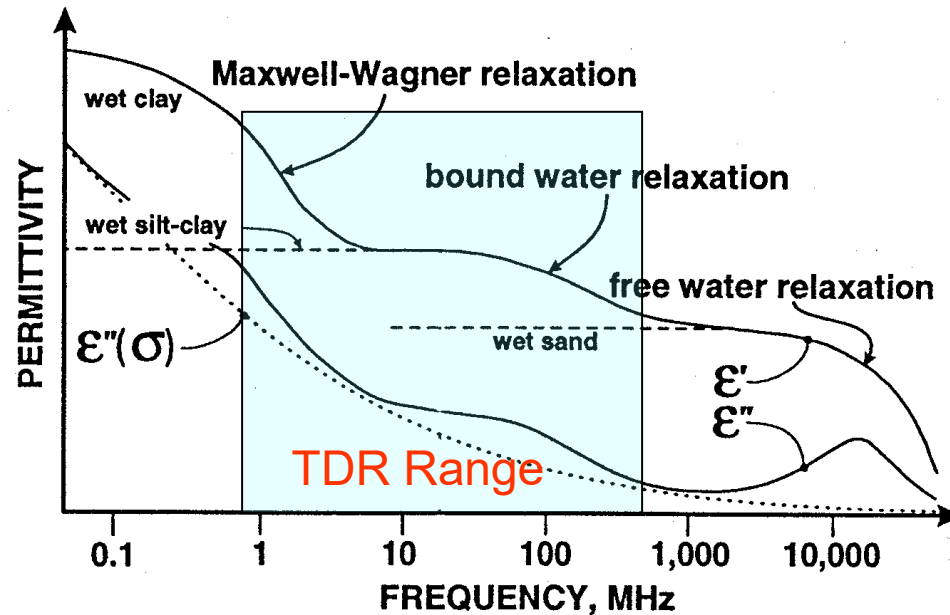


Tang and Lin (2007)

Inversion Analysis of TDR System



Dielectric permittivity of the measured material



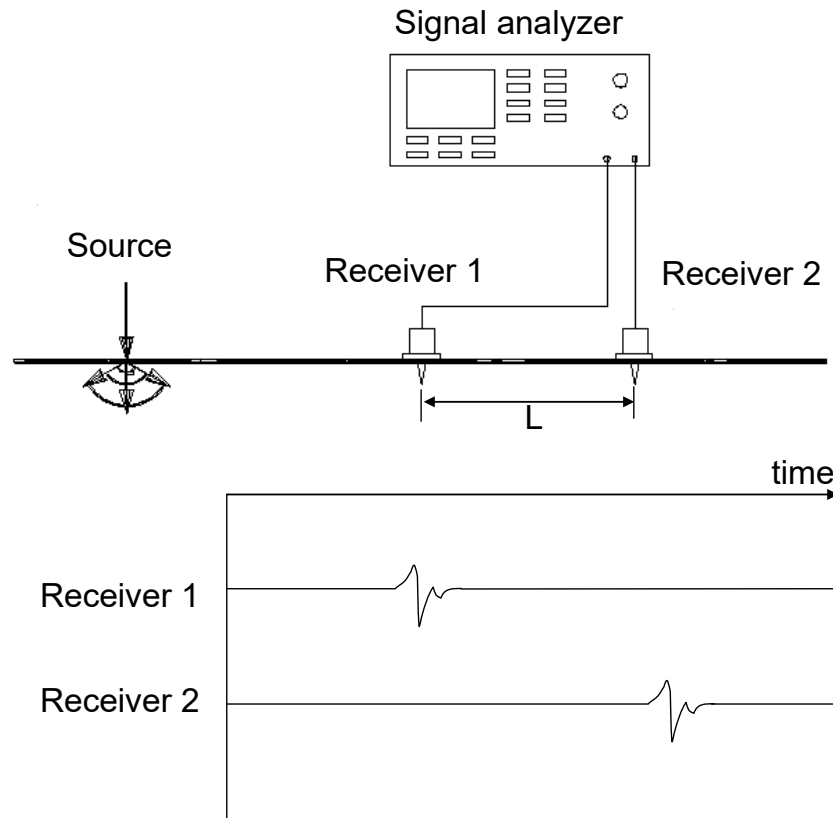
TDR Inversion methods

1. Model - free
2. Model - fits

Complex and unreliable at $f > 200$ MHz

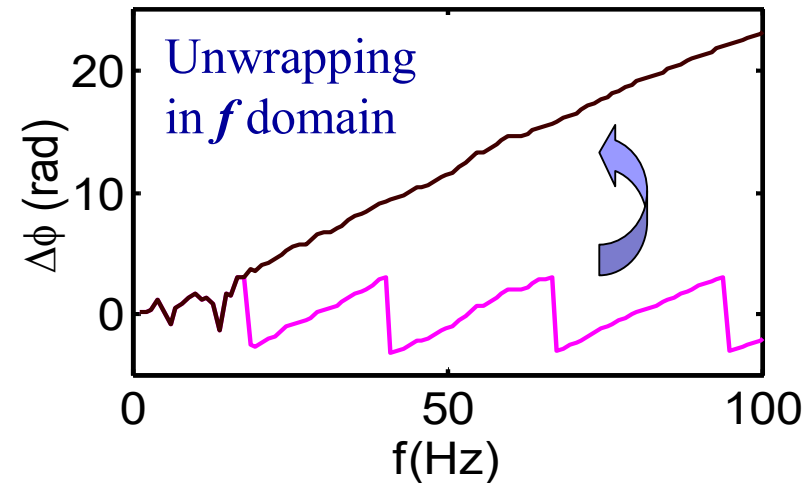
Frequency Domain Phase Velocity Method

Spatial analysis surface wave (SASW)



(modified after Foti, 2000)

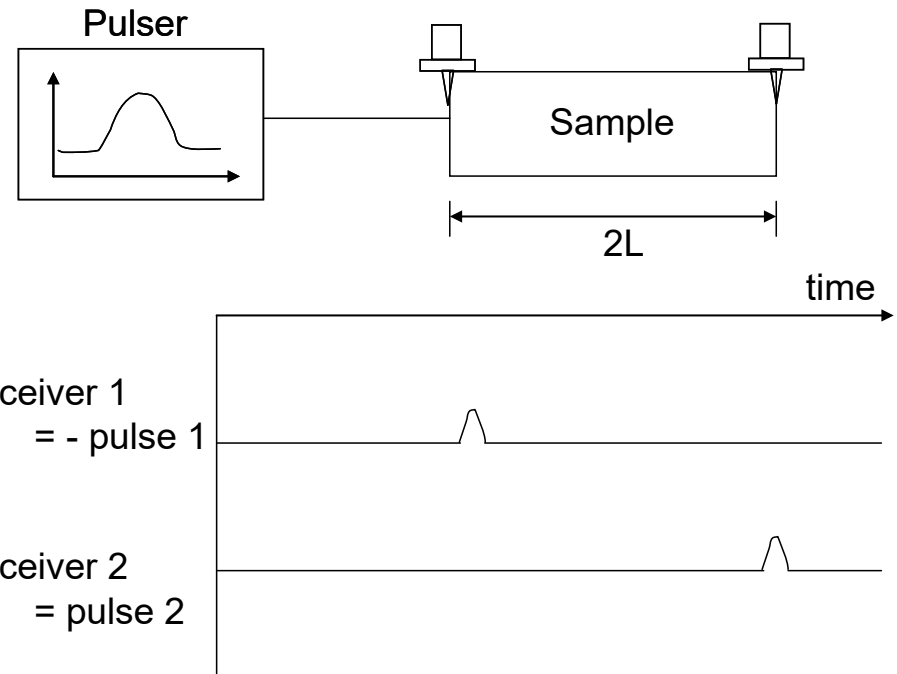
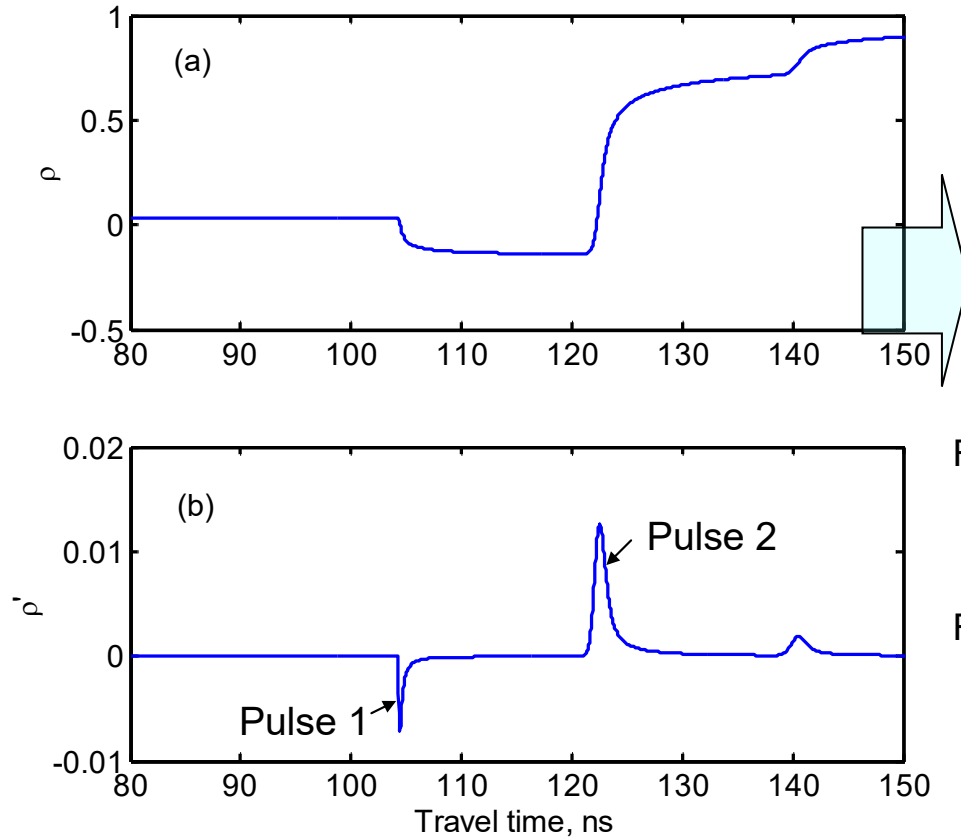
$$\Delta\phi(\omega) = \phi_2(\omega) - \phi_1(\omega)$$
$$= \text{Angle}[CSD(u_1(t), u_2(t))]$$



$$v(\omega) = \frac{\omega}{\frac{\Delta\phi(\omega)}{L}}$$

Frequency Domain Phase Velocity Method

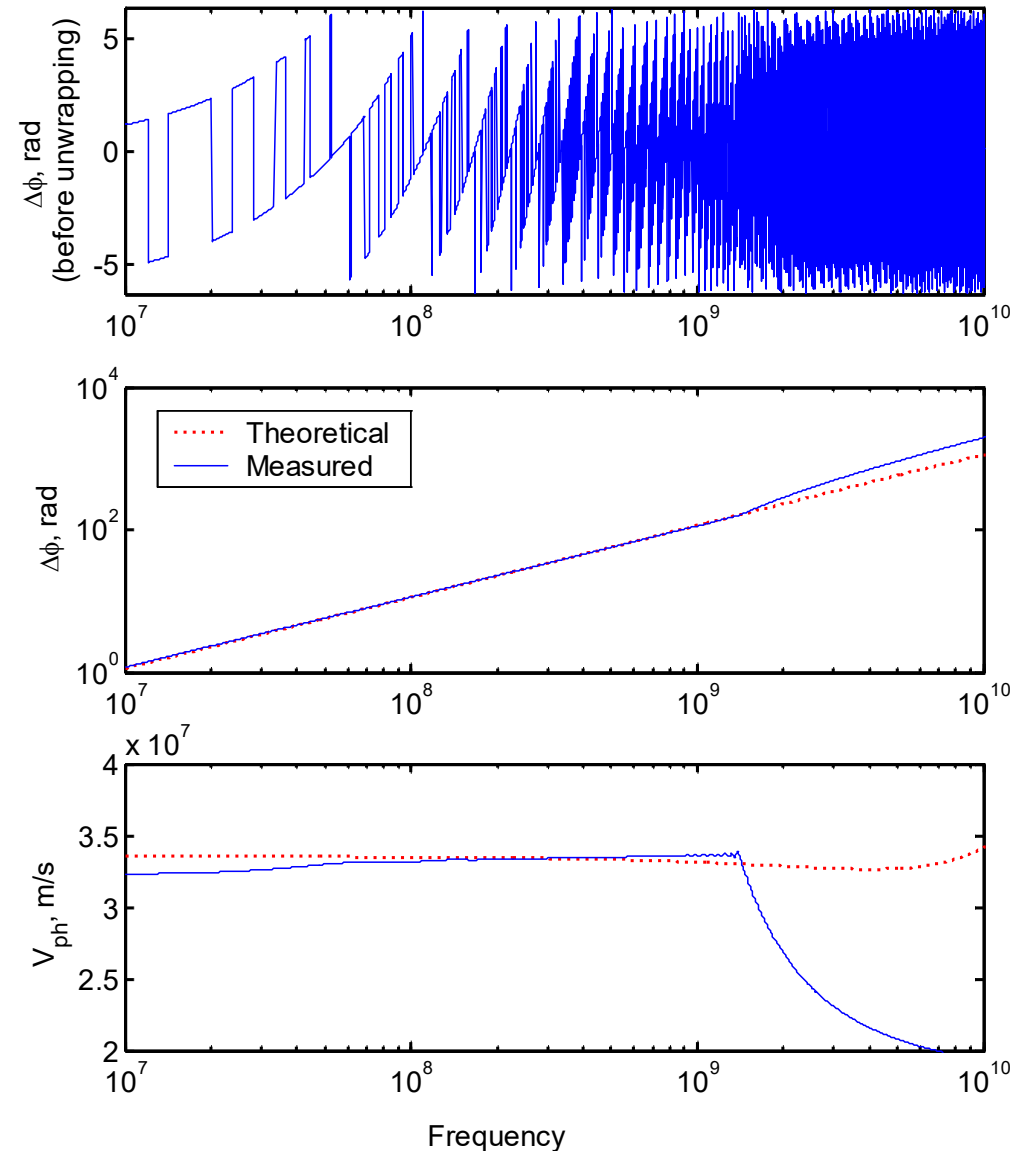
TDR waveform



Frequency Domain Phase Velocity Method

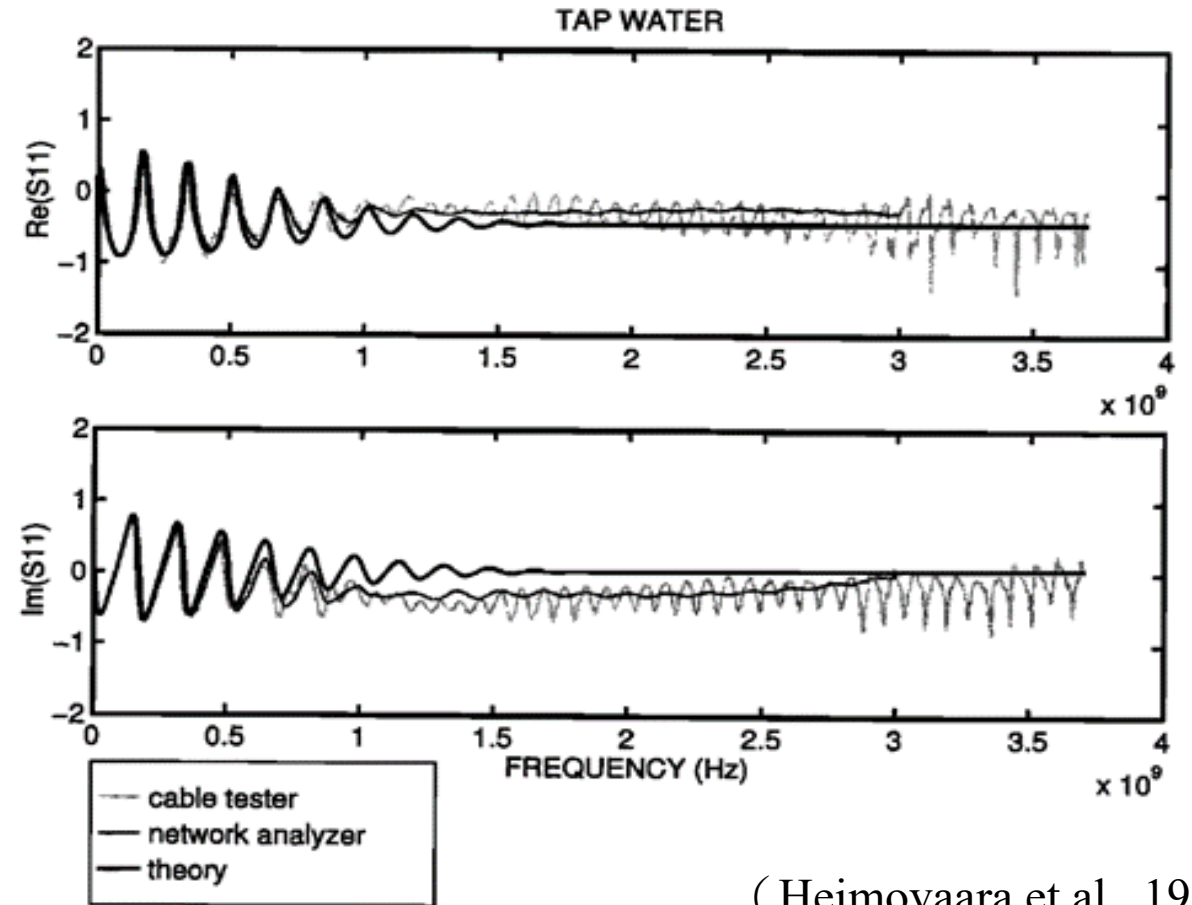
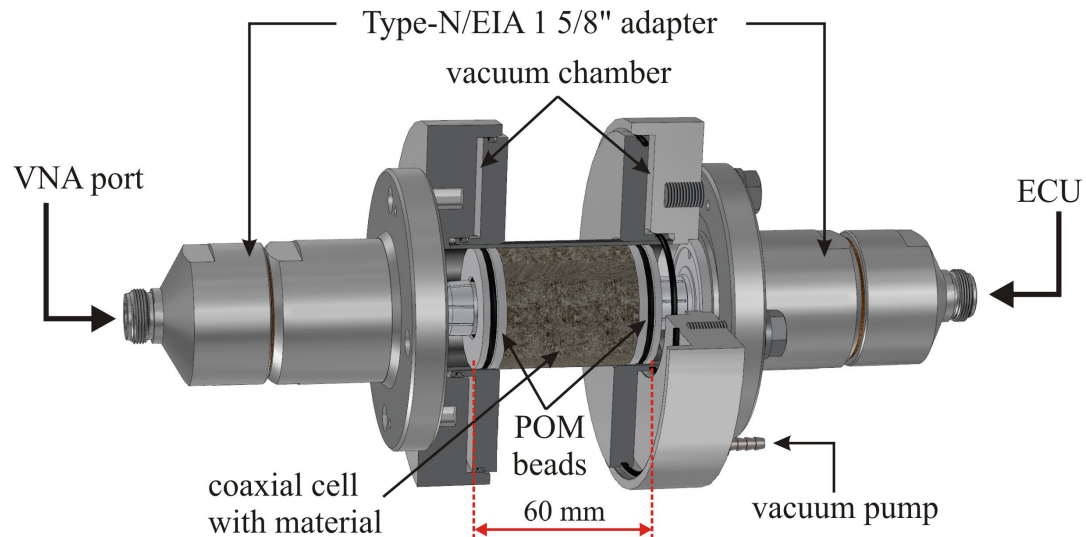
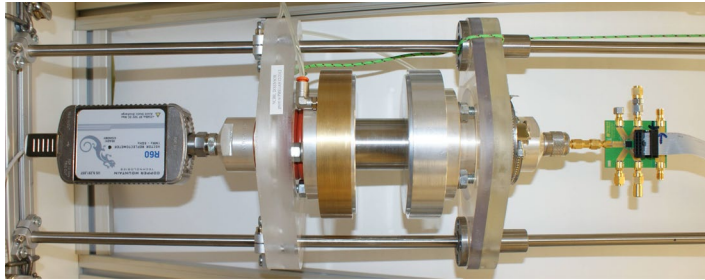
$$\Delta\psi = \text{Angle}(\text{pulse 1}) - \text{Angle}(\text{pulse 2})$$

Water



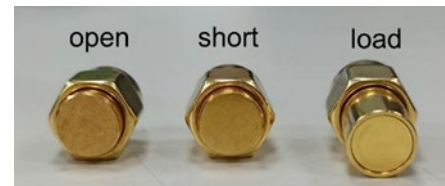
$$v_{ph}(\omega) = \frac{\omega}{\frac{\Delta\phi(\omega)}{2L}}$$

Vector Network Analyzer (VNA) Method

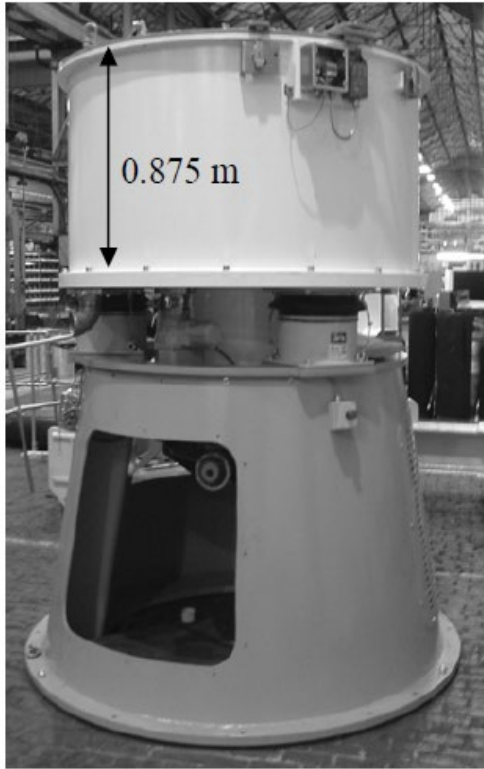


(Heimovaara et al., 1996)

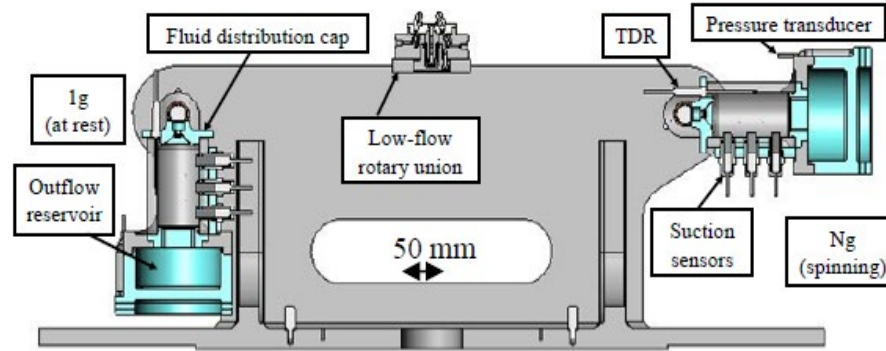
(Lewandowski et al. 2019)



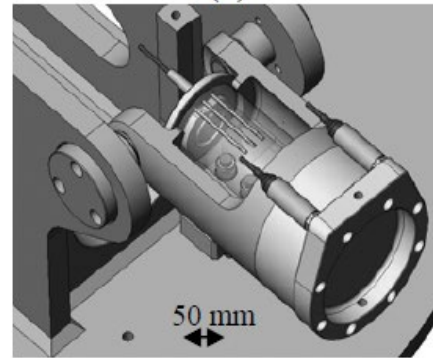
Centrifuge + TDR Method



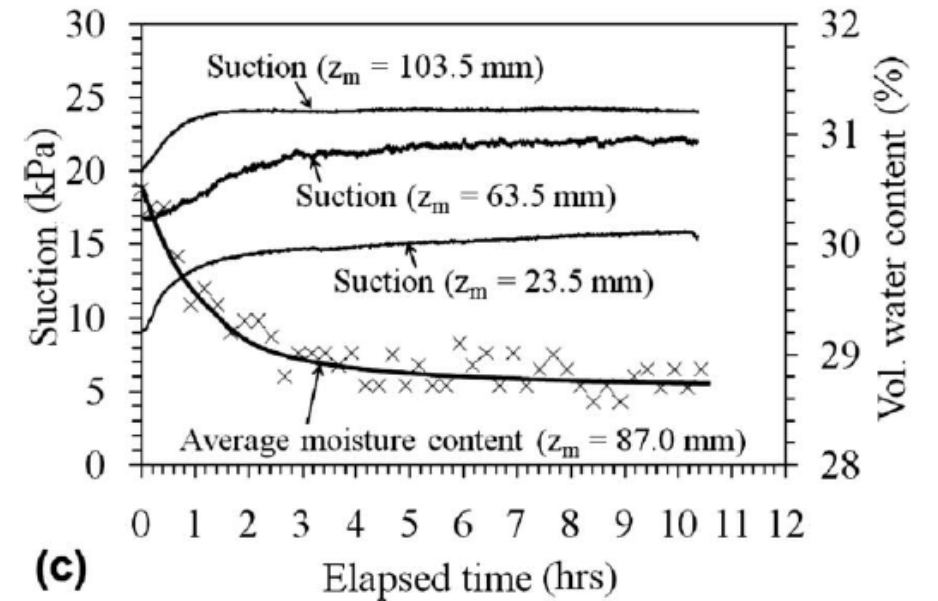
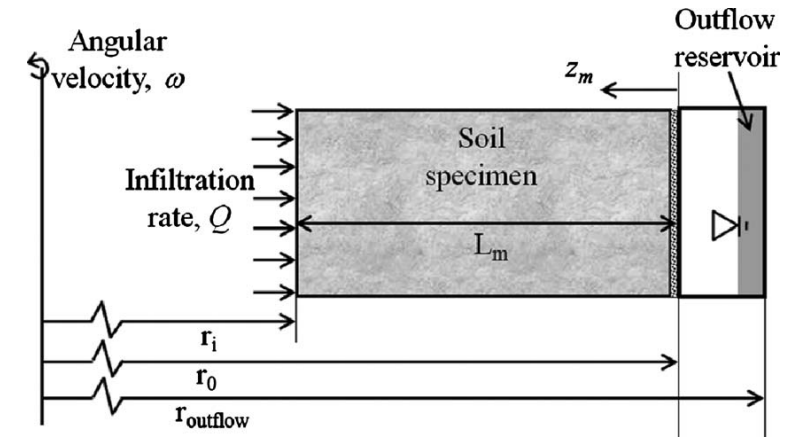
(a)



(b)



(c)

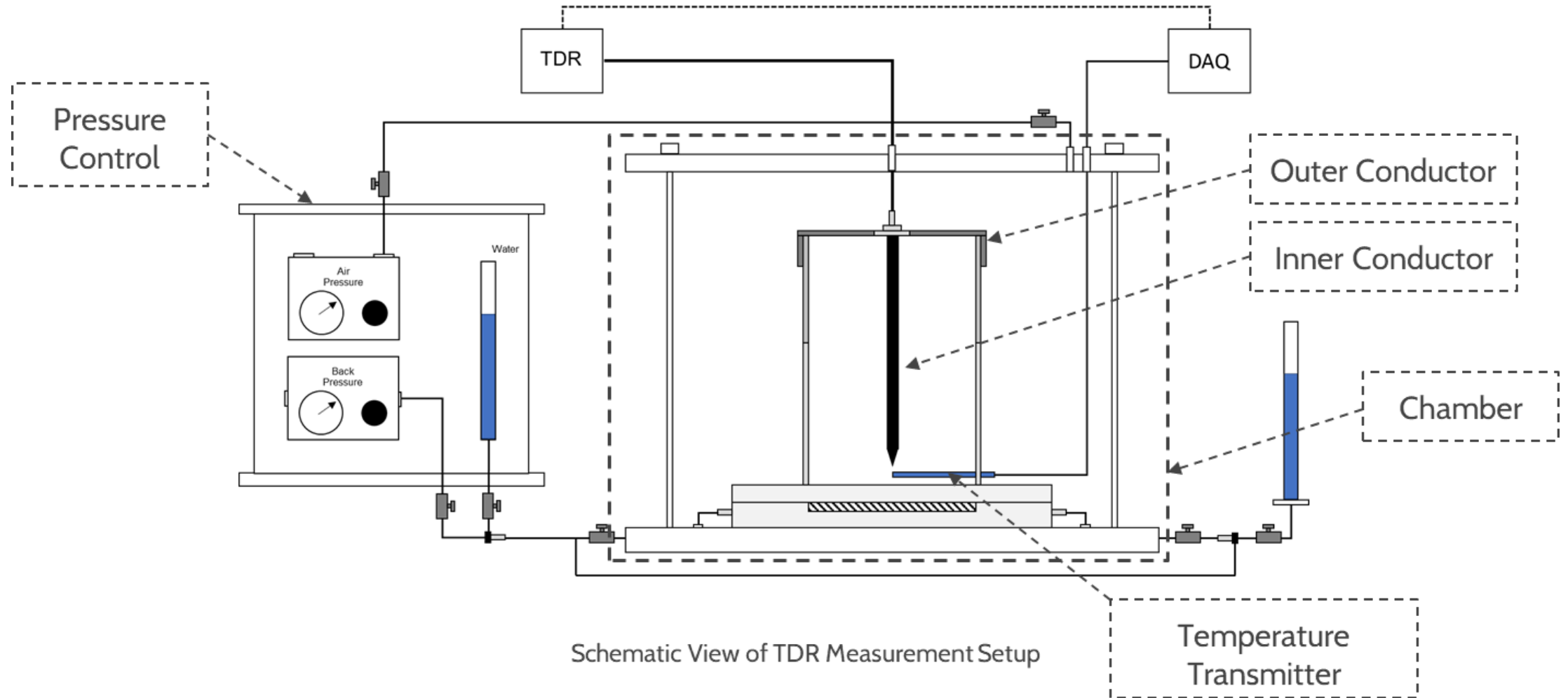


(c)

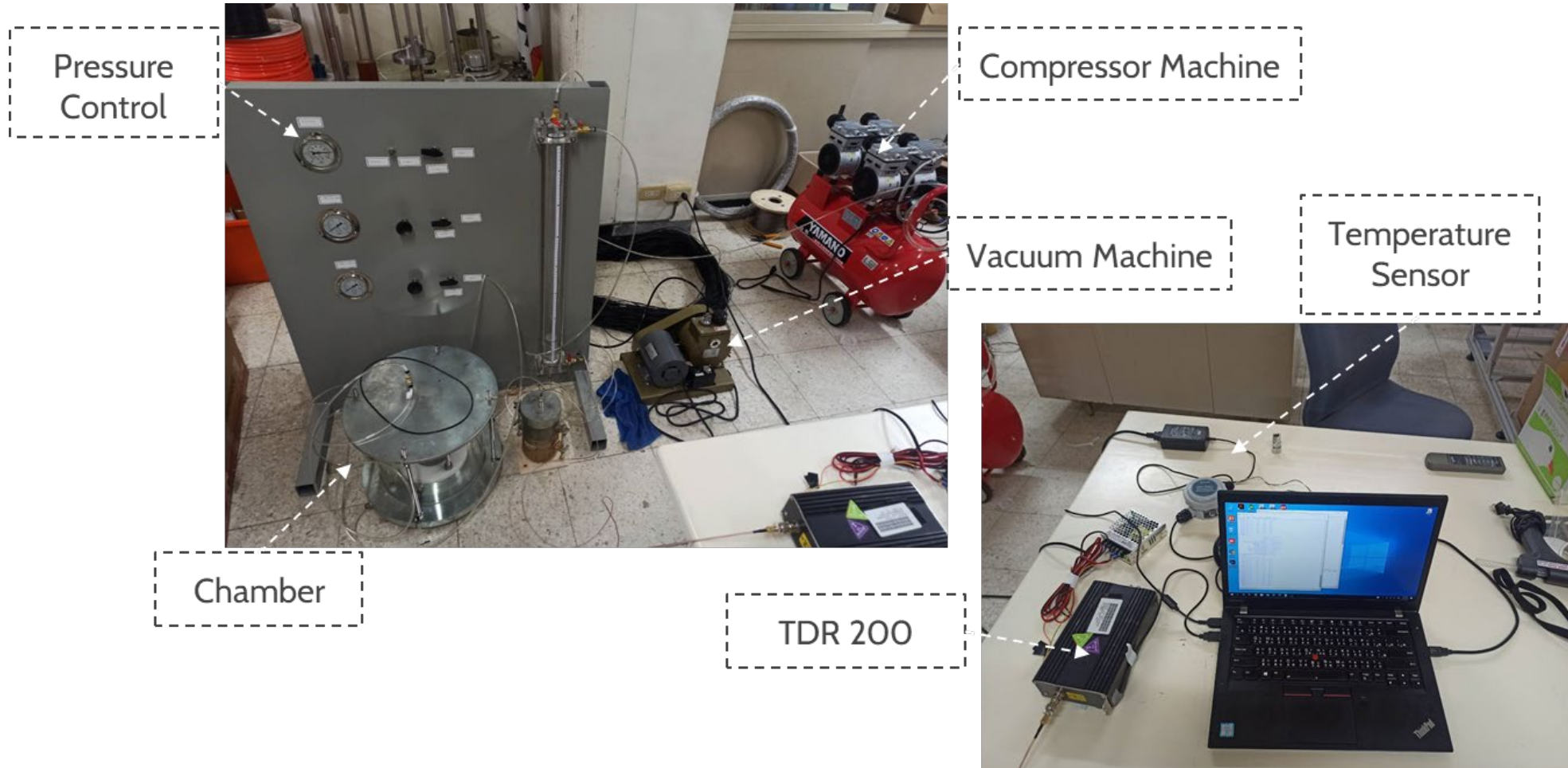
McCartney and Zornberg (2006)

Preliminarily Results

TDR Pressure Plate

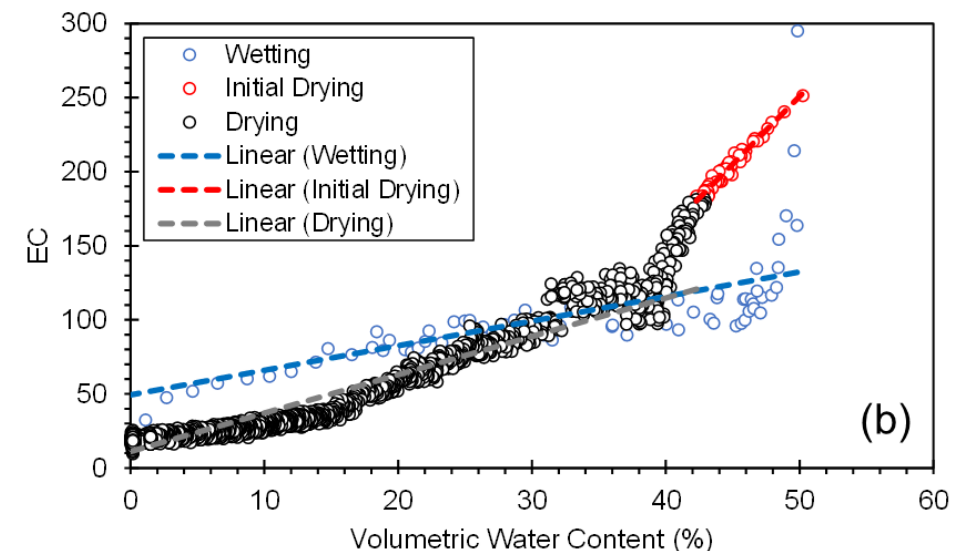
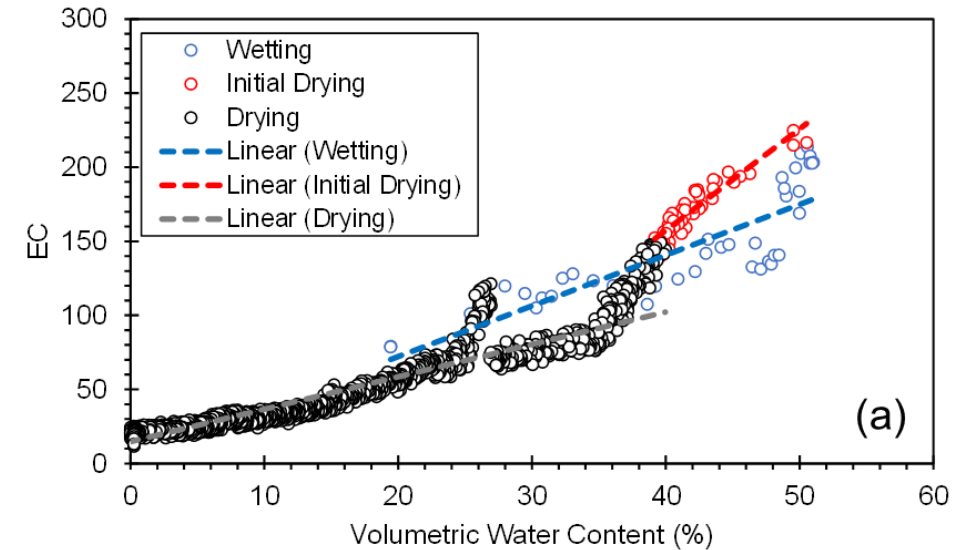
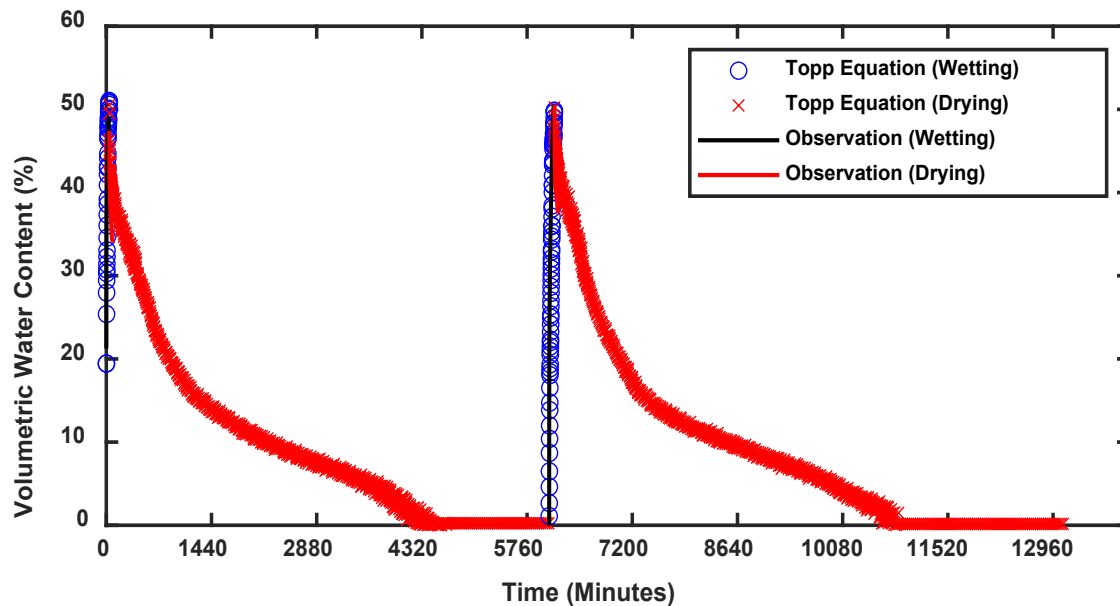


TDR Pressure Plate



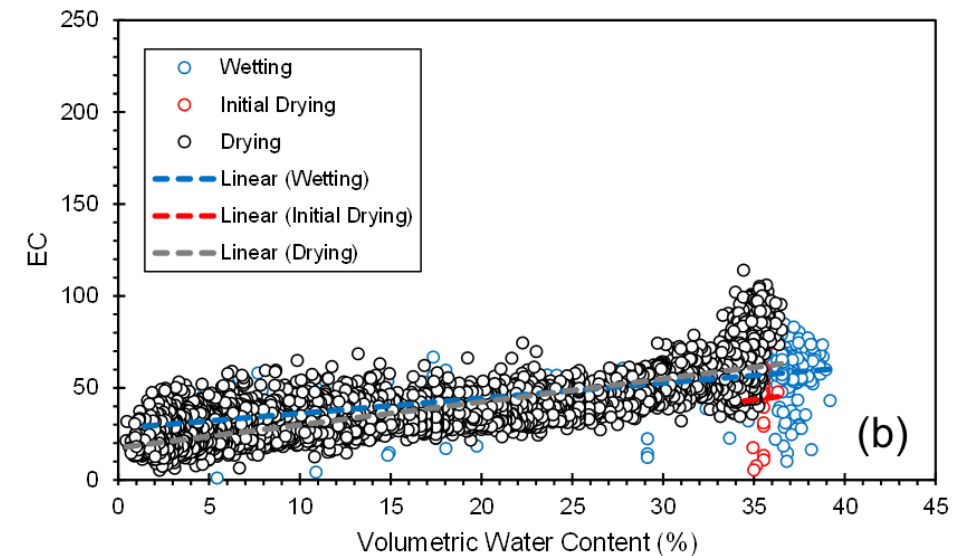
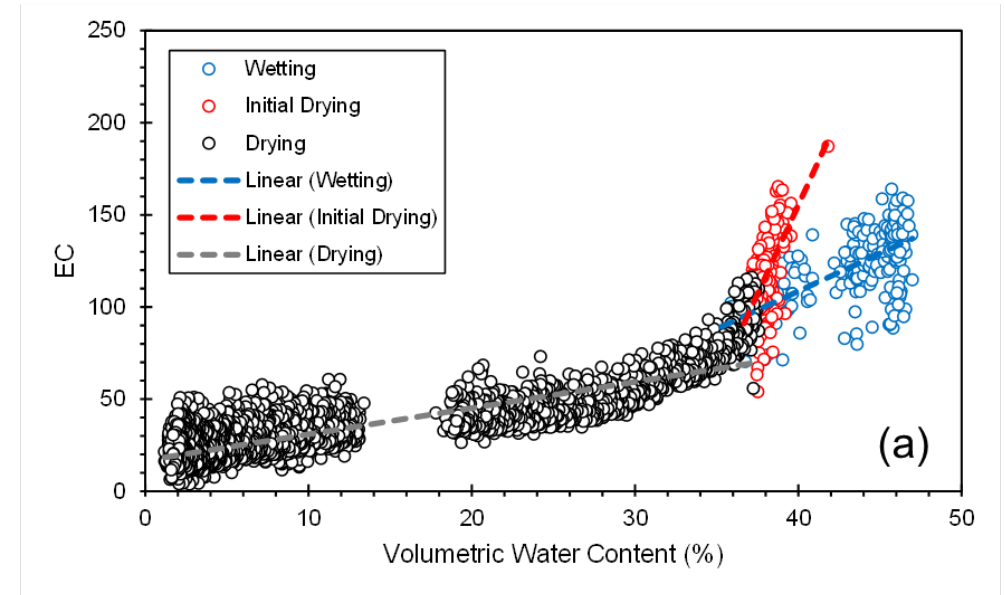
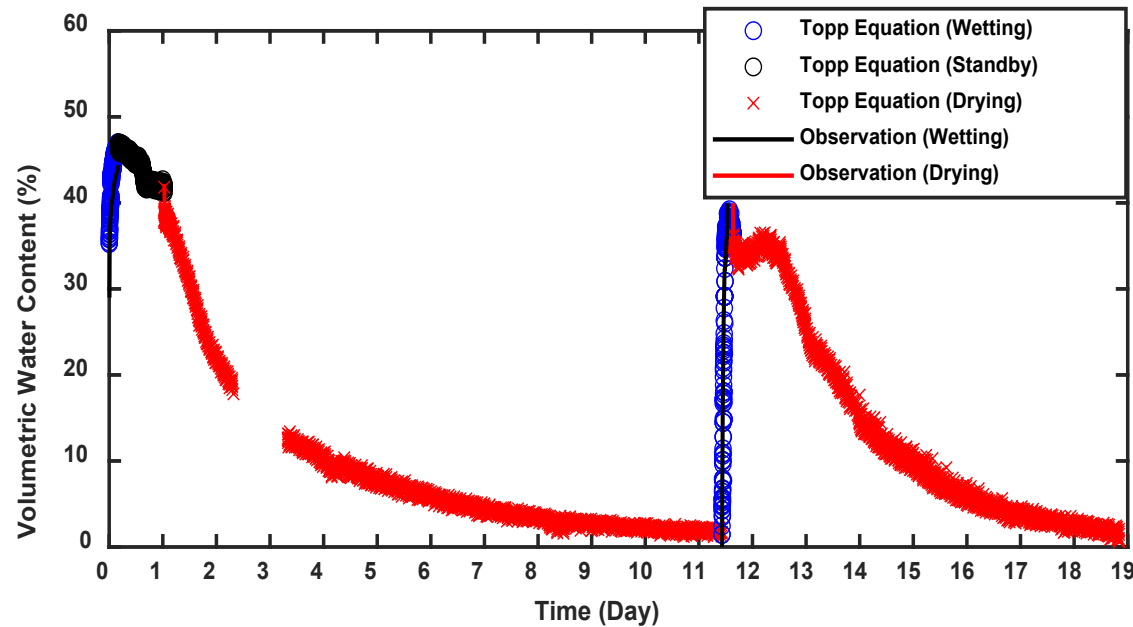
TDR Pressure Plate Test (Sample 1)

- 1.35 g/cm^3 , $\text{EC}_w=164 \mu\text{S/cm}$
- Wetting 1 = 40 minutes
- Drying 1 = 4 days
- Wetting 2 = 1 hours 10 minutes
- Drying 2 = 4 days.

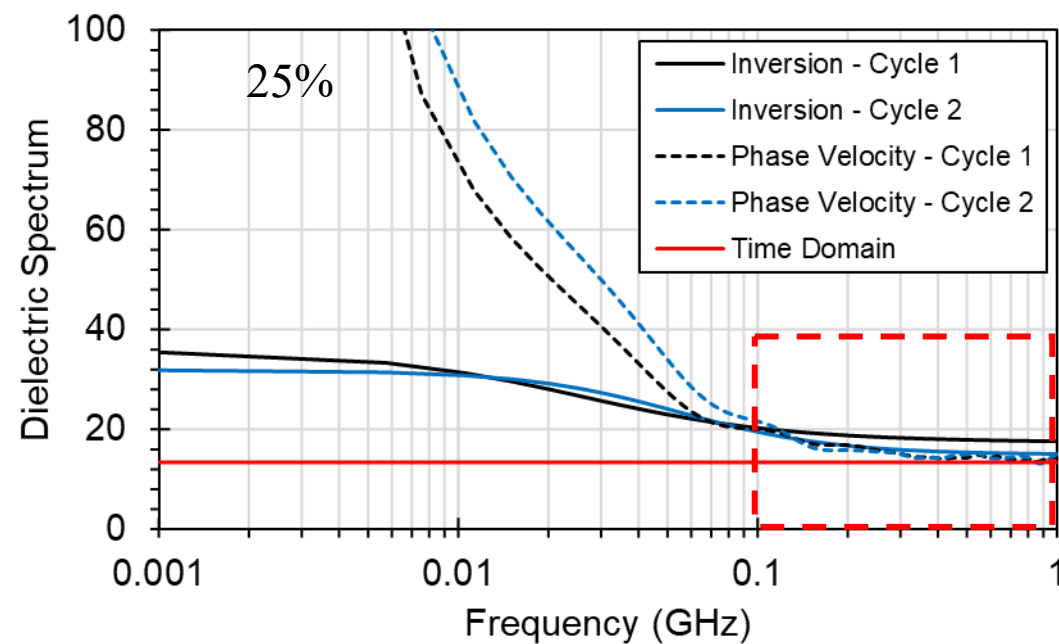
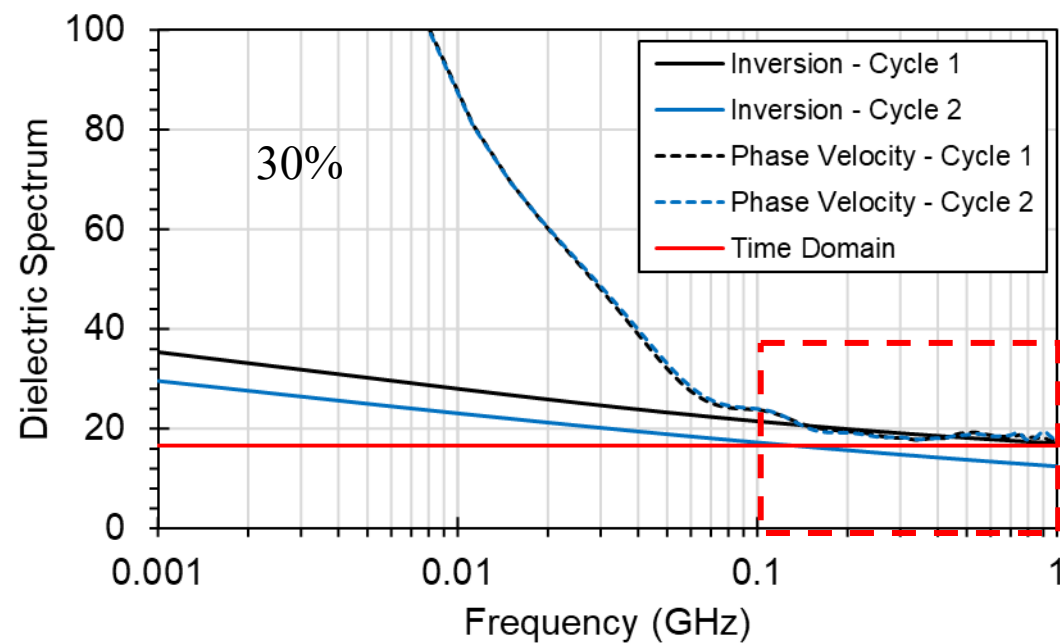


TDR Pressure Plate Test (Sample 2)

- 1.45 g/cm^3 , $\text{EC}_w=169 \mu\text{S/cm}$
- Wetting 1 = 40 minutes
- Drying 1 = 4 days
- Wetting 2 = 1 hours 10 minutes
- Drying 2 = 4 days.

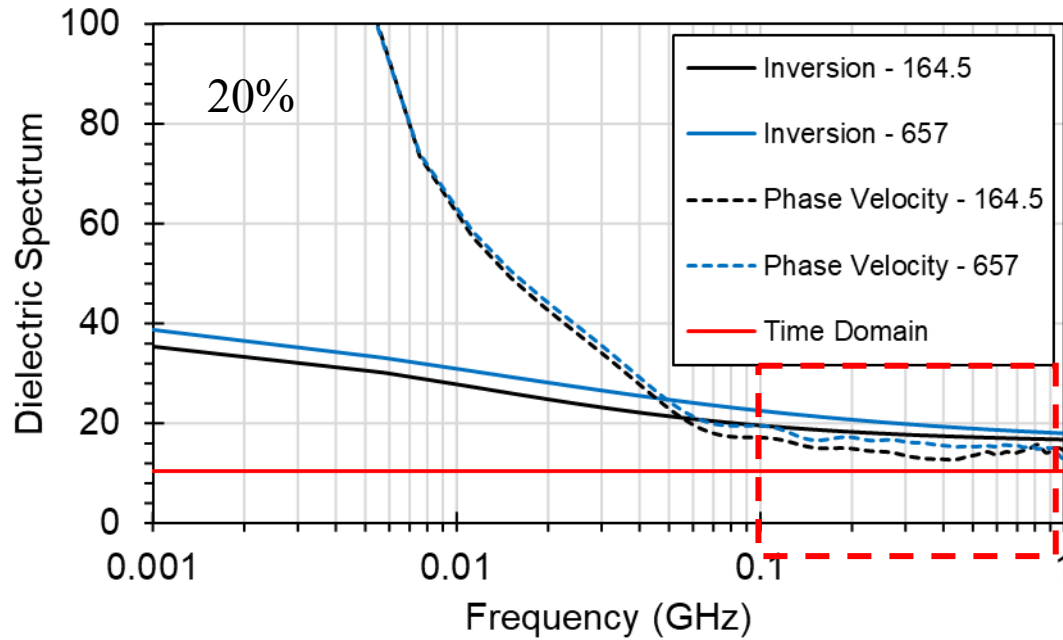


TDR Pressure Plate Test (Sample 2)

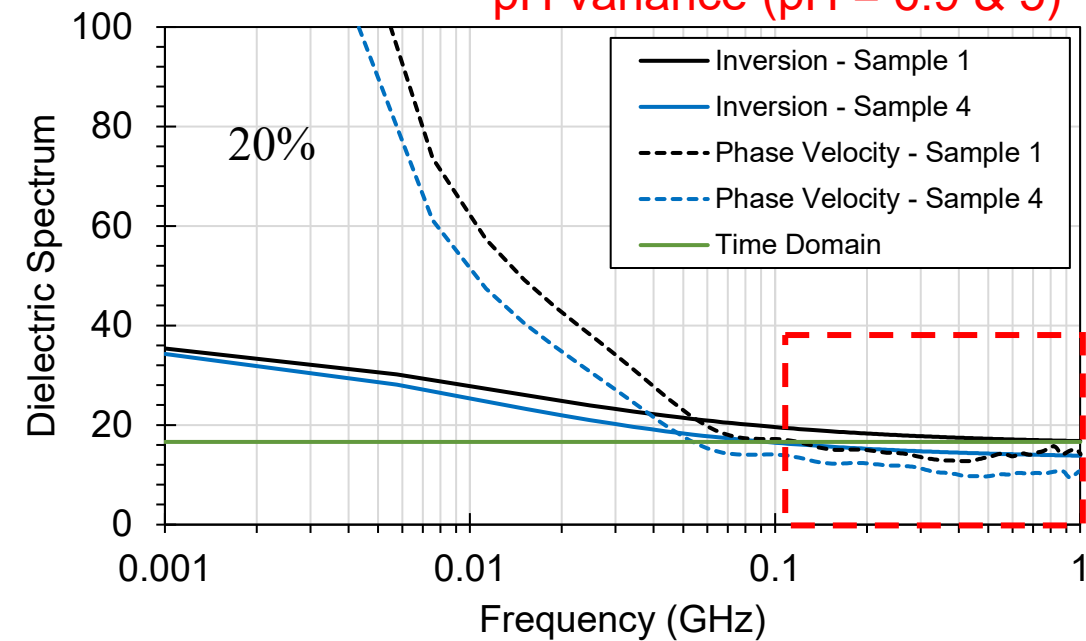


TDR Pressure Plate Test

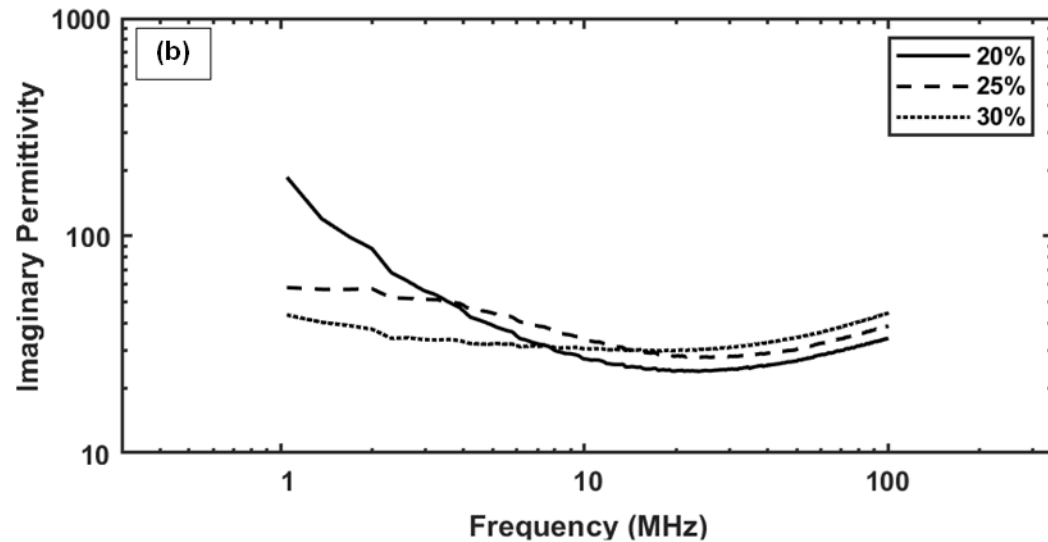
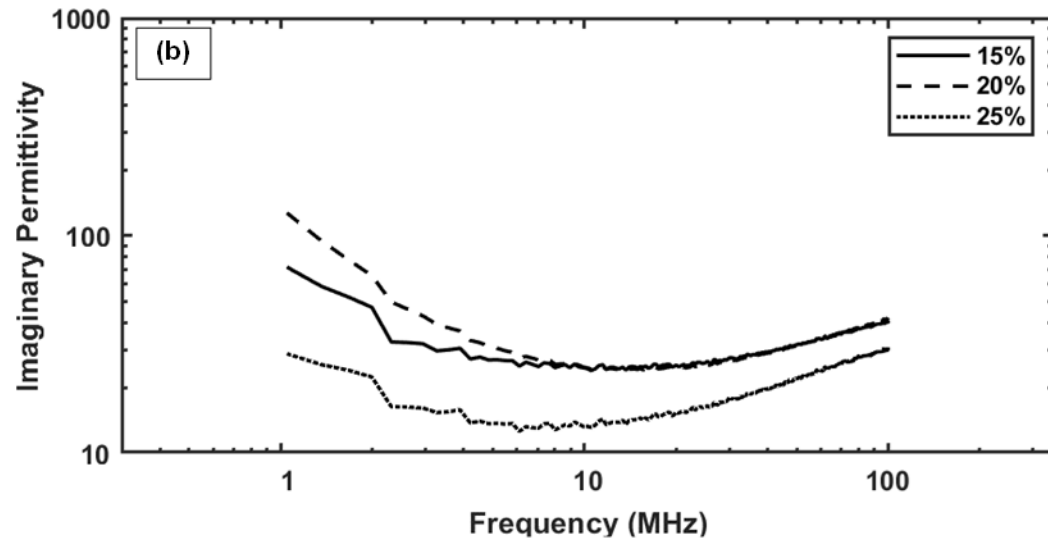
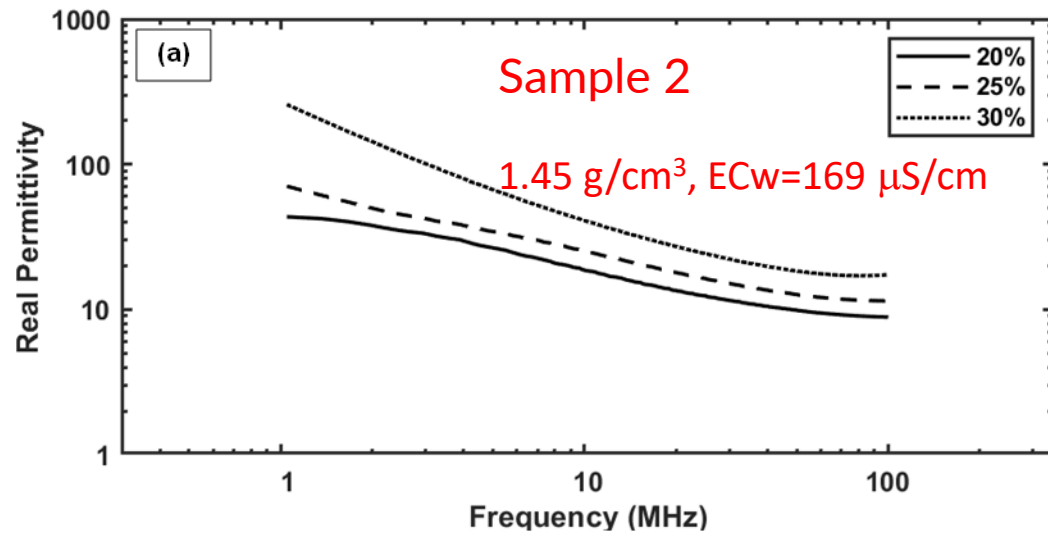
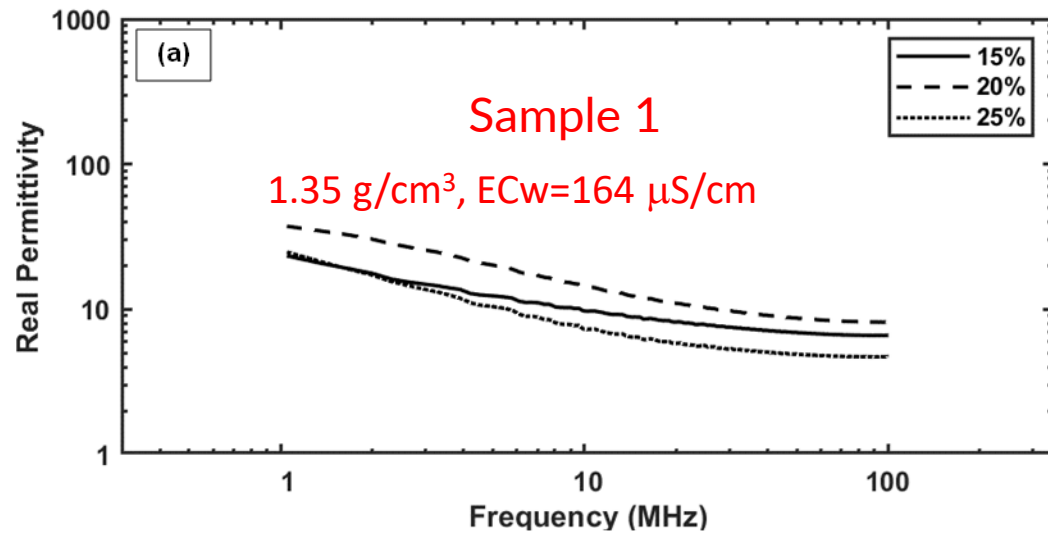
EC variance @ 1.35 g/cm³



pH variance (pH = 6.9 & 5)



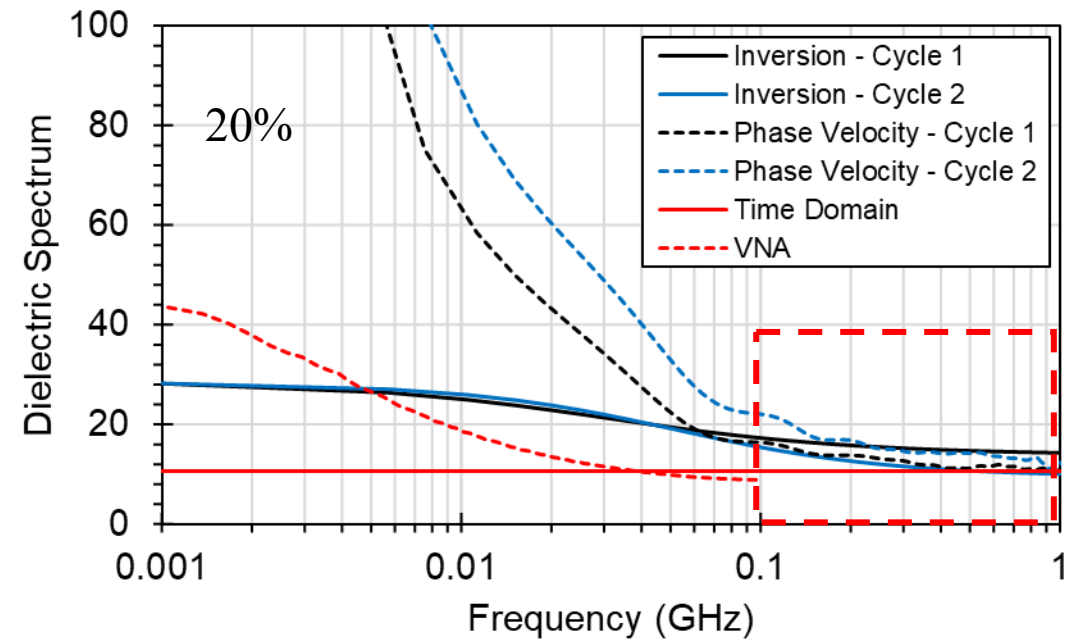
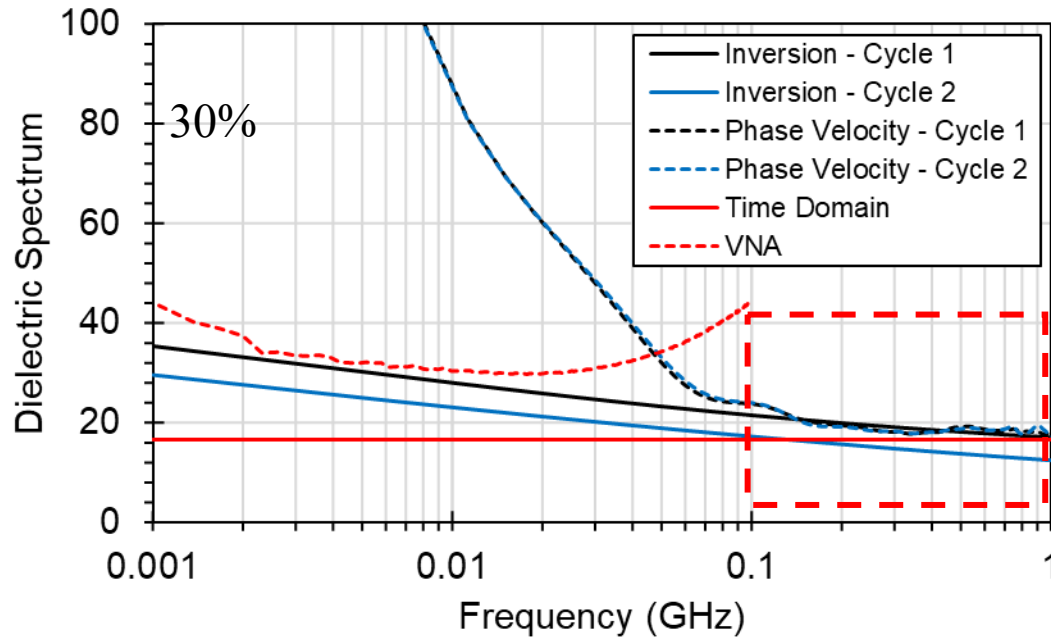
Vector Network Analyzer (VNA)



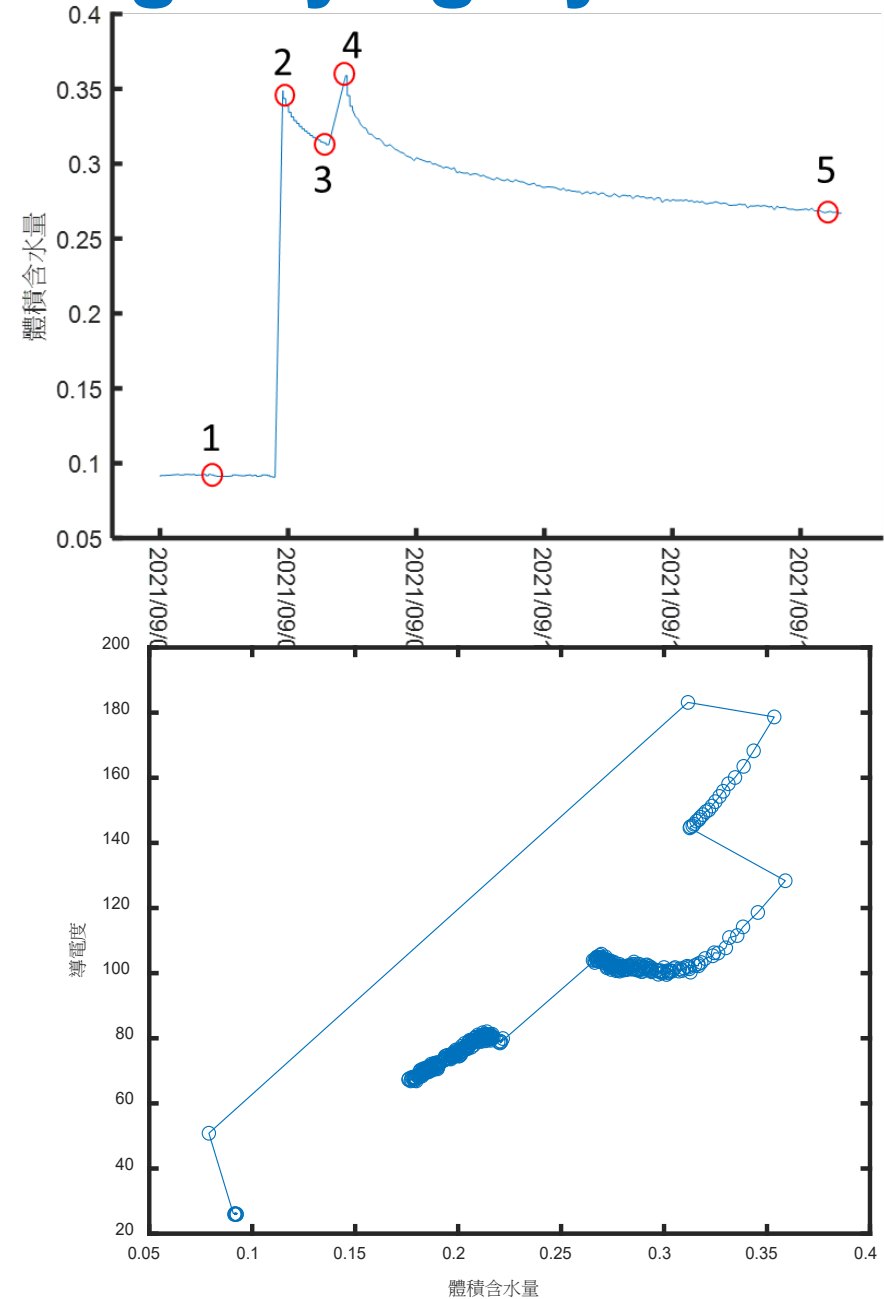
Vector Network Analyzer (VNA)

Sample 2

1.45 g/cm³, ECw=169μS/cm

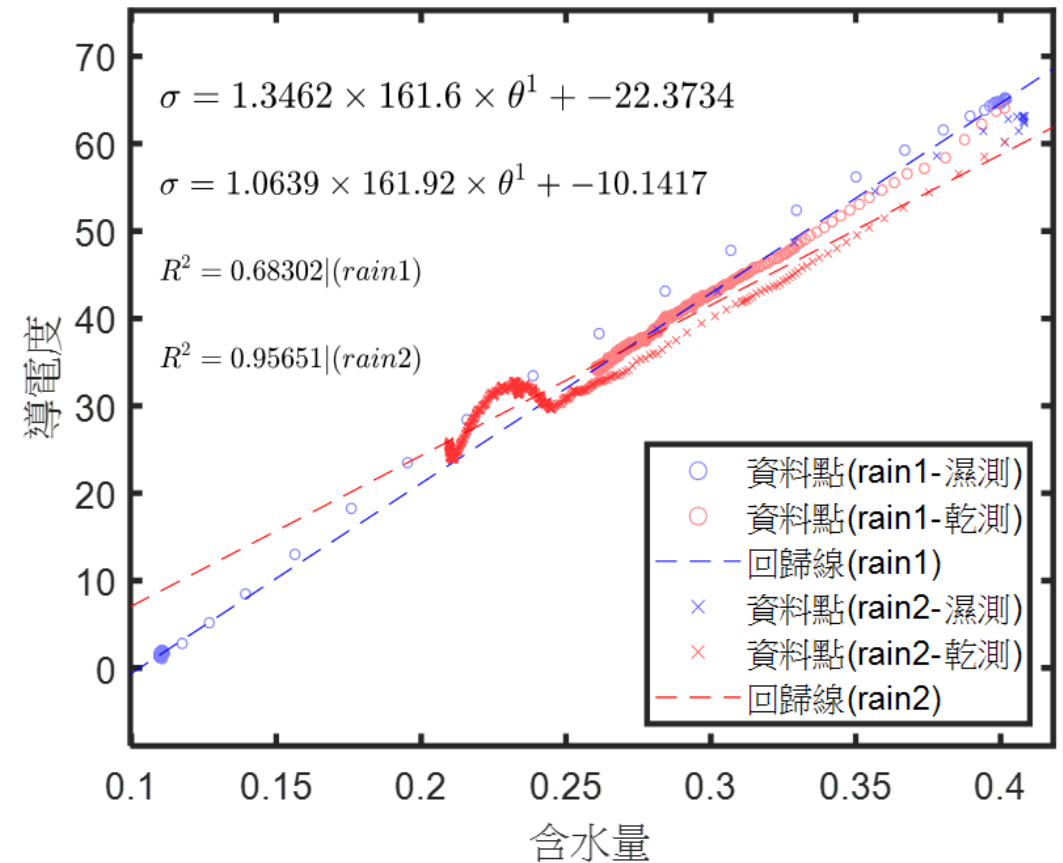
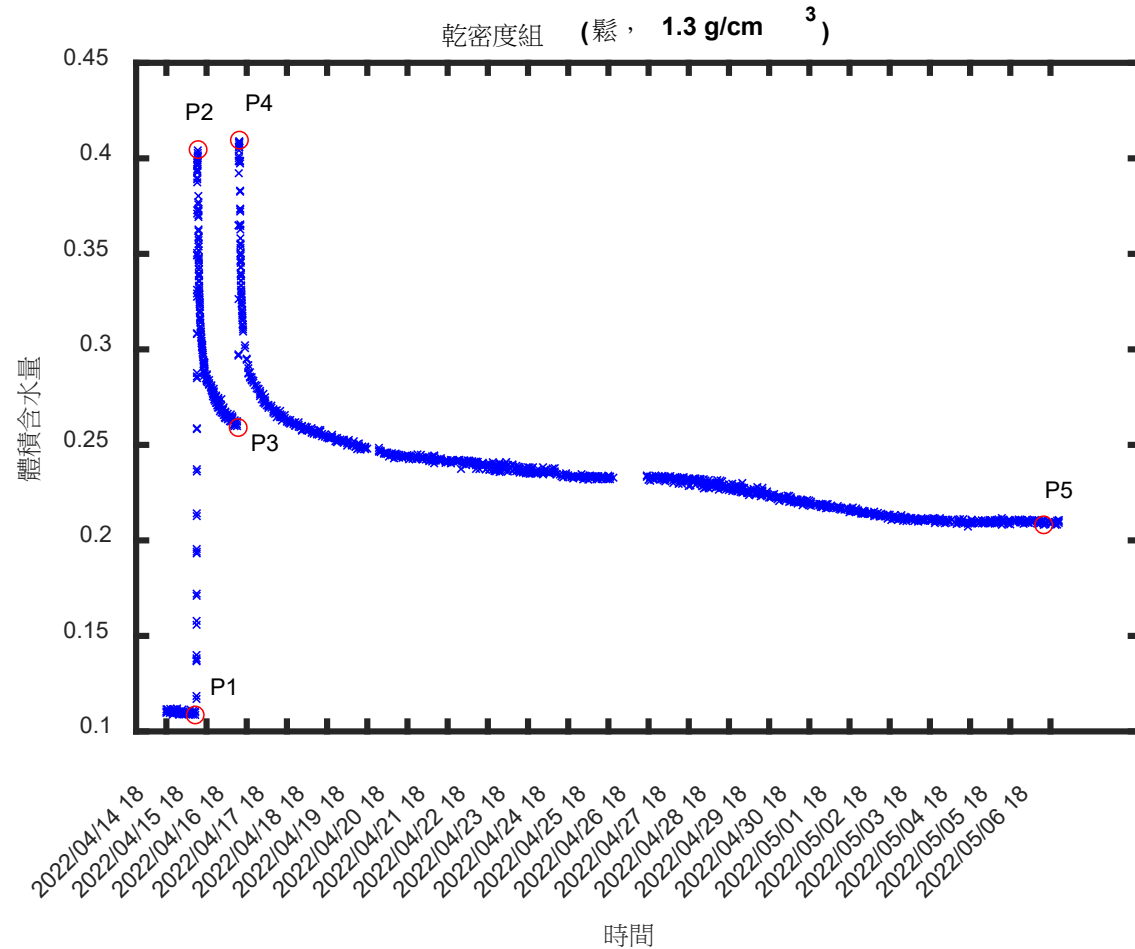


Sandbox Test for Soil Wetting-Drying Cycle



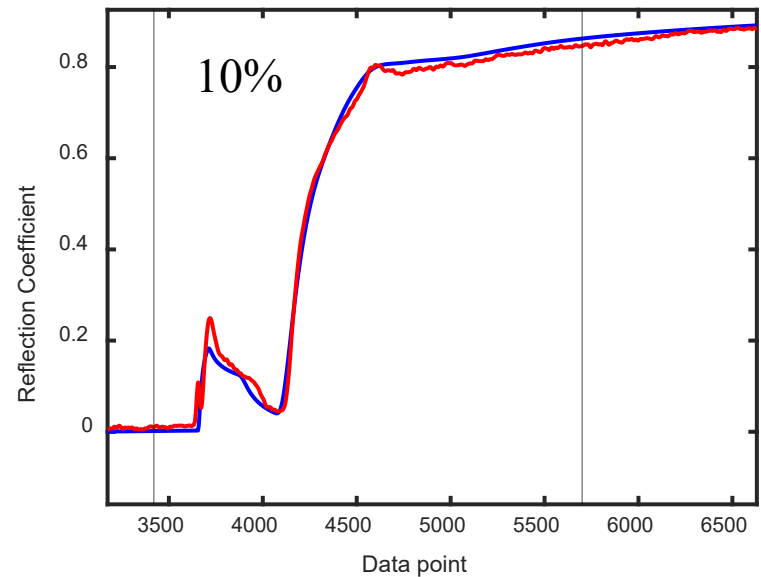
Sandbox Test Results

Dry Density Group (loose 1.3 g/cm³, 30μS/cm)

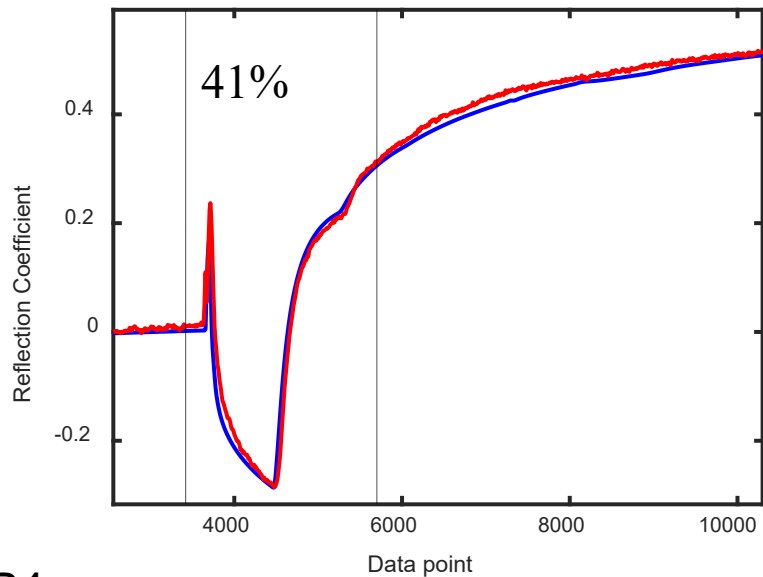


Sandbox Test Results

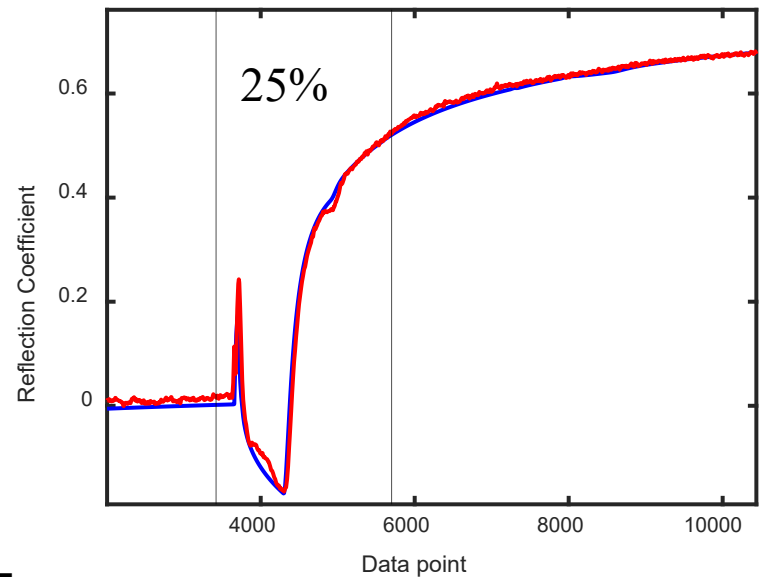
P1



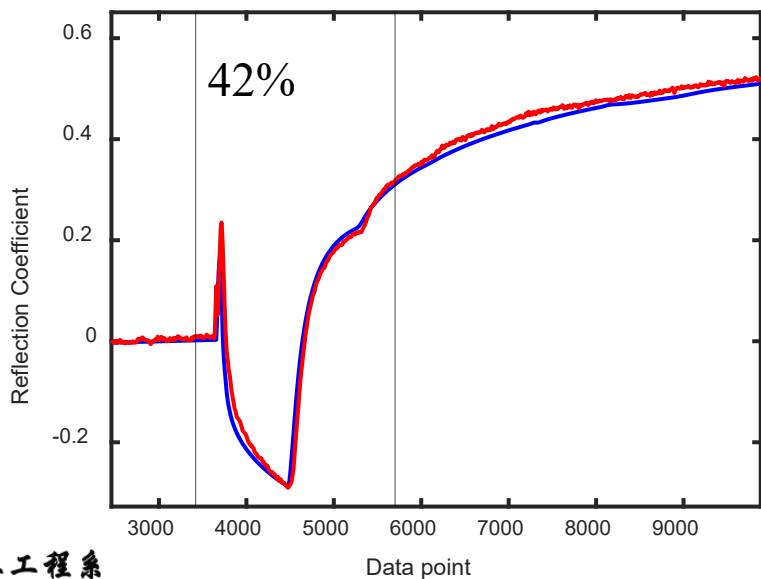
P2



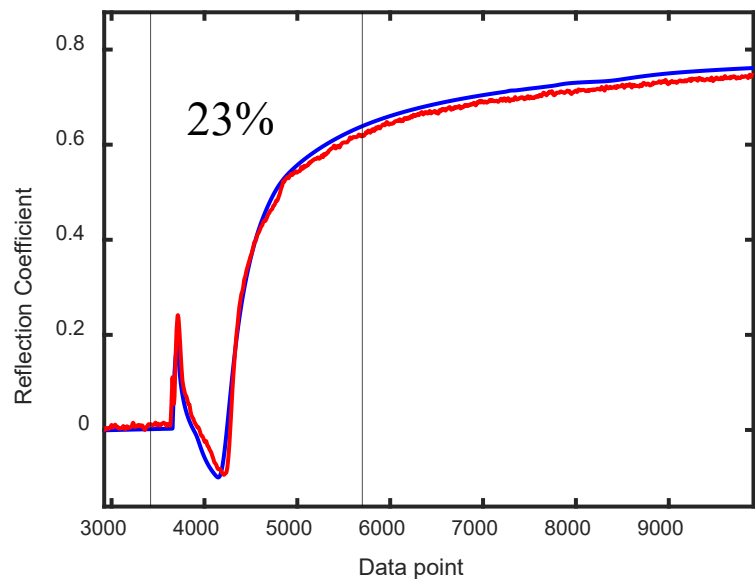
P3



P4

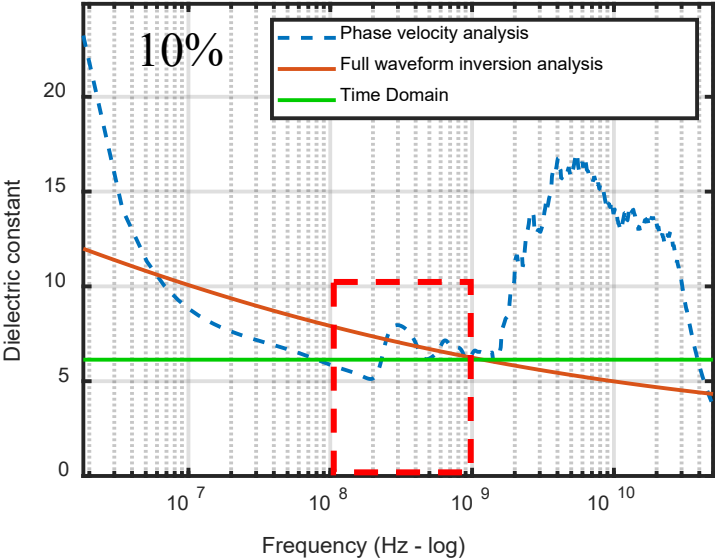


P5

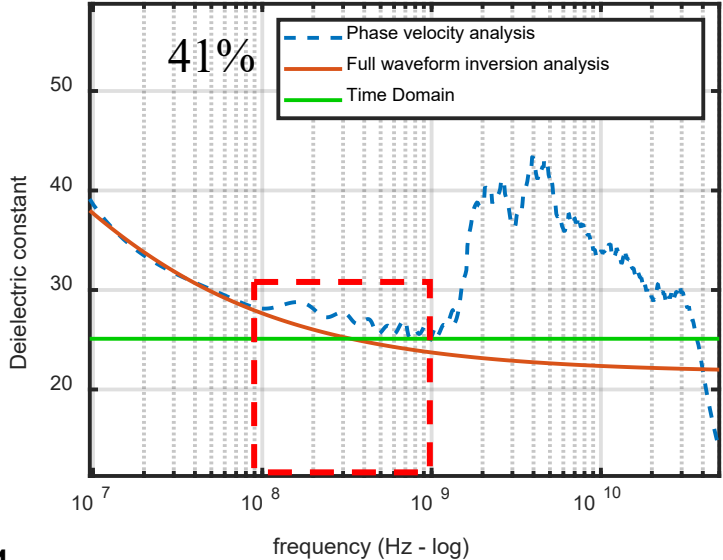


Sandbox Test Results

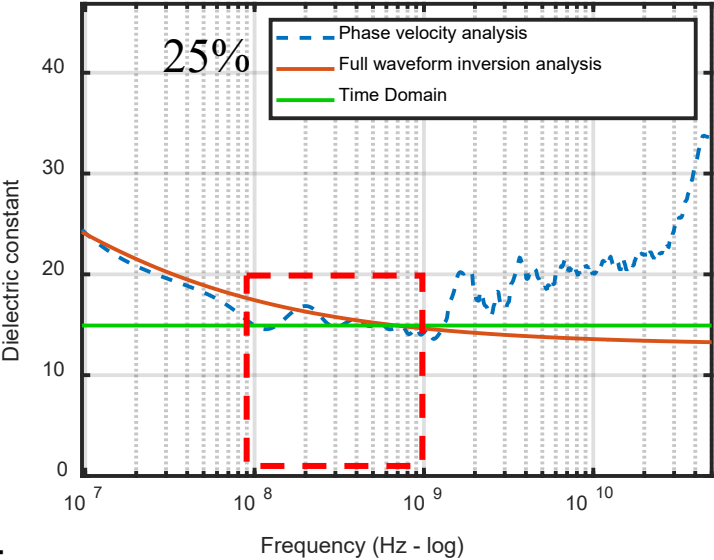
P1



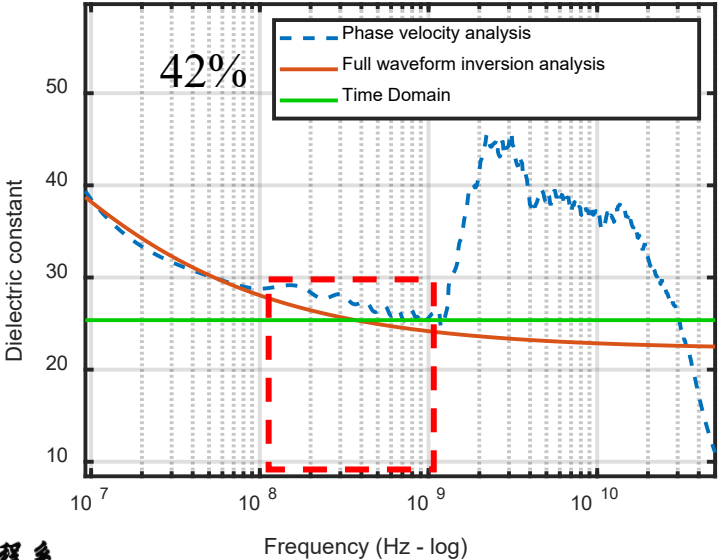
P2



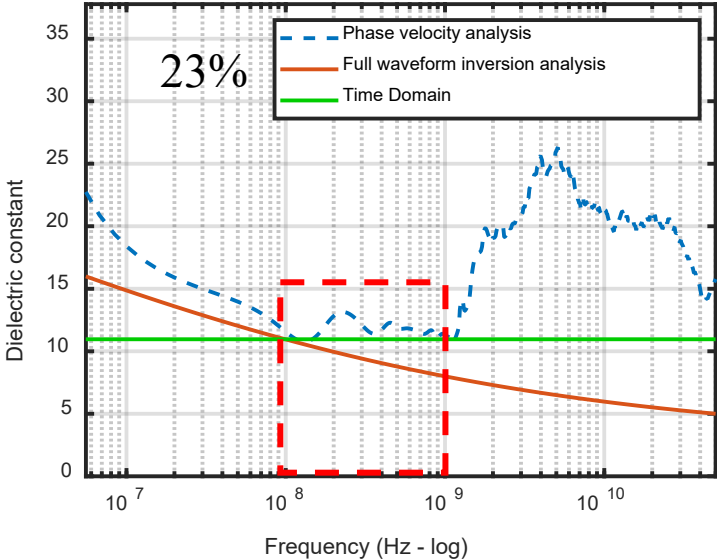
P3



P4

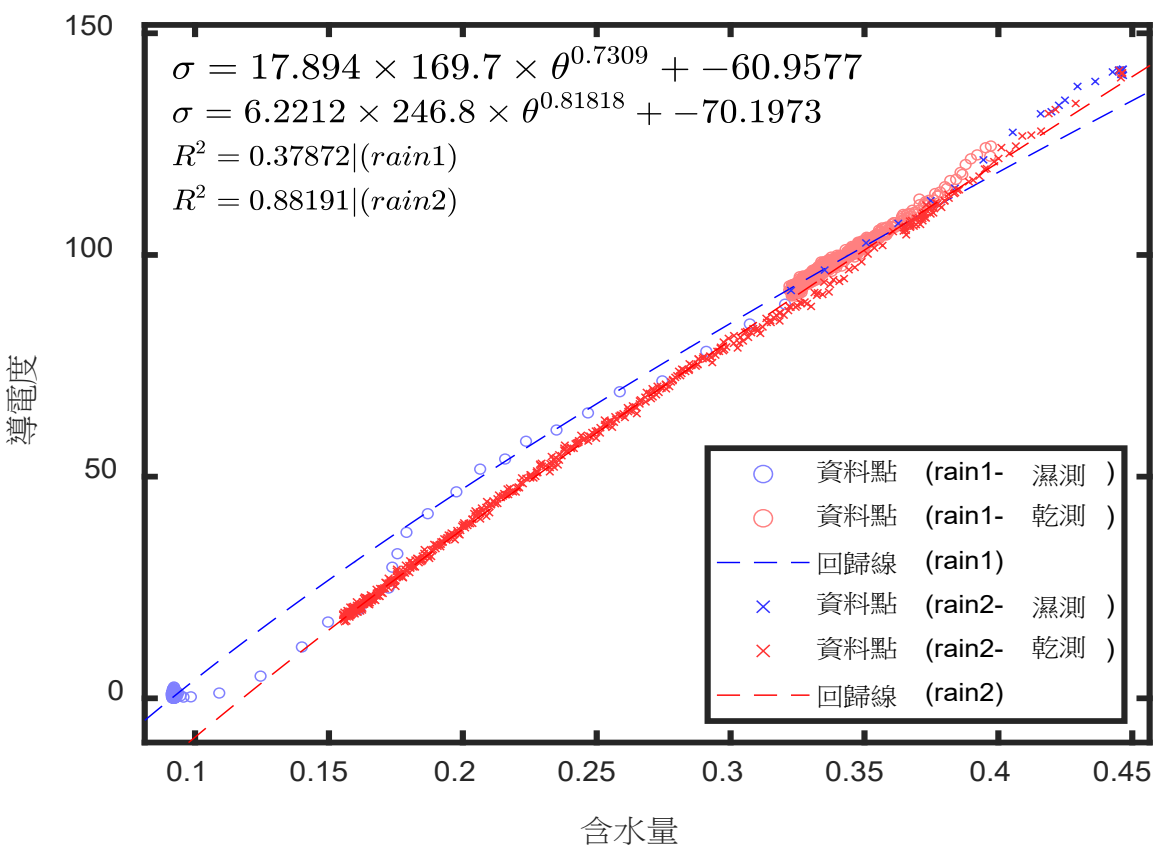
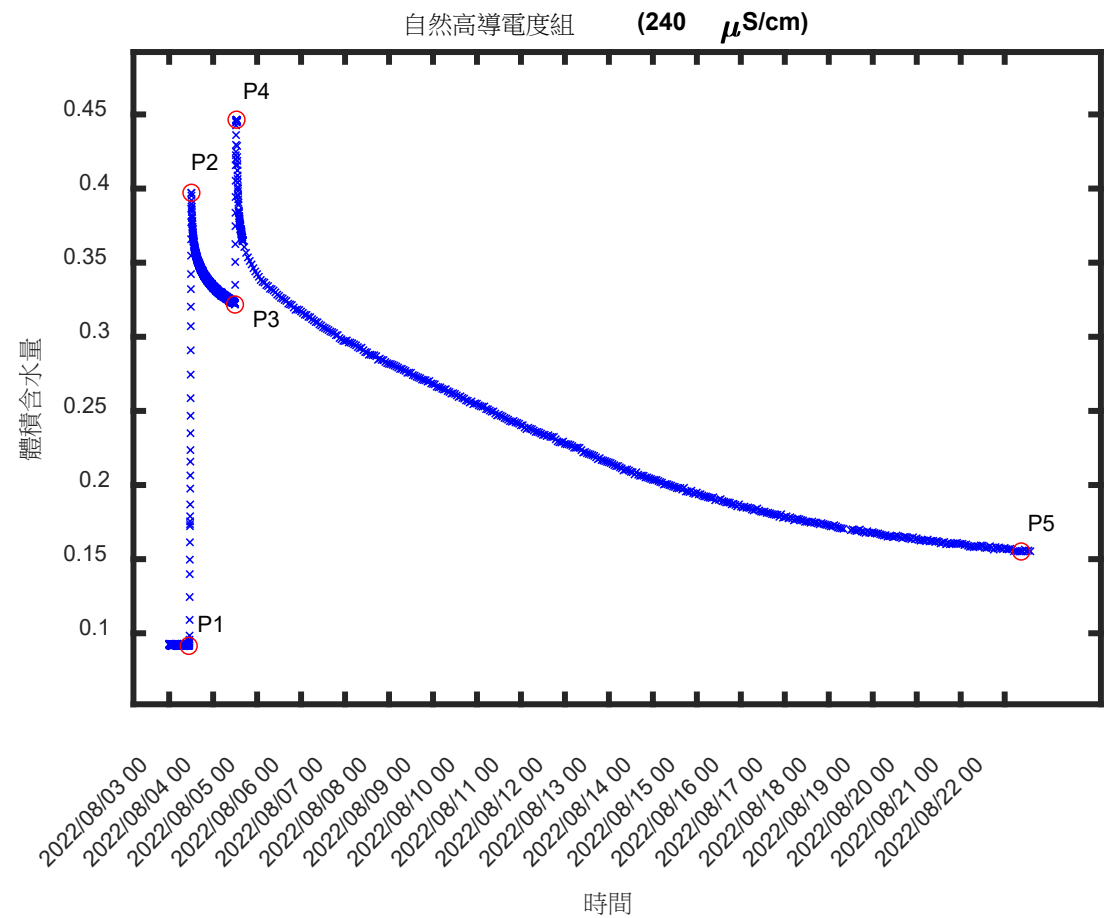


P5



Sandbox Test Results

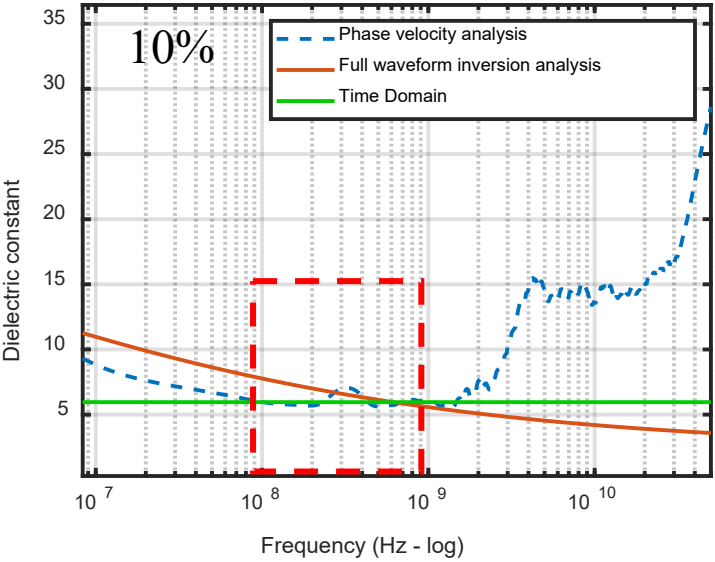
High Conductivity Group (1.3 g/cm³, 240 μS/cm)



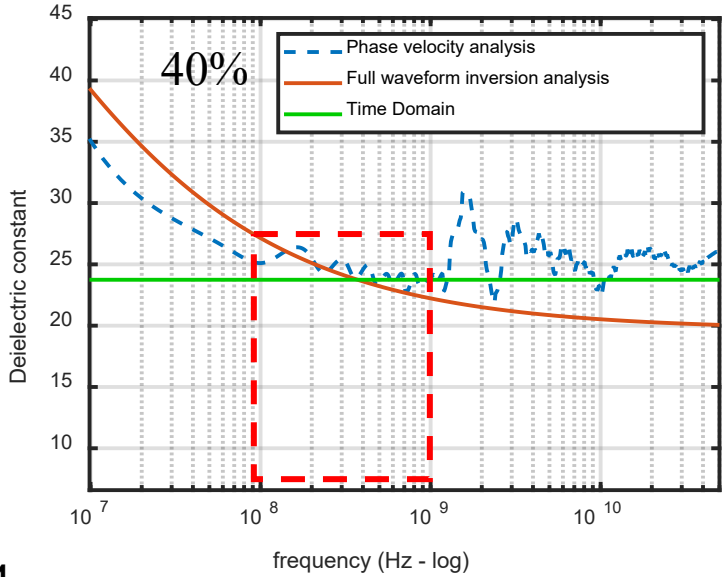
Sandbox Test Results

High Conductivity Group (1.3 g/cm^3 $240\mu\text{S/cm}$)

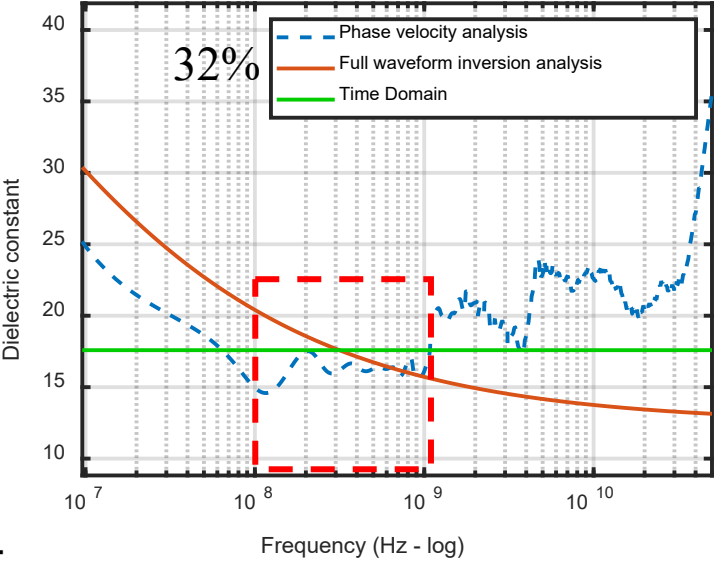
P1



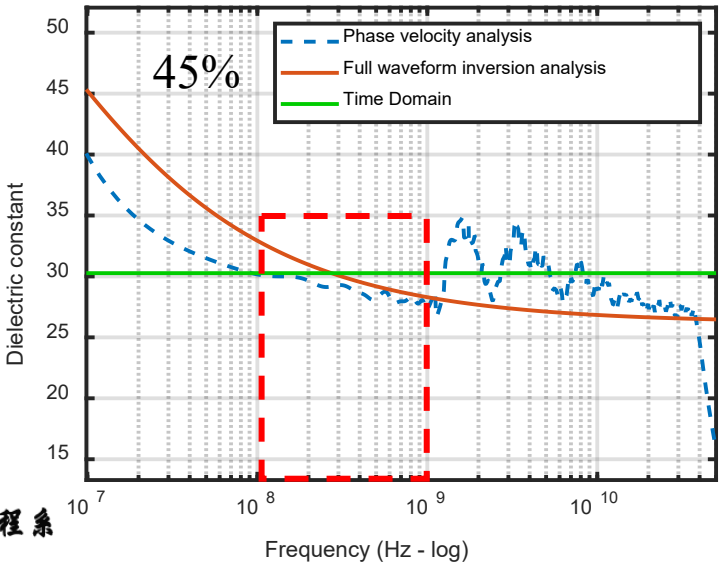
P2



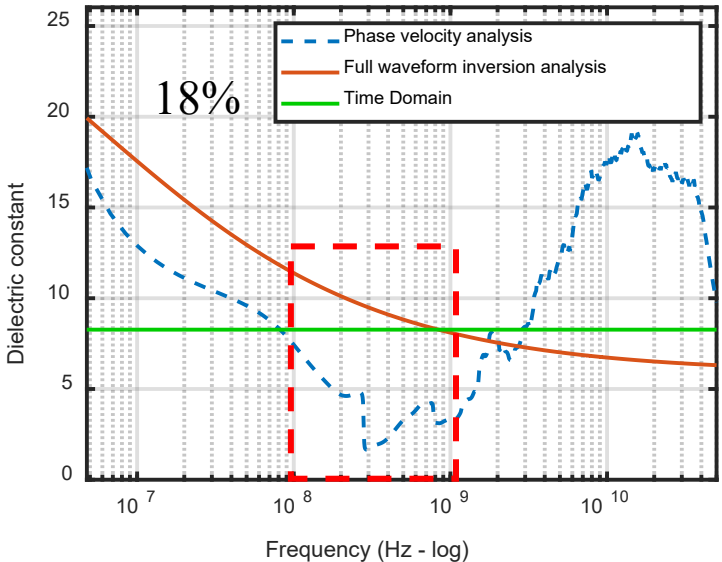
P3



P4

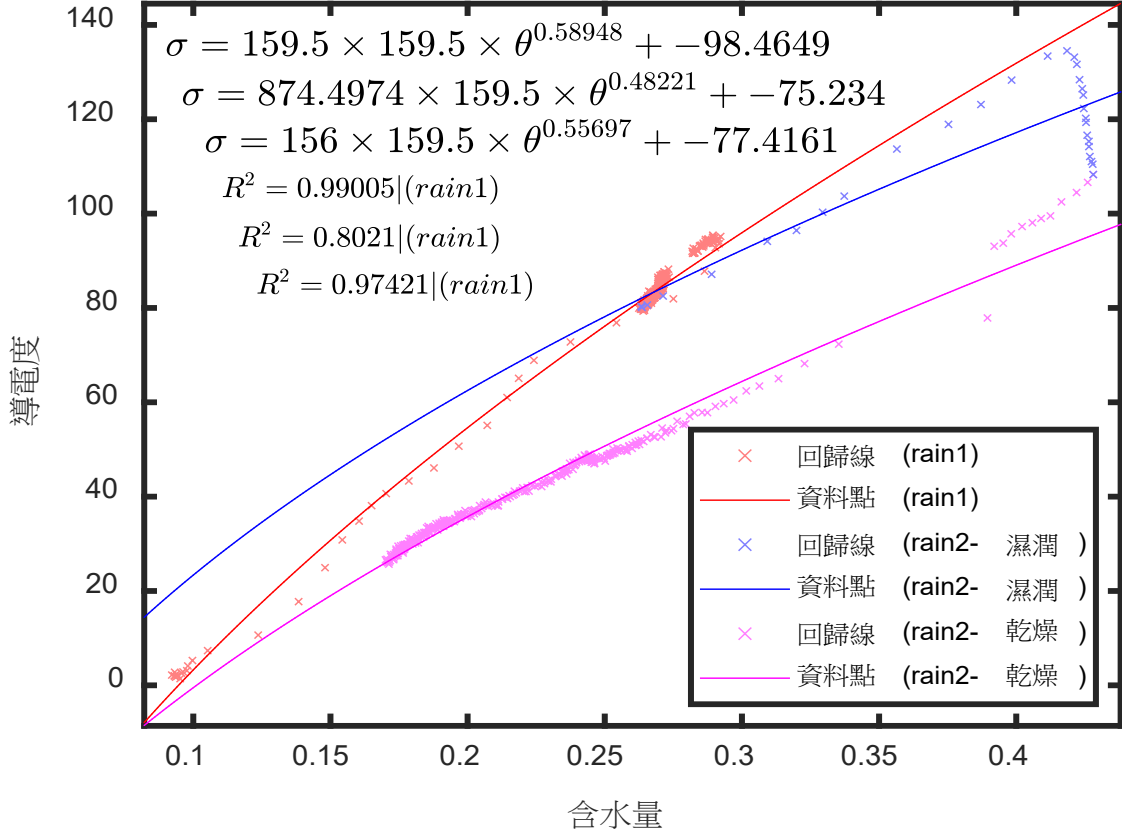
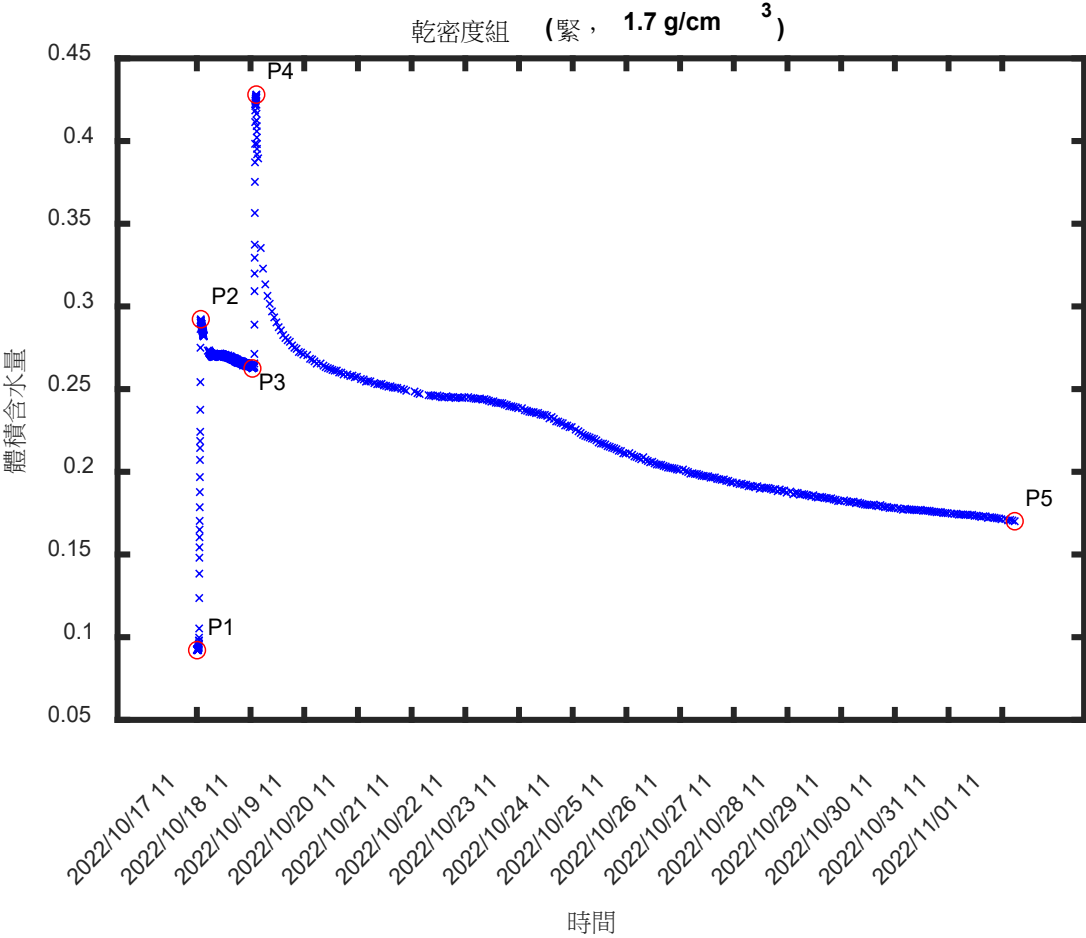


P5



Sandbox Test Results

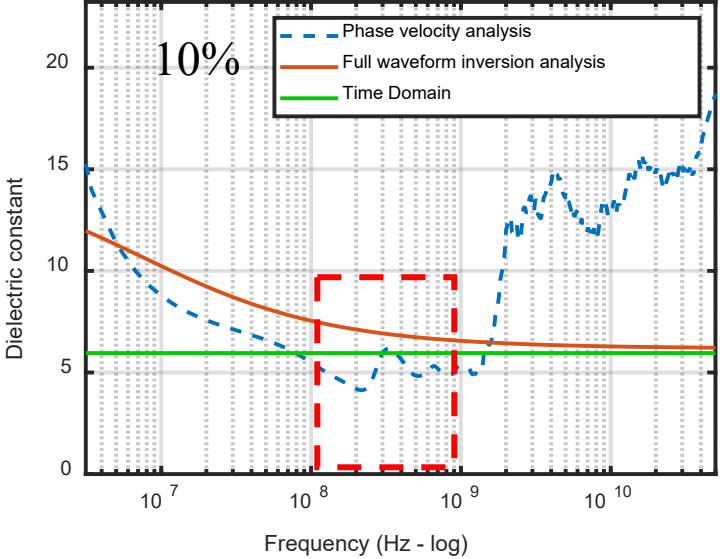
High Density Group (1.7 g/cm³ 30μS/cm)



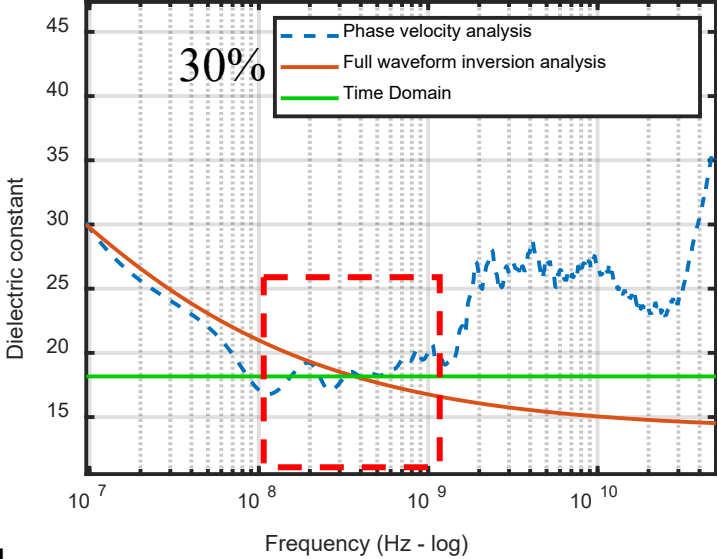
Sandbox Test Results

High Density Group (1.7 g/cm^3 , $30 \text{ }\mu\text{S/cm}$)

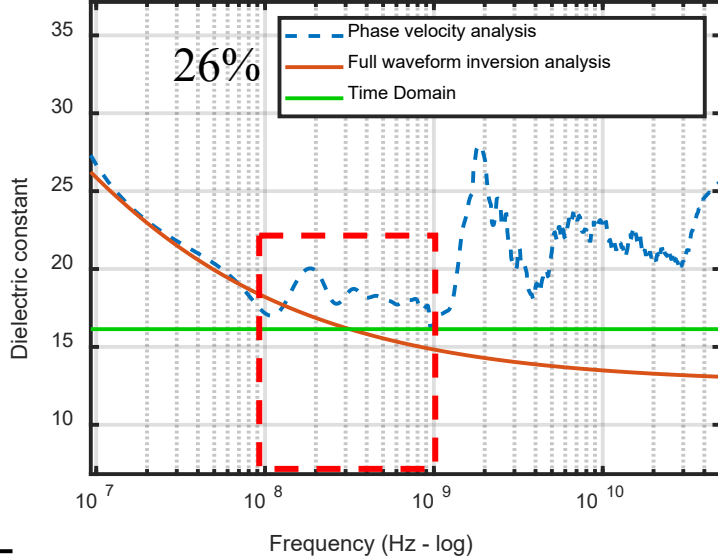
P1



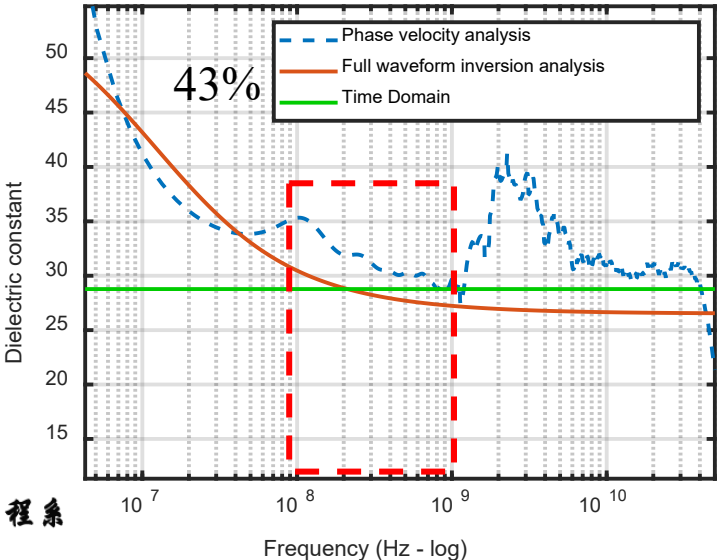
P2



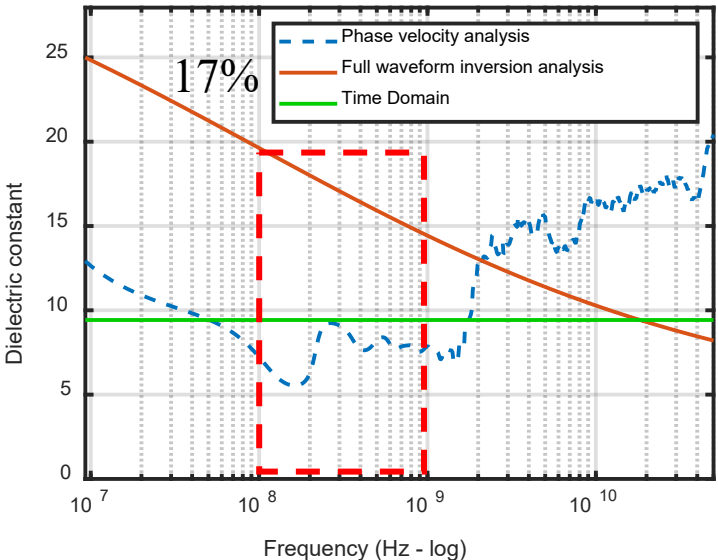
P3



P4

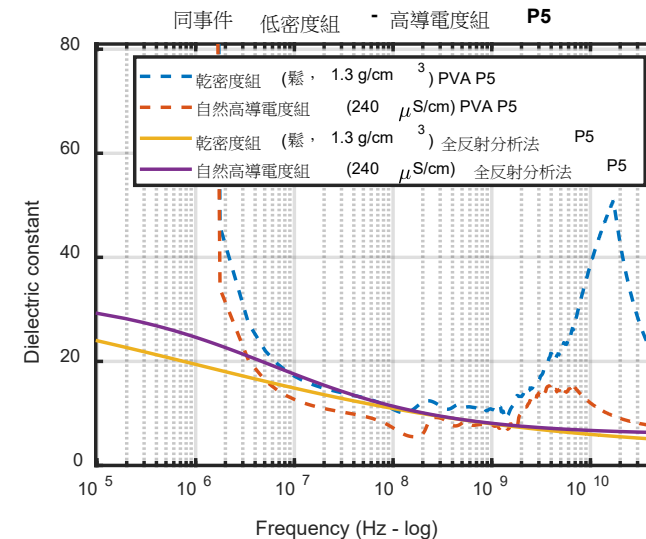
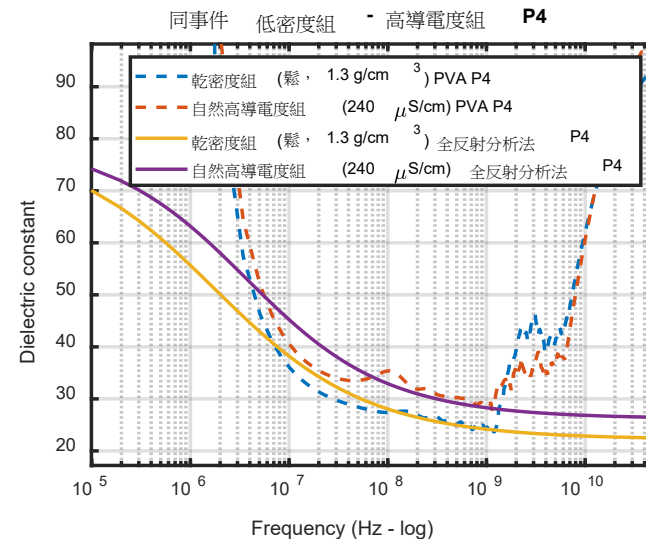
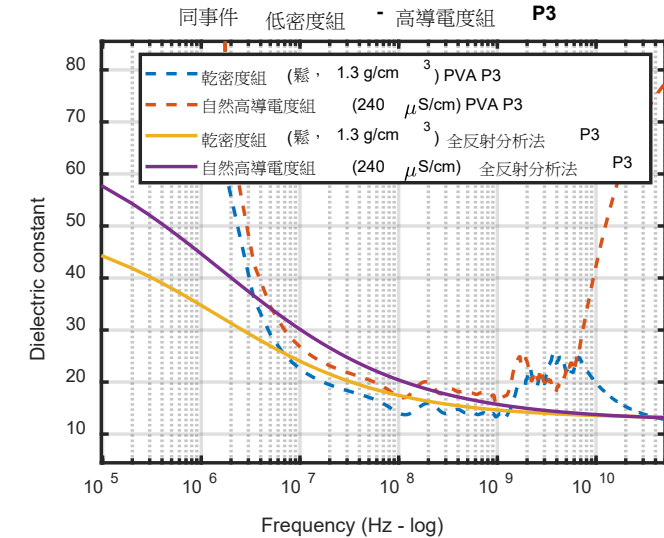
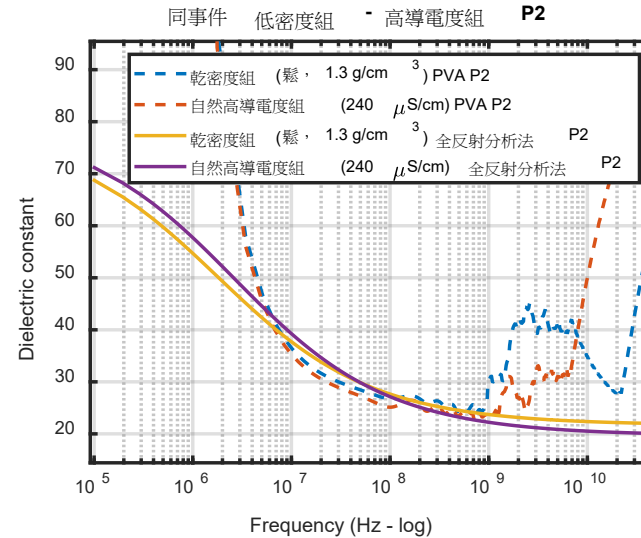
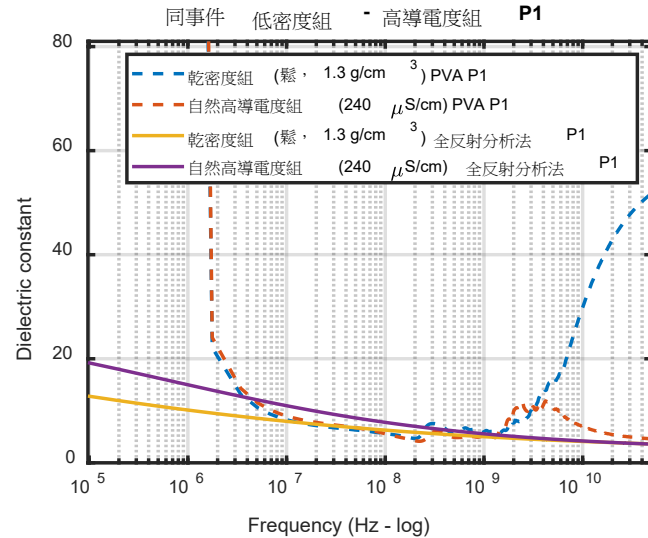


P5



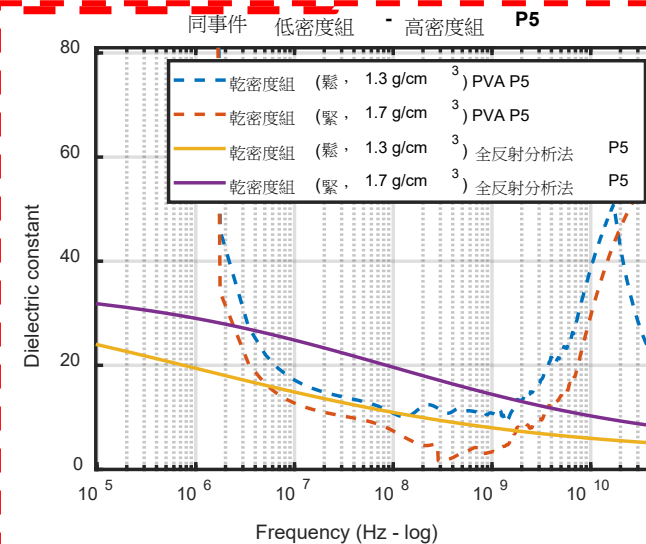
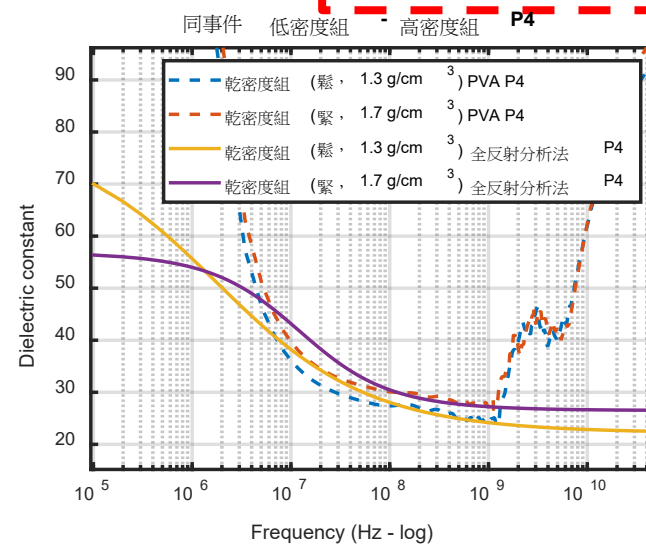
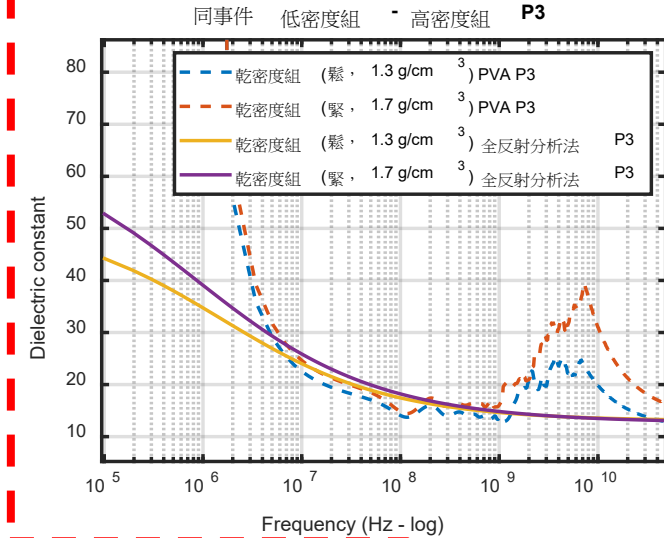
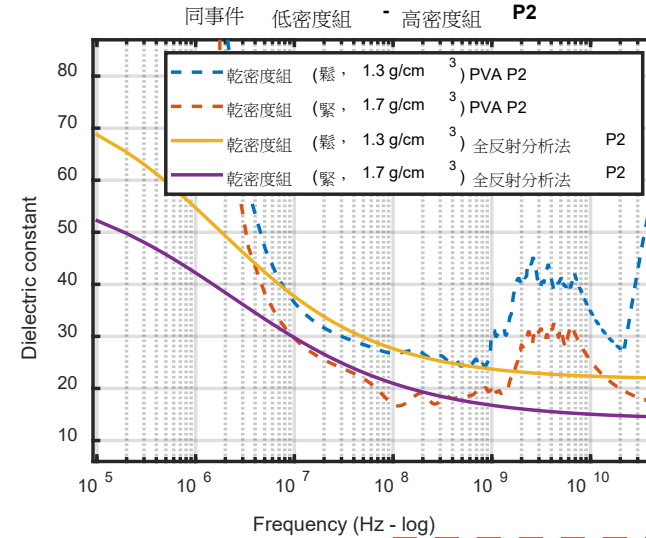
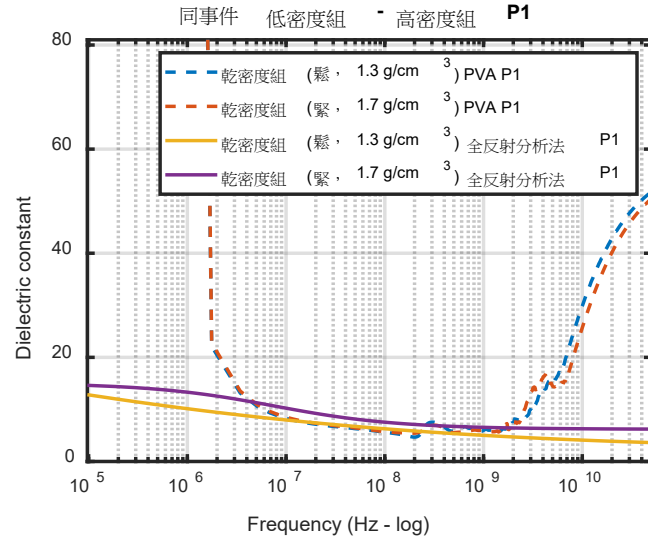
Sandbox Test Results: Spectrum Comparison

Low Density Group – EC comparison (30 vs. 240 $\mu\text{s/cm}$)

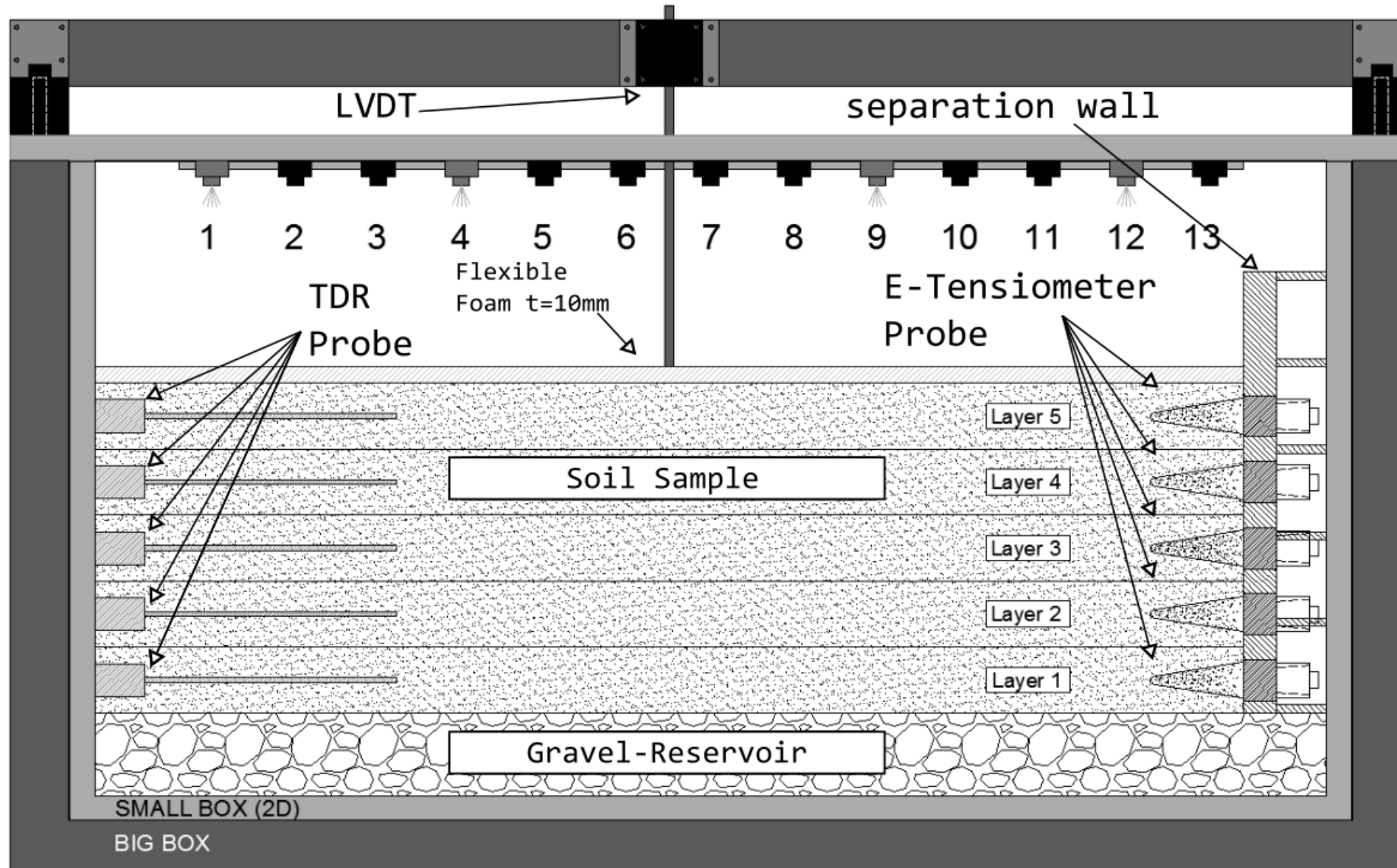


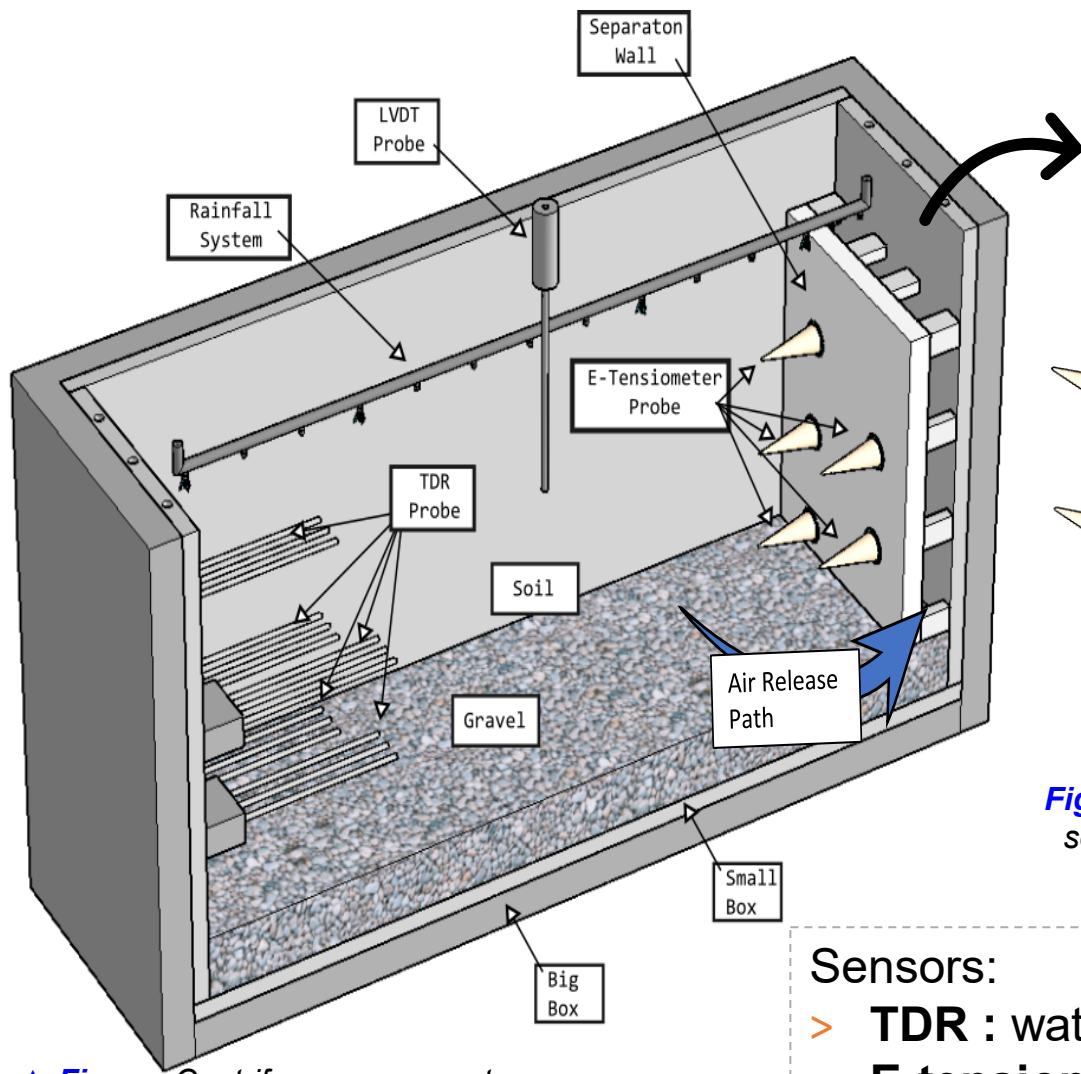
Sandbox Test Results: Spectrum Comparison

Low Density Group vs. High Density Group

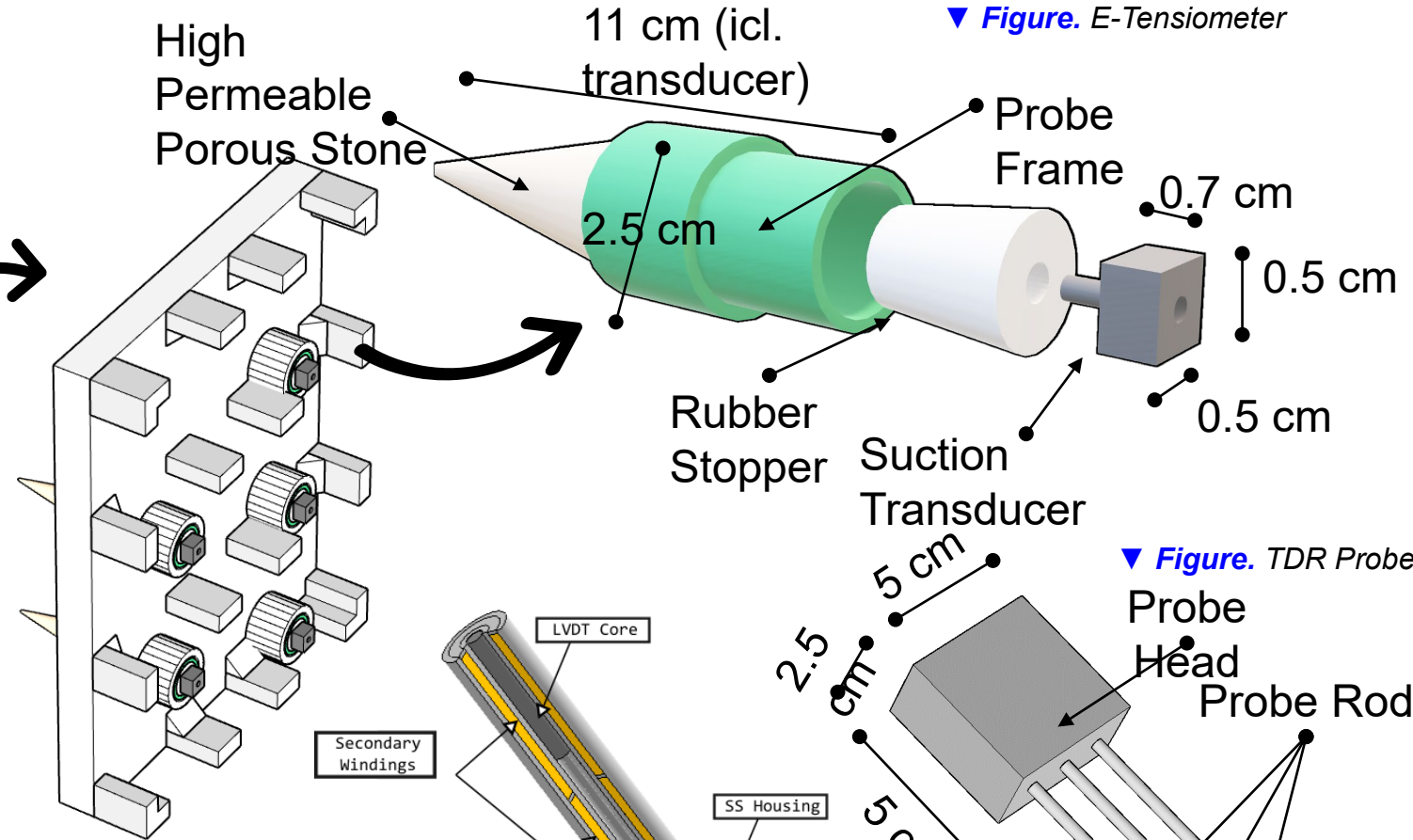


Centrifuge Permeameter





▲ **Figure.** Centrifuge permeameter model



▼ **Figure.** E-Tensiometer

▼ **Figure.** TDR Probe

▲ **Figure.** LVDT Probe

Figure. Carbon fiber separation wall

- Sensors:**
- > **TDR** : water content
 - > **E-tensiometer**: suction
 - > **LVDT** :sample deflection

$$\tau_1 = T_0 + \Delta t_1 = T_0 + \frac{2L\sqrt{k_{a1}}}{c}$$

Air

$$\tau_2 = T_0 + \Delta t_2 = T_0 + \frac{2L\sqrt{k_{a2}}}{c}$$

Water

$$\Delta t_1 - \Delta t_2 = \frac{2L(\sqrt{k_{a1}} - \sqrt{k_{a2}})}{c} \gg \text{got a solution } L$$

$$Ka = \left(\frac{c\Delta t}{2L}\right)^2$$



$$VMC = \frac{V_w}{V_{total}}$$



Figure. TDR: Ka Calibration

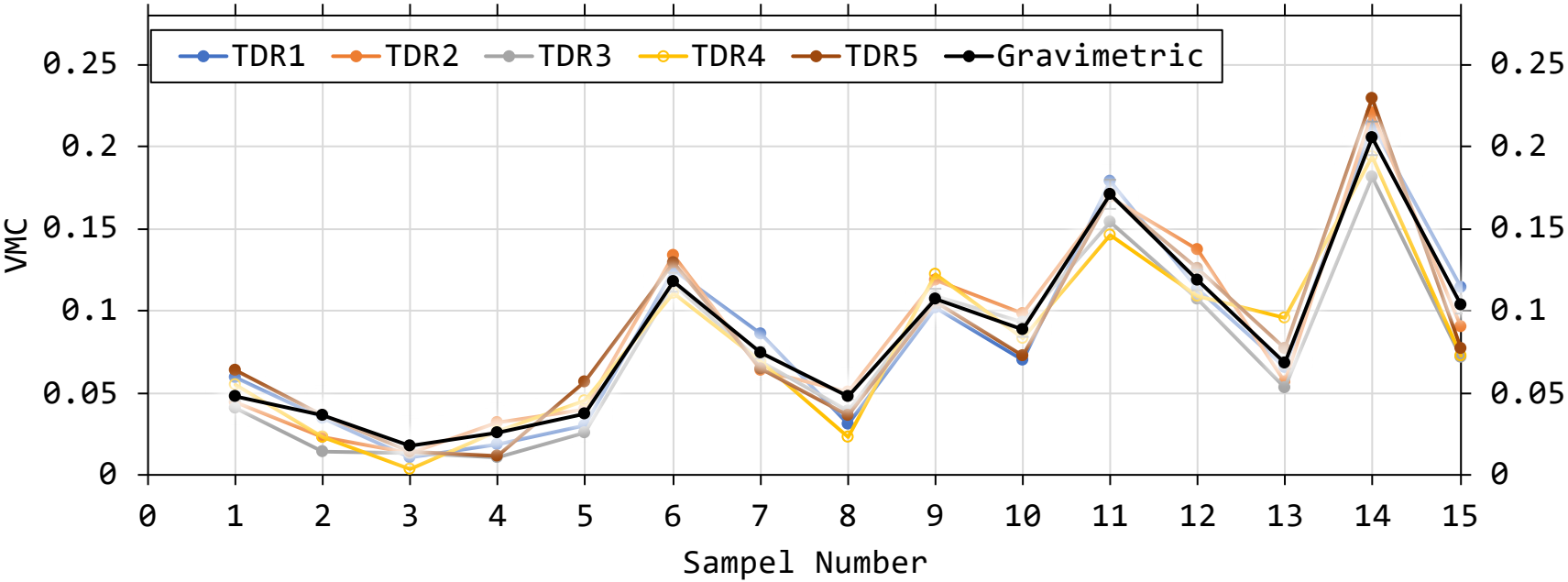


Chart. Real VMC value using gravimetric and Ka from TDR

Temp. : 17 °C
c : 2.998x10¹⁰ cm/s
γ_w : 0.998 gr/cm³

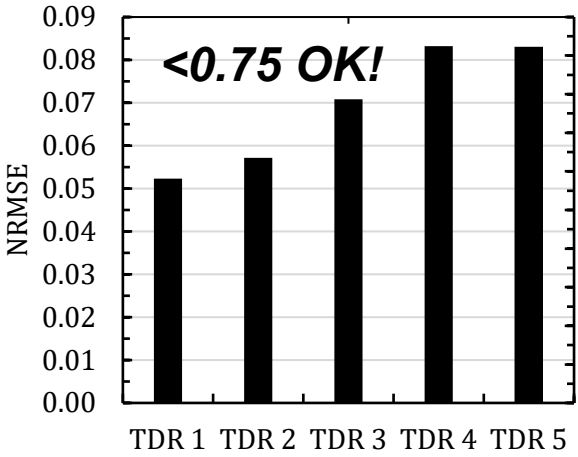


Figure. Error

Conclusions and Suggestions

- Topp et al., (1980) 估算體積含水量方程，在高潤濕速率的情況下會與實際測得(水室)比較下有延遲的現象。應用TDR在淺層滲透率大、含水量變化快速的土壤必須考慮這一現象
- 在導電度與體積含水量關係中，與較低的乾濕速率相比，乾濕速率較高的土壤具有較高的遲滯現象。高密度組(高密度組-- 1.7 g/cm^3)可以看到明顯的遲滯迴圈
- 乾燥速率較低的土壤相比，乾燥速率較高的土壤的介電頻譜在每個週期之間的差異較大



WLF 7 2026 7TH WORLD LANDSLIDE FORUM

Venue: Taoyuan Convention and Exhibition Center
Date: April 7 (Tue) – April 12 (Sun), 2026

TAIWAN
TAOYUAN

*Landslide Mitigation for
Better Sustainability*

www.wlf7.org

敬請指教

