

電探在坡地工程的應用、問題探討 及含水特性分析

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國立交通大學

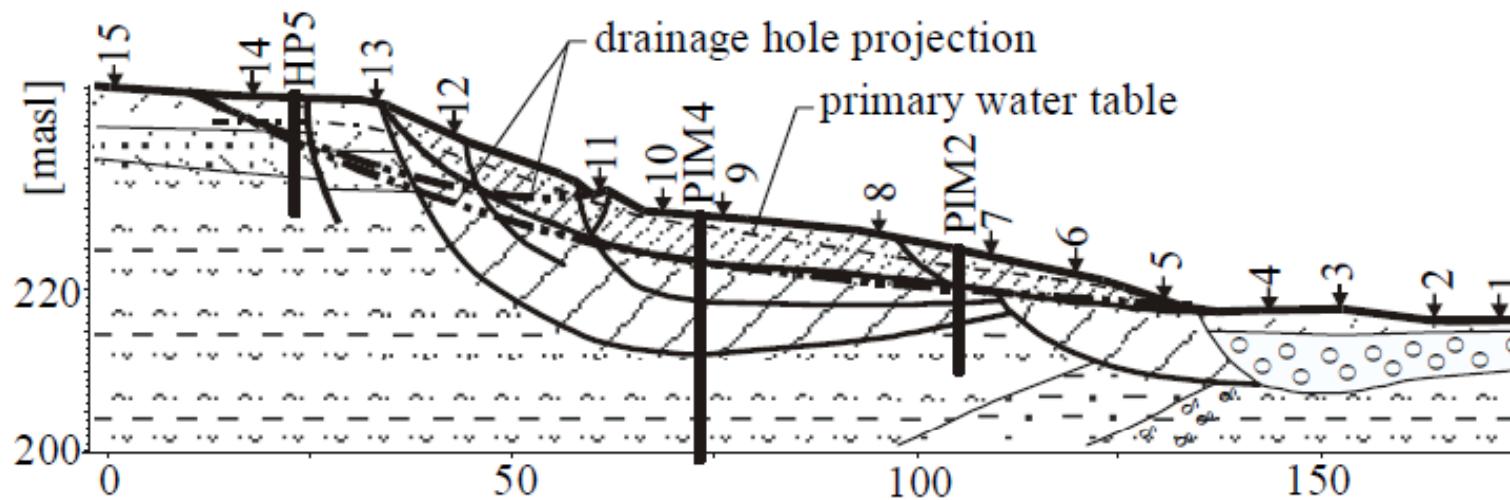


簡報大綱

- 坡地工程地球物理探測
- 二維地電阻探測應用案例
- 二維地電阻探測的解析能力、陷阱與對策
- 電探在坡地含水特性的量化分析

地滑評估需考慮的問題

- 水文地質模式與材料特性
- 滑動面位置與滑動體的三維幾何
- 邊坡位移的偵測與描述



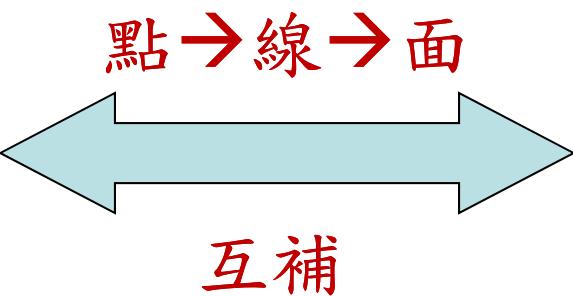
地物探勘的角色

- 調查邊坡的地質結構
- 量測與工程參數相關的物理性質

地工調查方法
(侵入式試驗)

鑽探
貫入試驗

力學反應
取樣空間小
量測範圍小
空間解析度高



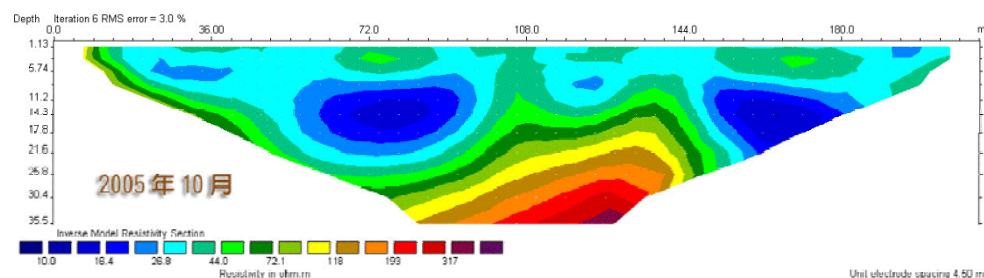
地球物理探勘
(非破壞性試驗)

震波
電力
電磁波...

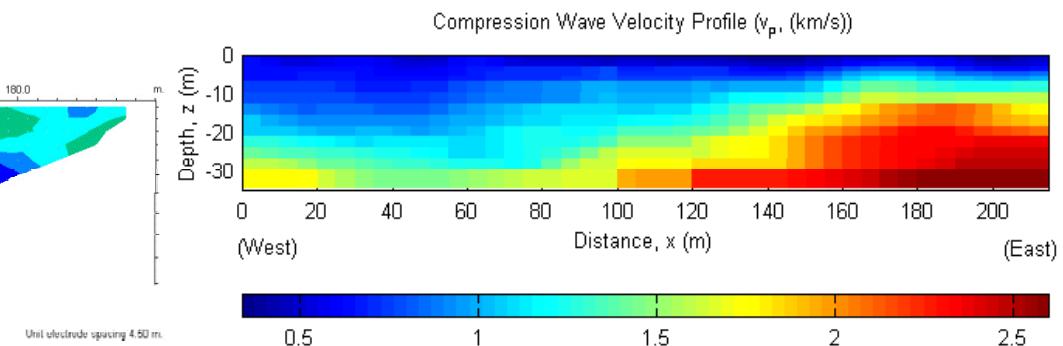
物理性質
取樣空間大
量測範圍大
空間解析度低

地物影像探測

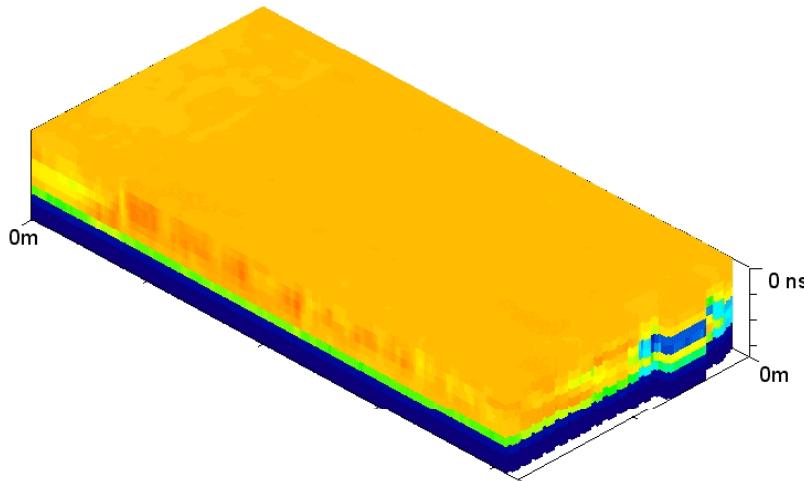
Resistivity (ERT)



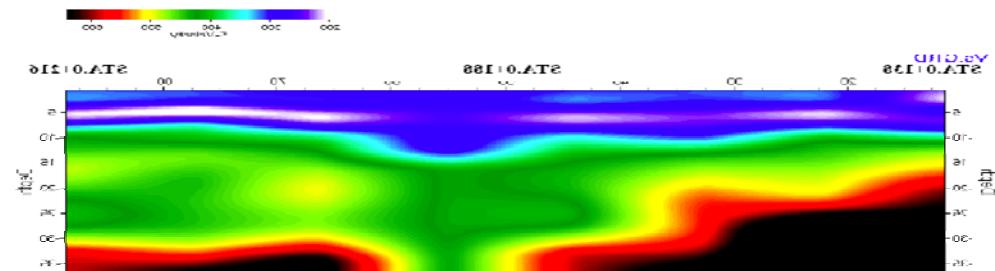
P-wave velocity (Travelttime)



Reflection



S-wave velocity (Surface Wave)



坡地工程地球物理探測

Tentative indication of suitability of various geophysical methods. It is assumed that basic boundary conditions have been fulfilled; for example, no highly conductive materials present in topsoil where a ground radar survey is to be done of the under laying rock mass.

Method		Artifacts, pipes, foundations, etc.	Property determination for geotechnical purposes	Structure			
				Low contrast*		High contrast*	
				Simple**	Complex**	Simple**	Complex**
Seismic	Refraction	--	+	-	--	++	-
	Reflection	-	+	+	-	++	+
	Tomography	-	+	++	++	++	++
Electro-magnetic	Low frequency groundradar	++	--	-	--	-	--
	Normal	++	--	++	+	++	++
Geo-electrical	2/3D imaging	-	--	++	++	++	++
Self-potential		--	--	--	--	-	-
Gravity		-	+	-	--	++	+

-- = not suitable, - = marginal, + = good, ++ = very good.

* Low and high contrast refer to the contrast in property values measured between the different materials that define the structure. ** Simple and complex structure refer to the complexity of the structure to be measured, for example, simple should be something like two horizontal or slightly inclined layers, e.g., a topsoil layer on a rock slope, complex should be a series of irregular layers and objects, e.g., a debris flow deposit.

(Hack 2000)

坡地工程地球物理探測

Methods		Rock slides	Soil slides	Quick clay landslides	Rock falls	Property determination for geotechnical purposes	e.g. artefacts, pipes, foundations	Ground water/soil moisture
Seismic methods	Refraction/Reflection	+	+	+	?	+	-/(+)	+/-
	Tomography	+	+	-	-	+	(+)	-
	Passive seismic	+	+	-	+	-		-
	Surface waves	?	?	+	-	+		-
Electro-magnetic methods (EM)	Low frequency	+	+	-	-	-	+	+
	Ground-penetrating radar (GPR)	+	+	(depends on clay content)	+	-	+	+
Resistivity measurements		+	+	+	?	-	(+)	+
Self-potential (SP)		+	+	-	-	-	-	+
Induced polarisation (IP)		-	-	+	-	-	-	+
Gravity		?	?	-	+	+	-	-
Magnetism		?	?	-	-	-		-

+ = suitable, (+) = partially suitable, - = not suitable, ? = depends on the site or needs further analysis

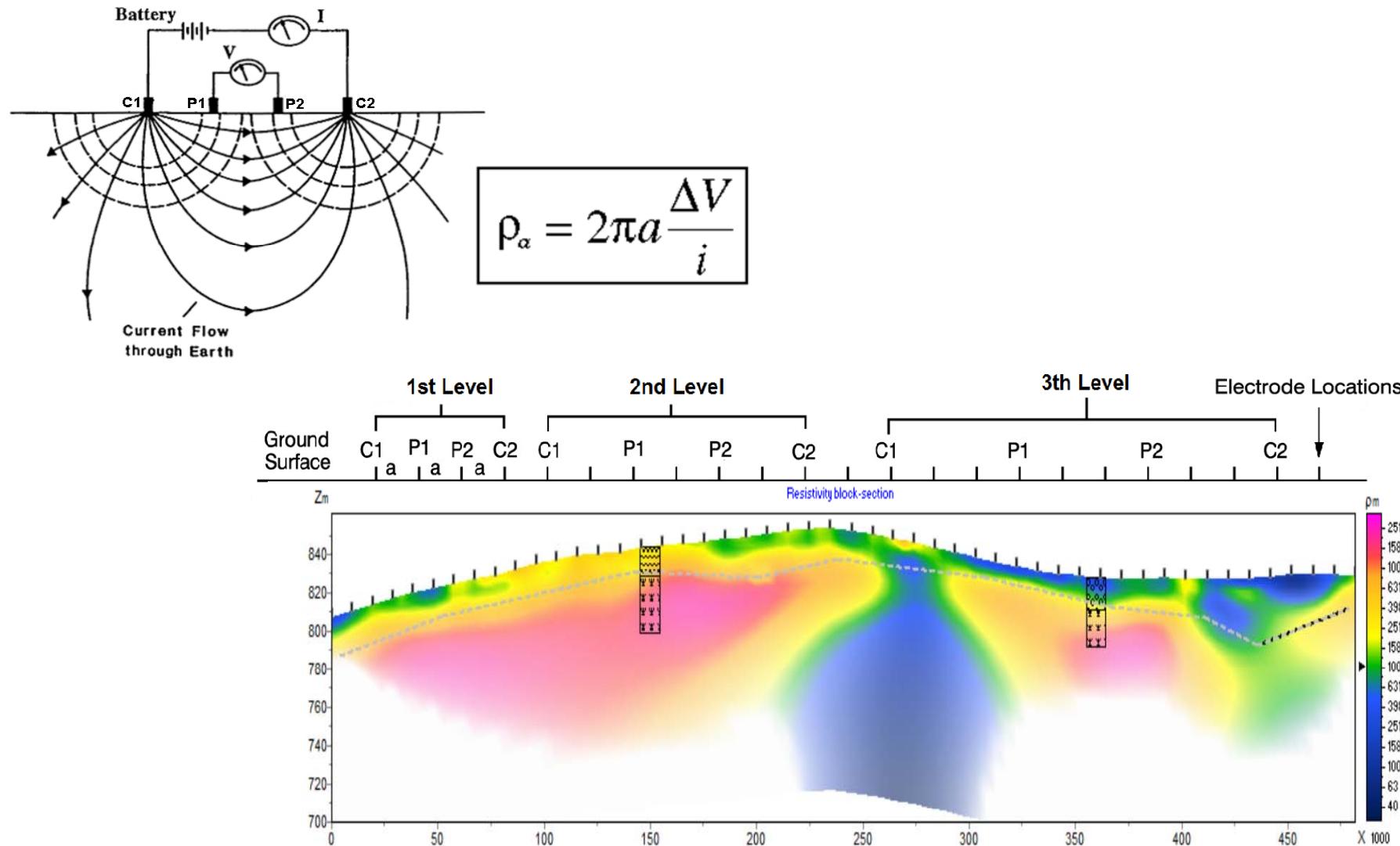
(Bell et al. 2006)

坡地工程地球物理探測案例

Method	Parameter -information	Geological context	Landslide type	Application	Authors
Seismic reflection	Vp, Vs, 2D vertical sections	Soft sediments (sand to clay)	Earth slide-debris flow ($\alpha=25^\circ$)	Geological boundary (80 m)	Bichler <i>et al.</i> [2004]
	Vp, Vs, 2D vertical sections	Gypsum, shale and sandstone	Complex active slide ($\alpha=10^\circ$)	Slip surface (50 m) within a gypsum layer	Bruno and Marillier [2000]
	Vp, Vs, 2D vertical sections	Phyllitic rocks, gneiss	Rockslide ($\alpha=26^\circ$)	Internal geometry (layering, faults)	Ferrucci <i>et al.</i> [2000]
Seismic refraction	Vp, Vs	Weathered marls and limestones	Active complex slide ($\alpha=7^\circ$)	Slip surface (3 m)	Glade <i>et al.</i> [2005]
	Vp, Vs	Limestone, shale and debris	Active rock fall-debris slides	Relief of the bedrock (30 m) and internal structure	Mauritsch <i>et al.</i> [2000]
	Vp, Vs	Black marls	Complex mudslide ($\alpha=26^\circ$)	Basal slip surface (9 m)	Caris and Van Asch [1991]
Seismic tomography	Vp, 2D vertical sections	Shale	Translational rockslide (vertical cliff)	Geometry of the slide (5-10 m)	Jongmans <i>et al.</i> [2000]
	Vp, 2D vertical sections	Micaschists	Rock slide ($\alpha=32^\circ$)	Characterisation of the slide material – lateral boundary	Méric <i>et al.</i> [2005]
Seismic noise measurements (H/V method)	Vs, 1D vertical profile	Varicoloured clays	Complex earth slide-flow ($\alpha=9^\circ-10^\circ$)	Thickness of slide (30 m), dislocated material	Lapenna <i>et al.</i> [2005]
	Vs, 1D vertical profile	Black marls	Complex mudslide ($\alpha=25^\circ$)	Failure surface (35 m)	Méric <i>et al.</i> [2006]
	Vs, 1D vertical profile	Varved clays	Translational slide ($\alpha=10^\circ$)	Slip surface (27-37 m) and bedrock depths (33-62 m)	Méric <i>et al.</i> [2006]
Vertical electrical sounding (VES)	p, 1D vertical profile	Clayey arenitic rock	Composite soil-rock slump ($\alpha=6^\circ$)	Slip surface (100 m)	Agnesi [2005]
	p, 1D vertical profile	Black marls	Complex mudslide ($\alpha=25^\circ$)	Slip surface and bedrock depths (15 m)	Schmutz <i>et al.</i> [2000]
	p, 1D vertical profile	Black marls	Complex mudslide ($\alpha=25^\circ$)	Bedrock depth (7.5 m)	Caris and Van Asch [1991]
Electrical tomography	p, 2D vertical section	Limestone to shale	Rock slide ($\alpha=22^\circ$)	Slip surface depth (10 m)	Batayneh and Al-Diabat [2002]
	p, 2D vertical section	Soft sediments (sand to clay)	Earth slide-debris flow ($\alpha=25^\circ$)	Geological boundary and slip surface depth	Bichler <i>et al.</i> [2004]
	p, 2D vertical section	Alluvial debris on gneissic rock	Large rockslide ($\alpha=40^\circ$)	3D slip surface geometry and water flows	Lebourg <i>et al.</i> [2005]
	p, 2D vertical section	Clay and sand	Multiple earth slide ($\alpha=8^\circ$)	Geological boundary and slip surface depth	Demoulin <i>et al.</i> [2003]
	p, 2D vertical section	Varicoloured clays	Complex earth slide-flow ($\alpha=9^\circ-10^\circ$)	Slip surface depth (30 m)	Lapenna <i>et al.</i> [2005]
	p, 2D vertical section	Arenite and clay		Slip surface depth (20 m)	Havenith <i>et al.</i> [2000]
	p, 2D vertical section	Micaschists	Large rockslide	Lateral boundaries and thickness of the rockslide (100 m)	Méric <i>et al.</i> [2005]
	p, 2D vertical section	Clayey sand over crystalline rock		Slip surface depth	Wisen <i>et al.</i> [2003]
Spontaneous Potential (SP)	V, 1D horiz. profile and 2D map	Gypsum, shale and sandstone	Complex active slide ($\alpha=10^\circ$)	Upward flow of water on the landslide	Bruno [2000]
	V, 1D horiz. profile and 2D map	Varicoloured clays	Complex earth slide-flow ($\alpha=9^\circ-10^\circ$)	Landslide boundary, and water flows	Lapenna <i>et al.</i> [2005]
Electro-magnetism (EM34 or TEM)	p, 1D horiz. profile and 2D map	Gypsum, shale and sandstone	Complex active slide ($\alpha=10^\circ$)	Lateral boundary of the slide	Bruno and Marillier [2000]
	p, 1D horiz. profile and 2D map	Micaschists	Large rockslide	Lateral boundary of the slide	Méric <i>et al.</i> [2005]
	p, 1D horiz. profile and 2D map	Black marls	Complex mudslide ($\alpha=25^\circ$)	Slip surface and bedrock depths (15 m)	Schmutz <i>et al.</i> [2000]
	p, 1D horiz. profile and 2D map	Limestone and shale, debris	Active rock fall-debris slides	Location of saturated areas	Mauritsch <i>et al.</i> [2000]
	p, 1D horiz. profile and 2D map	Black marls	Complex mudslide ($\alpha=26^\circ$)	Differences in water content	Caris and Van Asch [1991]
	p, 1D horiz. profile and 2D map				
Ground penetrating Radar (GPR)	g, 2D vertical sections	Soft sediments (sand to clay)	Earth slide-debris flow ($\alpha=25^\circ$)	Geological boundary and slip surface depth	Bichler <i>et al.</i> [2004]
	g, 2D vertical sections	Limestone	Rock slide	Geometry of the moving mass (5m)	Petinelli <i>et al.</i> [1996]
	g, 2D vertical sections	Limestone	Rock slide	Location of fractures (15 m)	Jeannin <i>et al.</i> [2005]
Borehole radar		Gneiss		Location of fractures (49 m)	Willenberg <i>et al.</i> [2004]

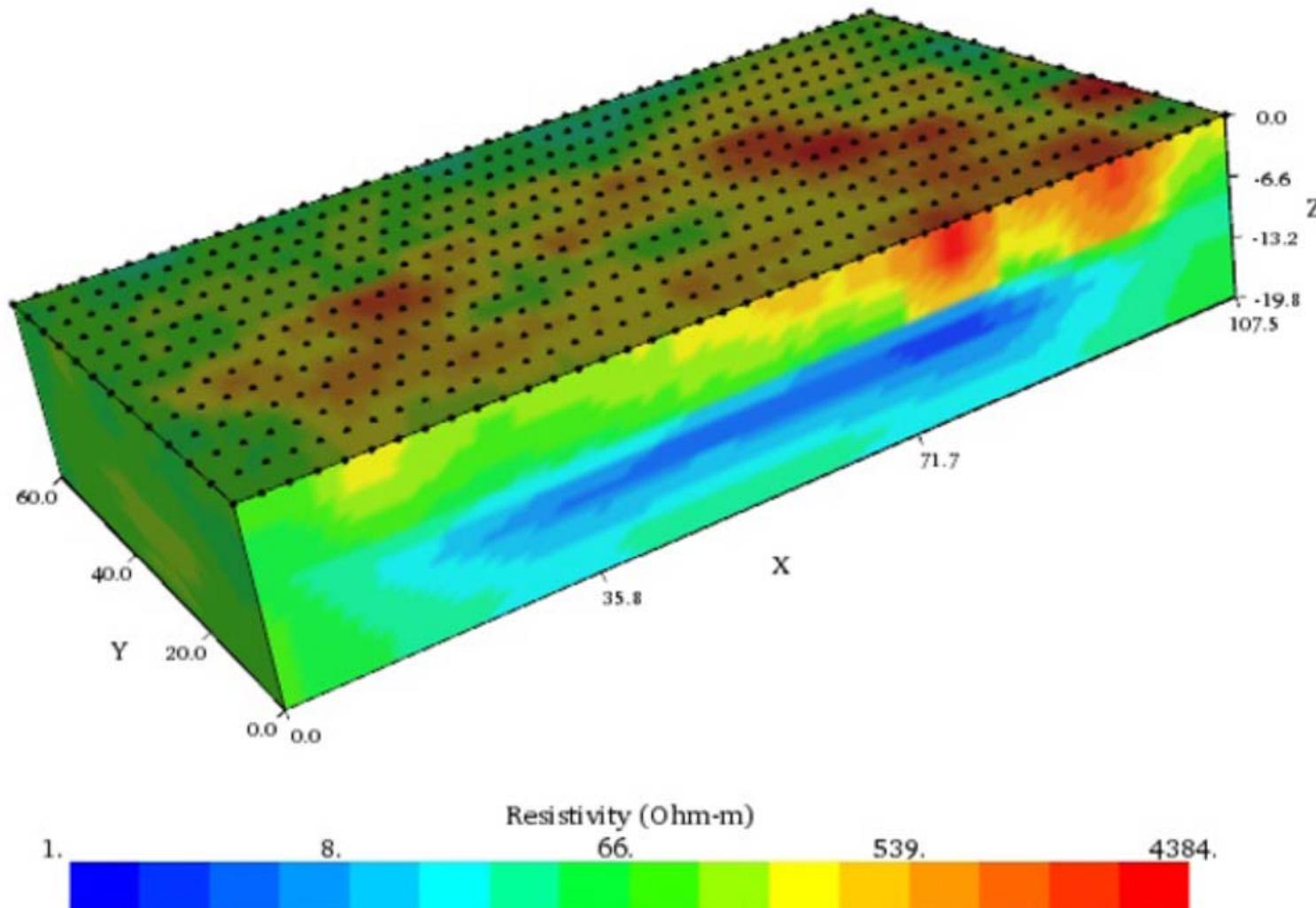
(Jongmans & Garambois 2007)

地電阻影像探測

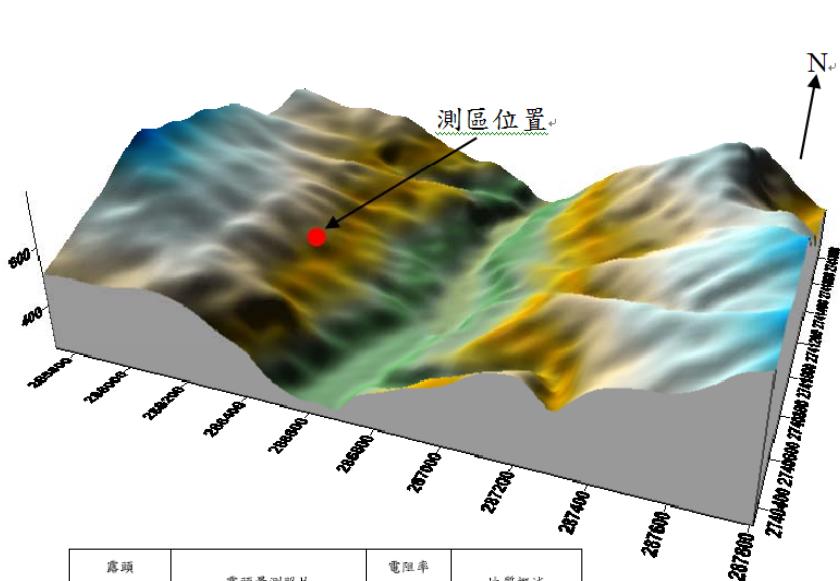


Electrical Resistivity Tomography(ERT)

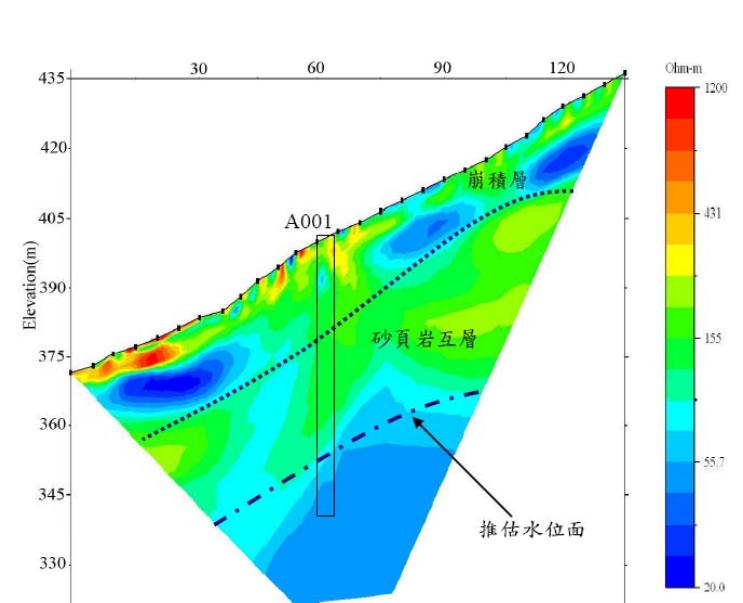
1D → 2D → 3D



二維地電阻探測應用案例



露頭編號	露頭量測照片	電阻率 (ohm·m)	地質概述
A-1		713	天氣陰，地表濕潤，觀測地表為砂岩。
A-2		118	天氣陰，地表濕潤，觀測地表為崩積土。
A-3		147.7	天氣陰，地表濕潤，觀測地表為砂岩與頁岩互層。
A-4		69.8	天氣陰，地表濕潤，觀測地表為頁岩。

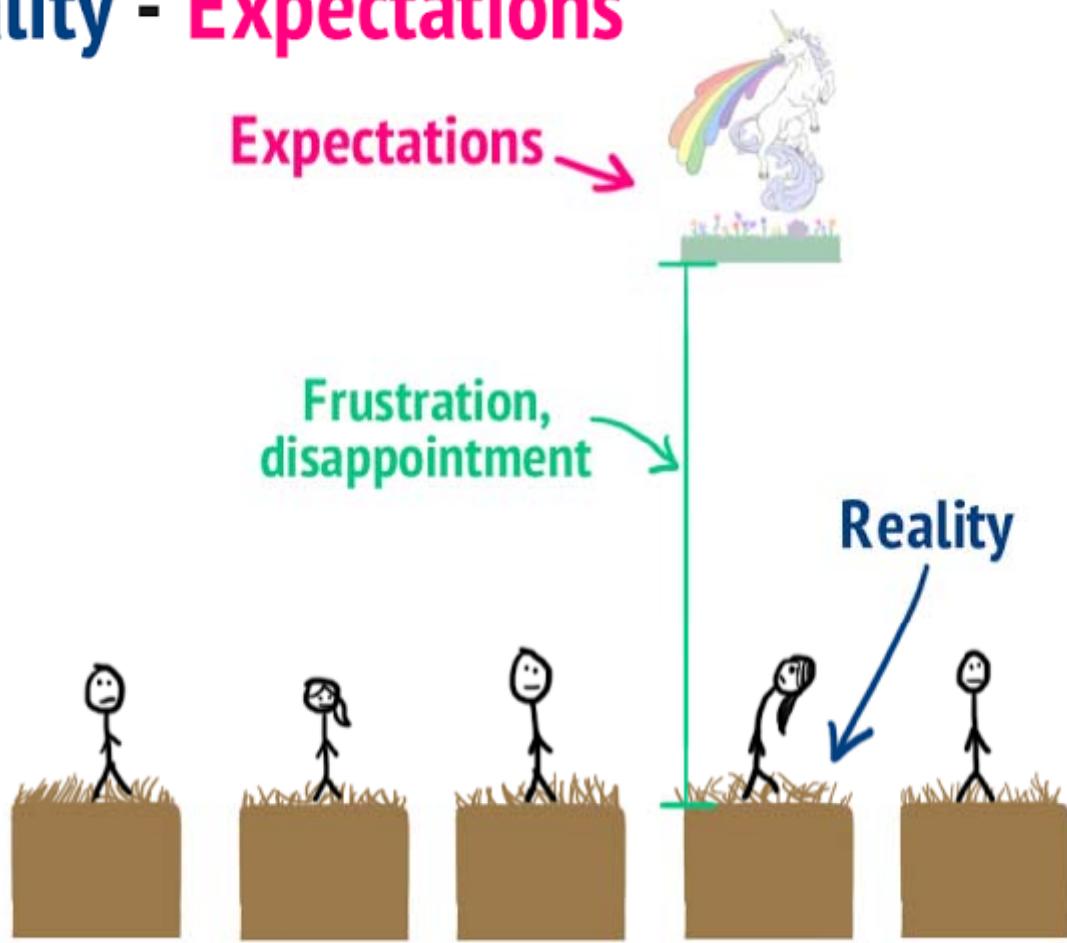


鑽孔編號	深度(m)	鑽探成果照片	地質描述
A001	0-27		崩積層，砂、泥岩塊
	27-50		岩盤，砂頁岩互層

地物探勘應用的瓶頸

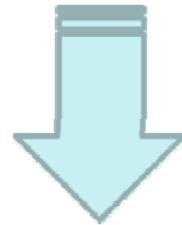
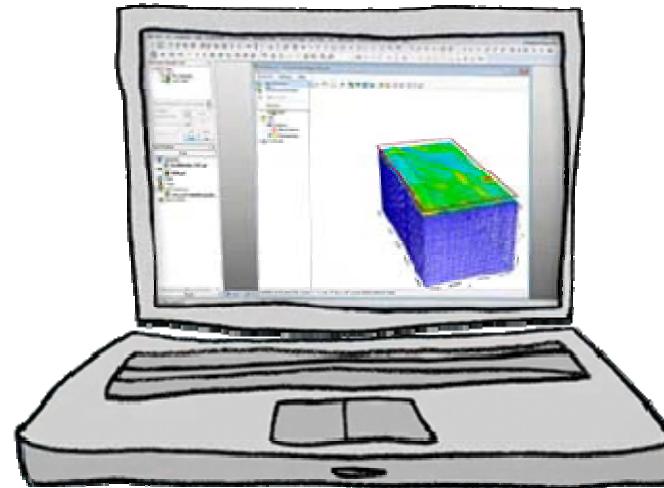
- 物理性質與工程性質的連結
- 地物探勘結果的過度承諾

Happiness = Reality - Expectations



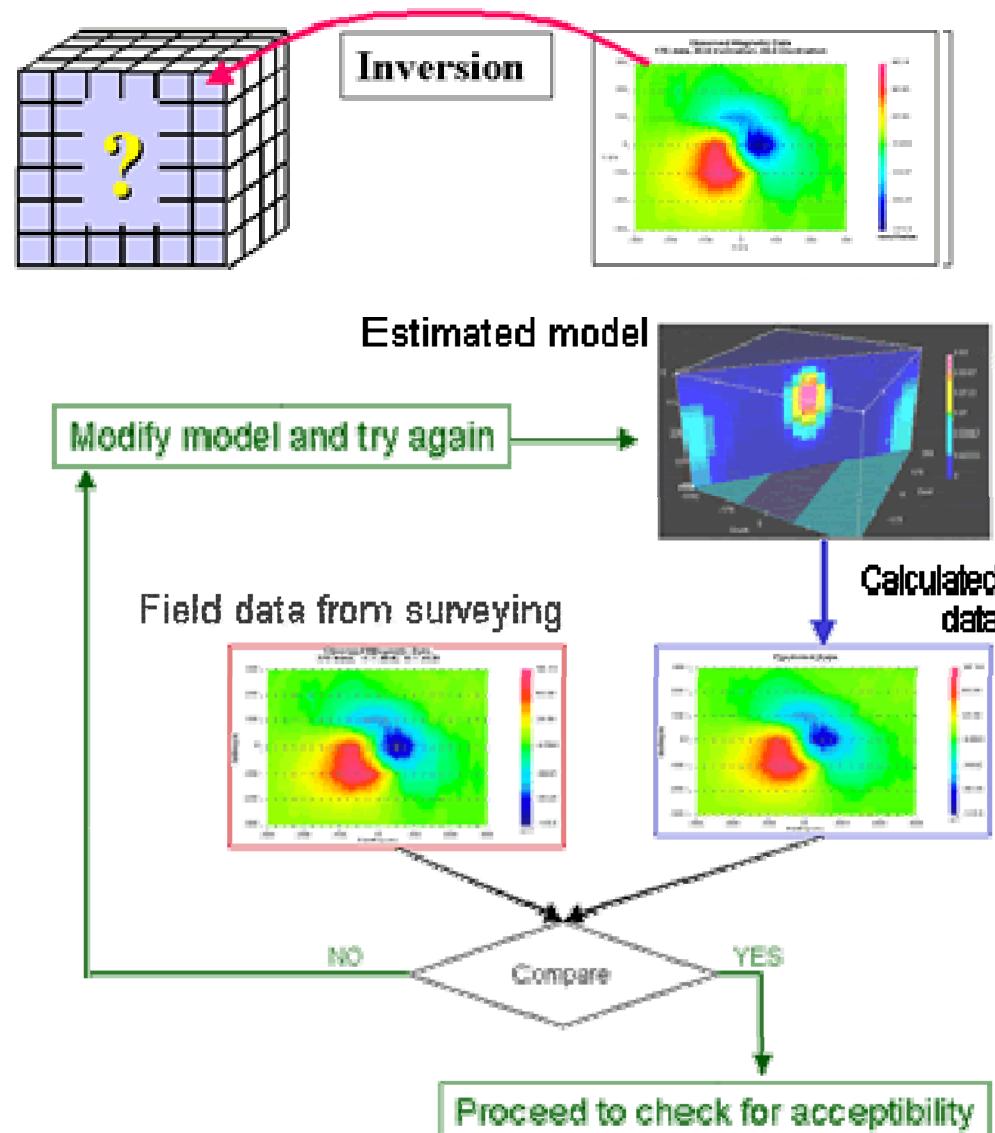
2D-ERT的解析能力、陷阱與對策

- 反算的非唯一性
- 探測深度與解析度
- 陷阱-三維效應



To help people understand the limitation of what they can achieve through geophysics and much more on the value of compromise, consensus, and collaboration.

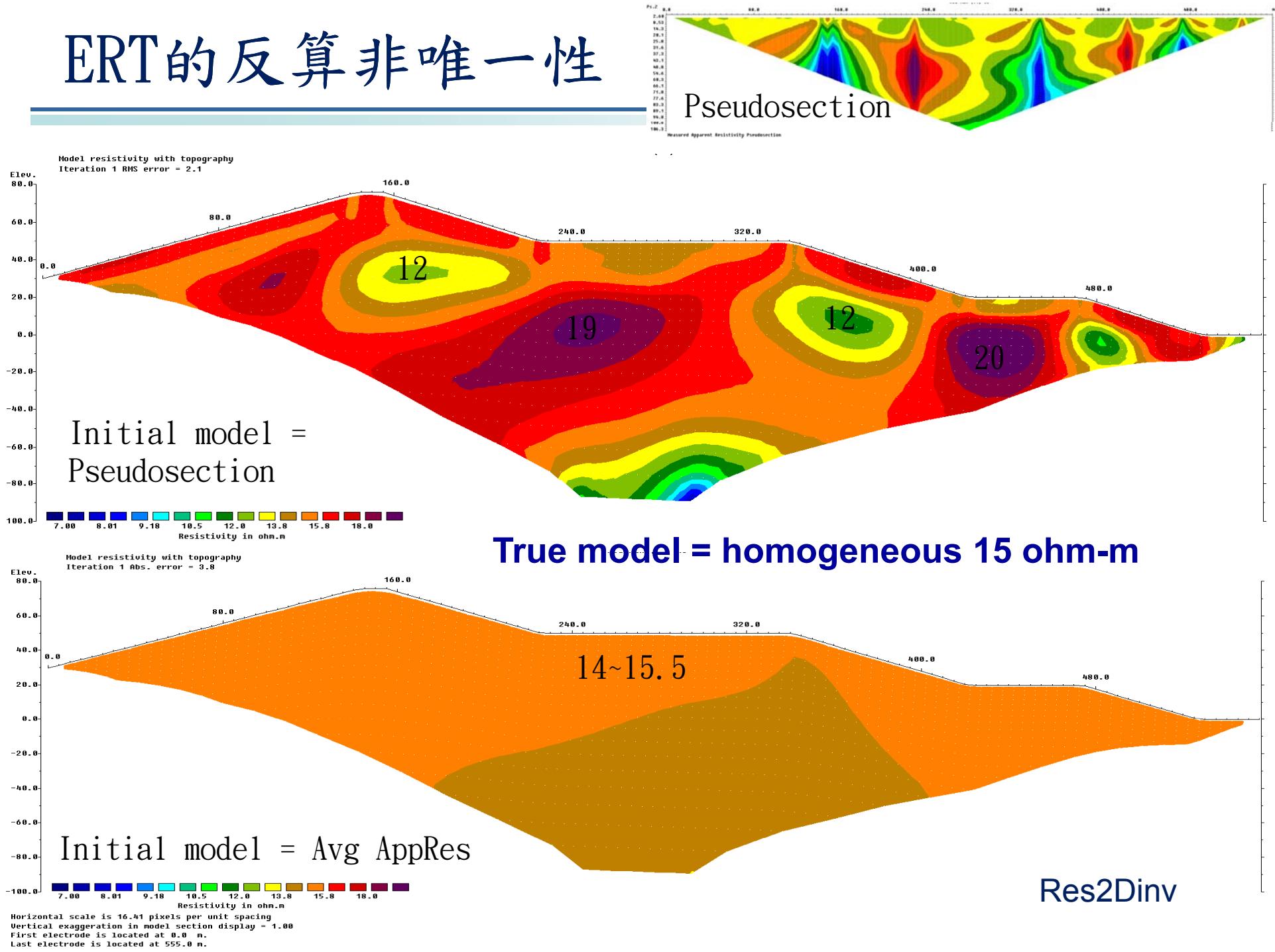
地物探測的反算



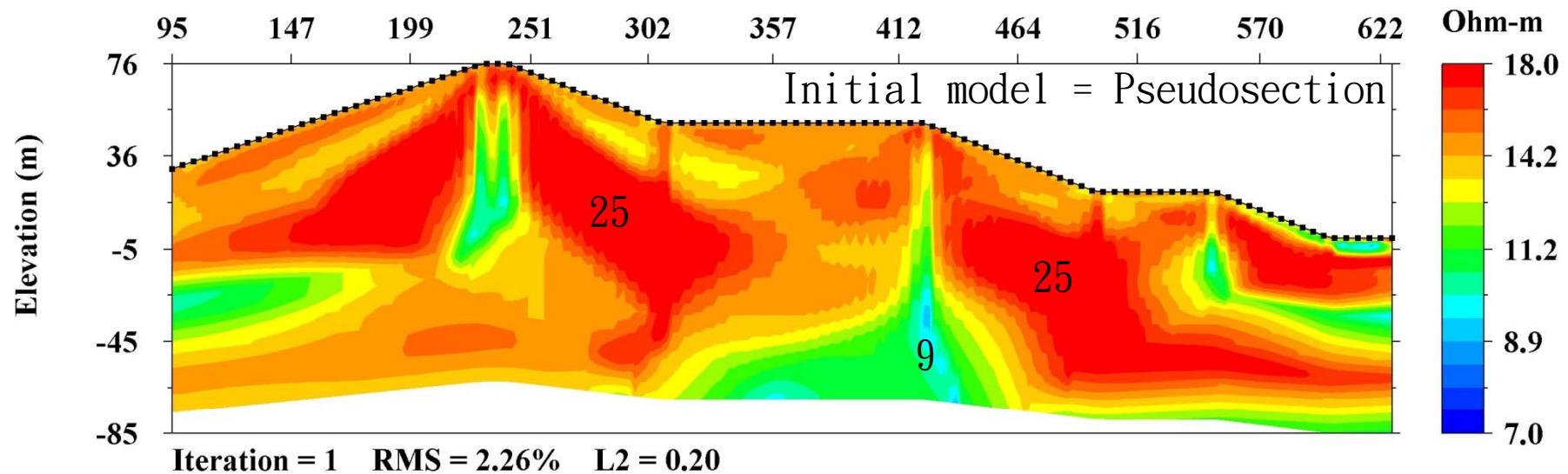
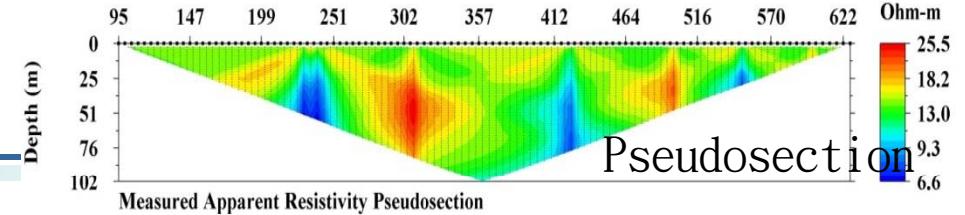
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2e.

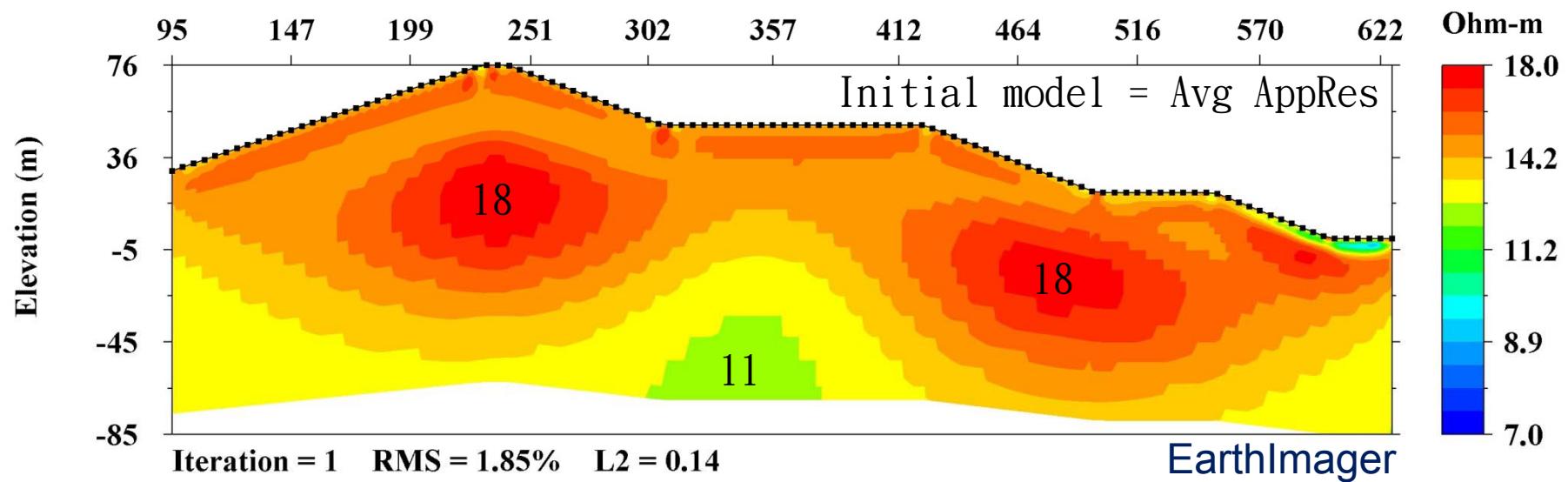
ERT的反算非唯一性



ERT的反算非唯一性

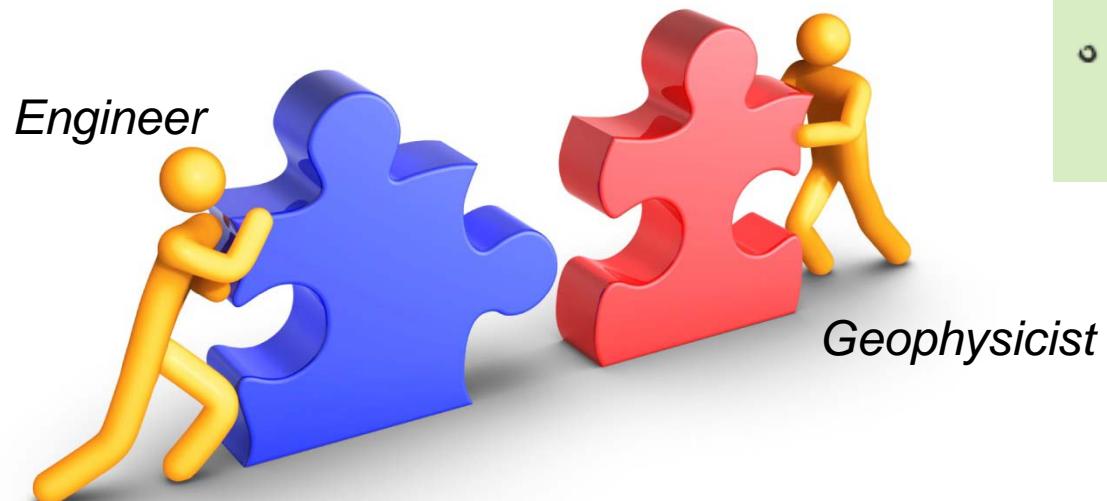


True model = homogeneous 15 ohm-m



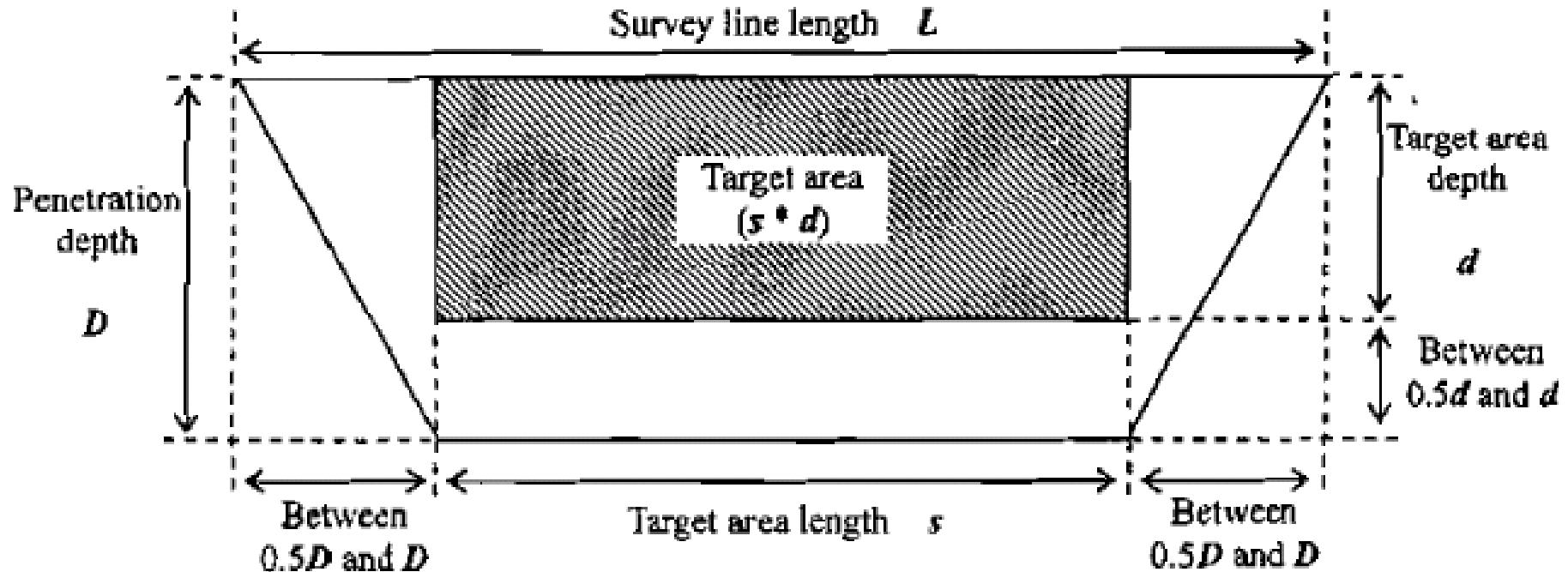
ERT的反算非唯一性 - 對策

- 測試不同初始模型
- 以既有資訊束制或優選反算解
- Joint inversion



- - Geophysical inversion is a non-unique process: many models produce the same response.
 - A priori information must be included in the inversion: smoothness, geology, drilling, other geophysical data and inversions, etc.
 - Integrating other information improves reliability and greatly increases the acceptance of the inversion into the exploration process.
 - From a practical perspective, these processes must be robust and easy to use.
 - Integration, Integration, Integration

2D-ERT測線規劃與探測深度及解析度



Electrode spacing:

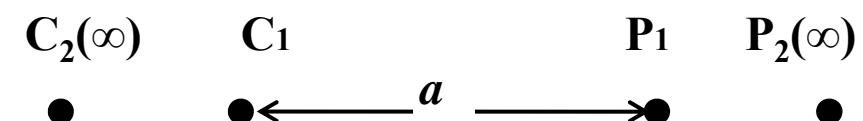
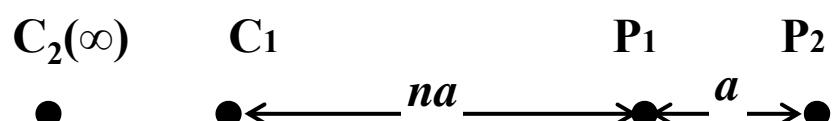
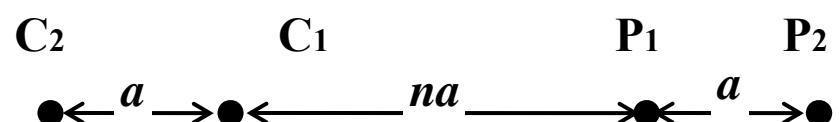
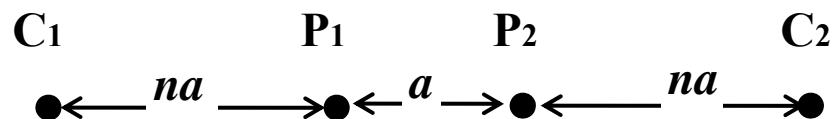
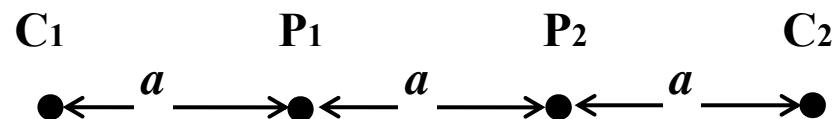
Trade off between resolution and penetration depth

Usually, 2 m spacing for $L=100$ m

5m spacing for $L=200 \sim 500$ m

10 m spacing for $L = 500\sim1000$ m

Electrode spacing $\approx 1/10\sim1/20$ maximum penetration depth

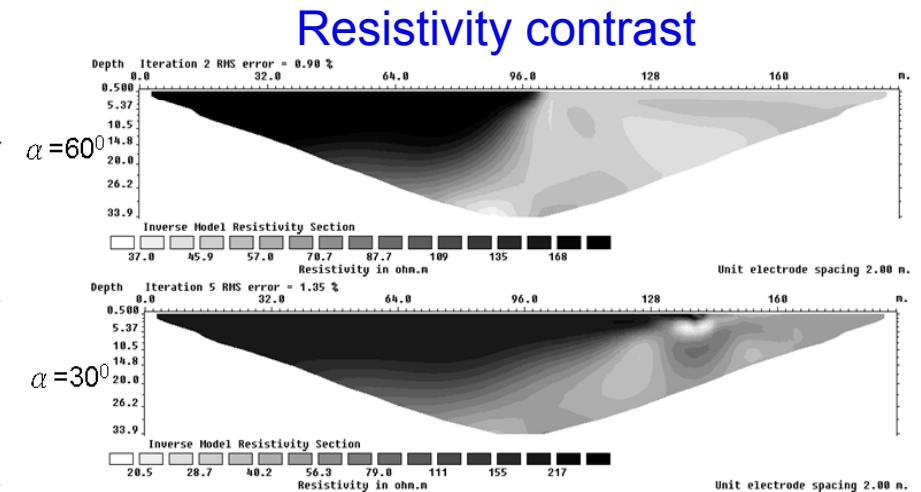
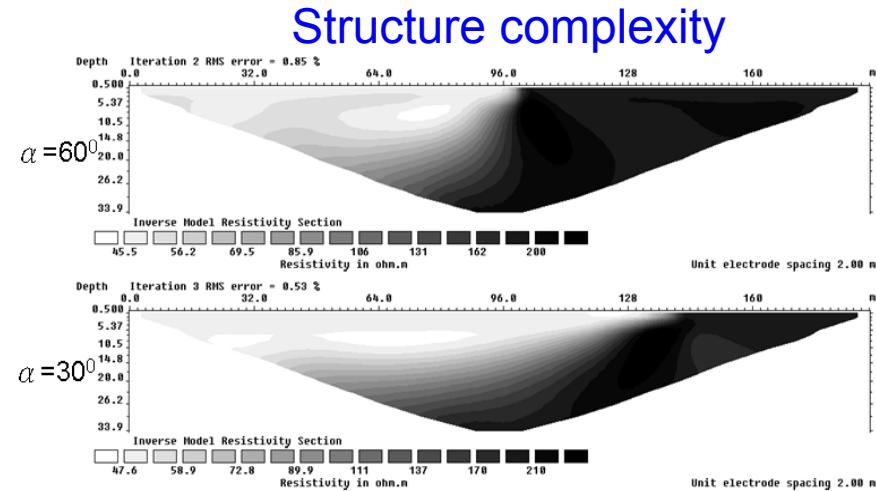
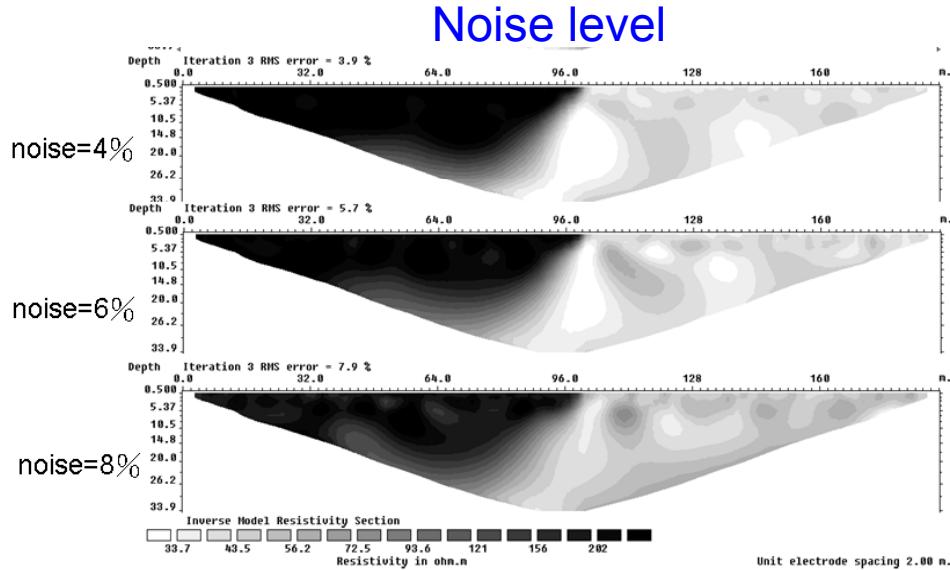
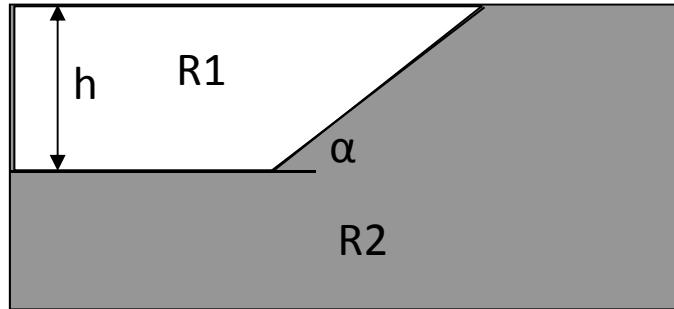


電極排列法	展距 L	幾何參數 K
Wenner	$3na$	$2\pi a$
Wenner-Schlumberger	$(2n+1)a$	$\pi n(n+1)a$
Dipole-Dipole	$(n+2)a$	$\pi n(n+1)(n+2)a$
Pole-Dipole	$(n+1)a$	$2\pi n(n+1)a$
Pole-Pole	na	$2\pi a$

Characteristics of different electrode arrays

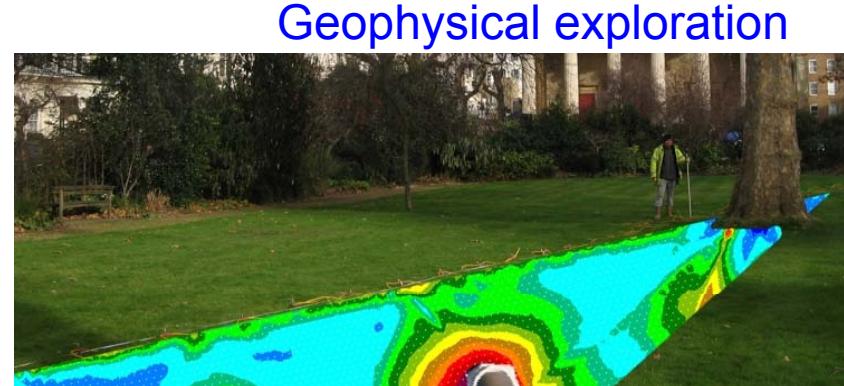
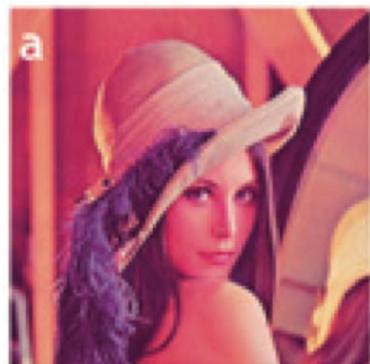
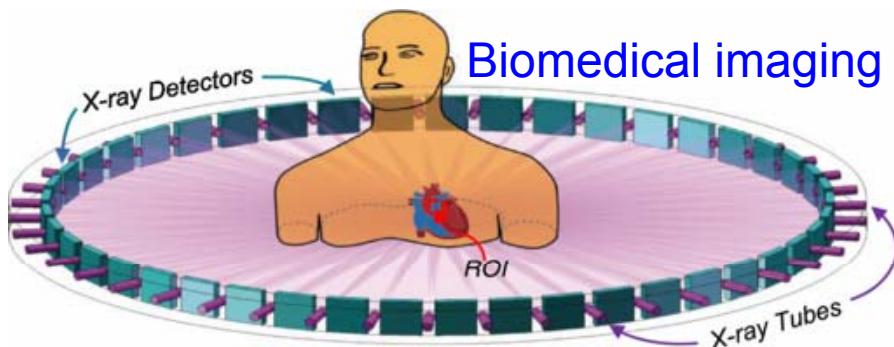
Array	Depth Ze/L	Horizontal Coverage	Signal Strength	Resolution
Wenner	0.173	Poor	Strong	Vertical
Wenner-Schlumberger	0.173~0.19	Medium	Medium	Vertical-Lateral
Dipole-Dipole	0.139~0.224	Good	Low	Lateral
Pole-Dipole	0.36	Good	Medium Low	Lateral
Pole-Pole	0.862	Widest	Telluric noise	Poor

2D-ERT的解析度

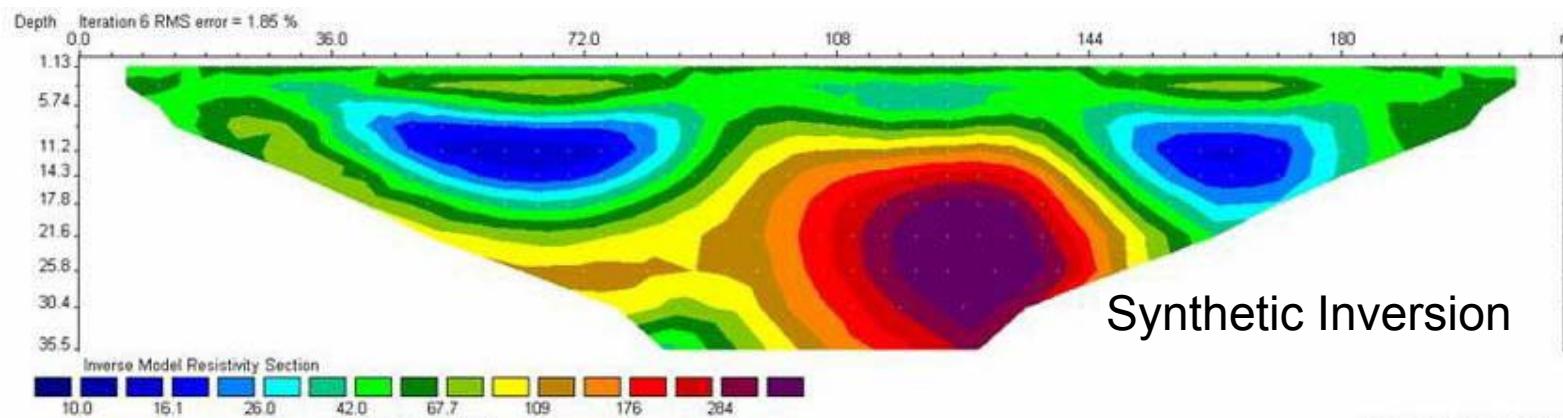
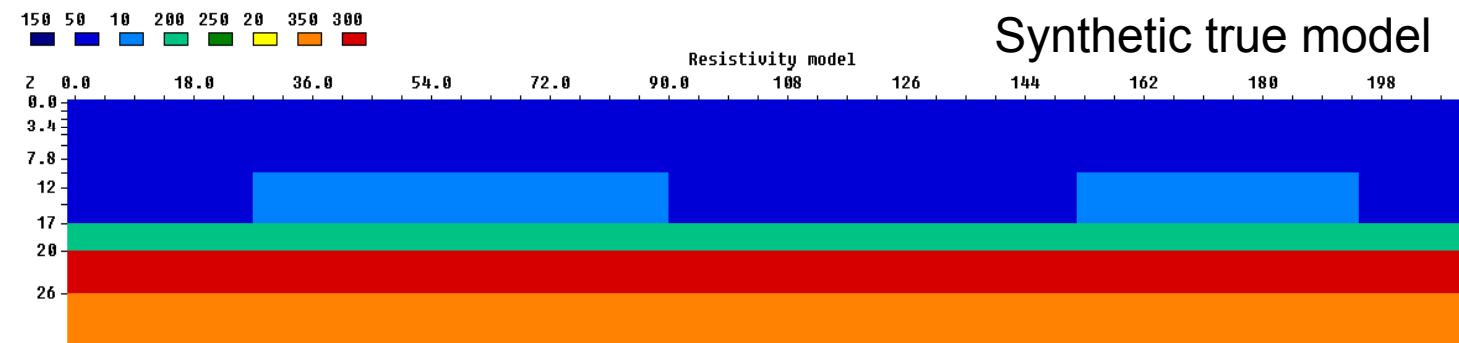
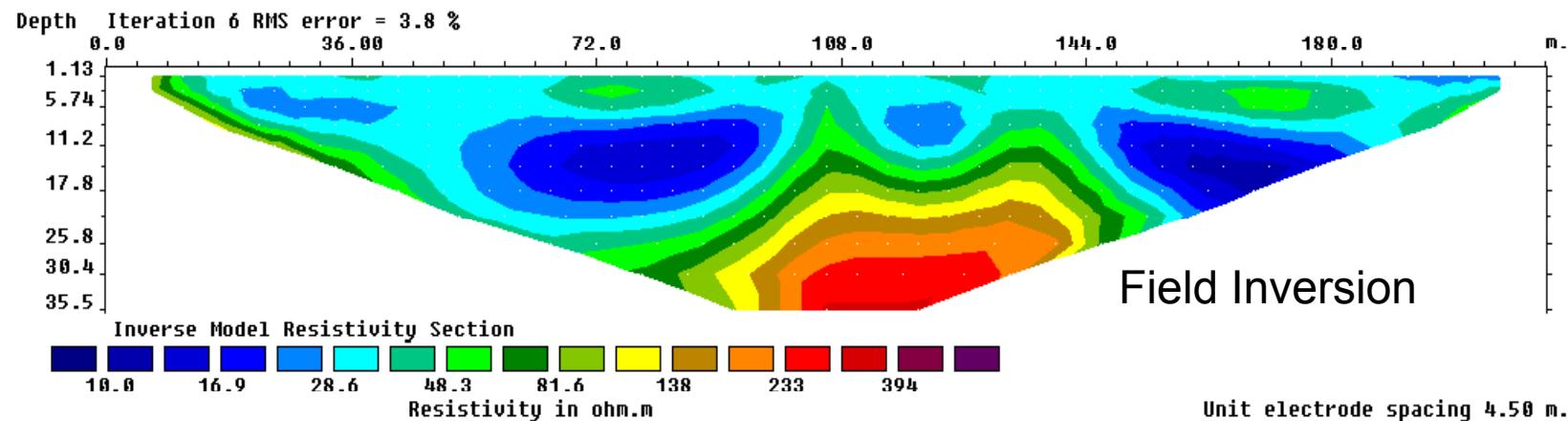


2D-ERT解析能力-對策

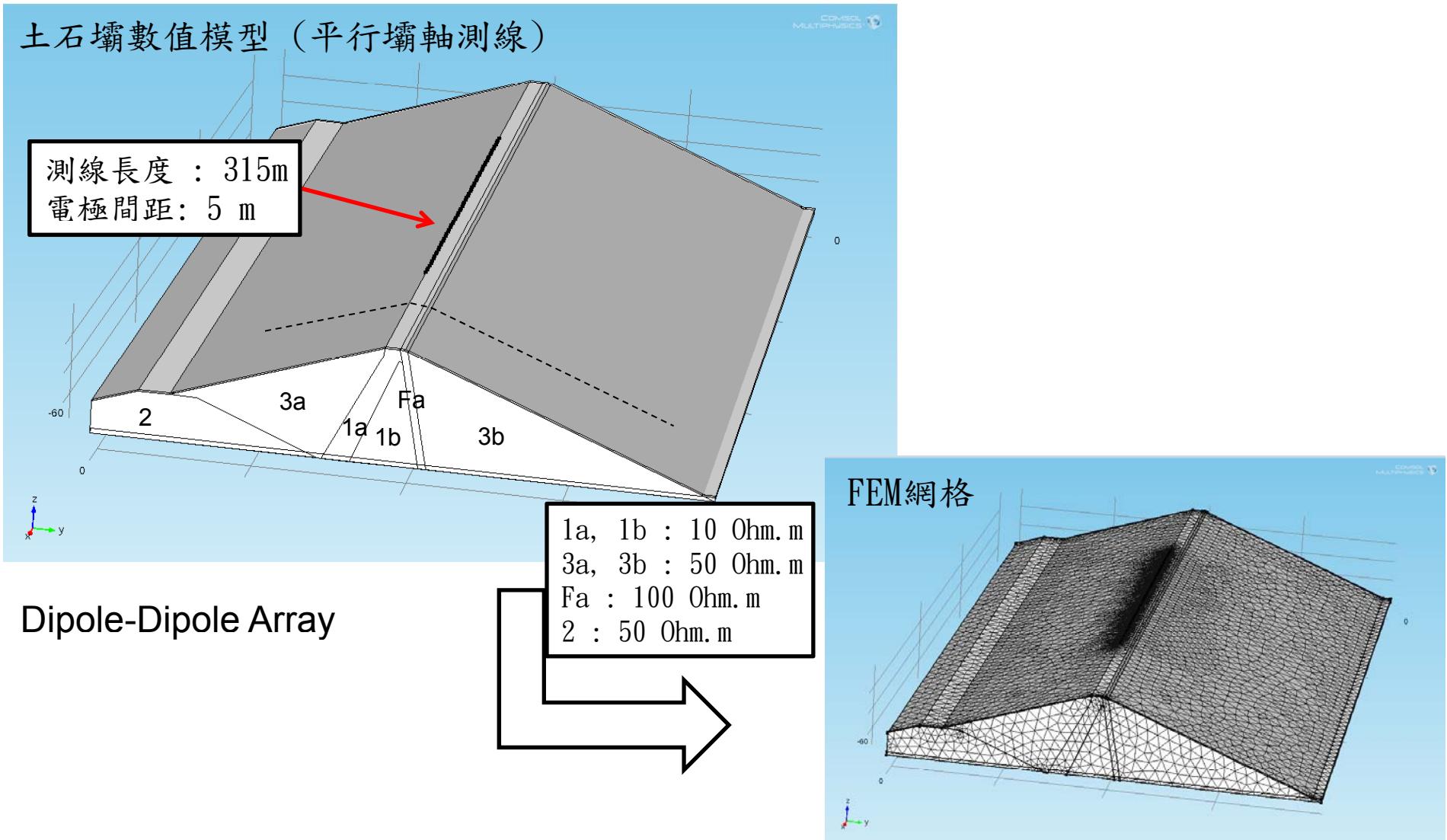
- 縮短電極間距
- 選擇適當的Array與反算方法
- 解析度隨深度增加而降低，且與電阻率的分佈有關，避免過度的解讀。可透過建模定性探討。



Qualitative Model Appraisal

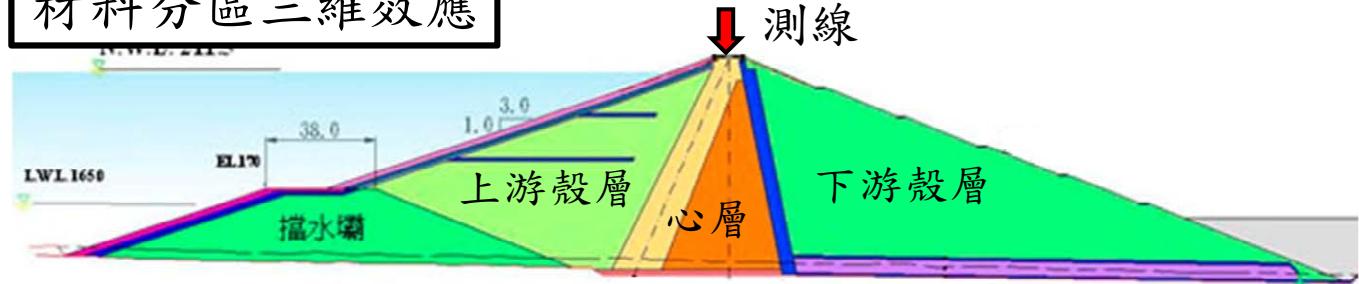


2D-ERT三維效應示範例

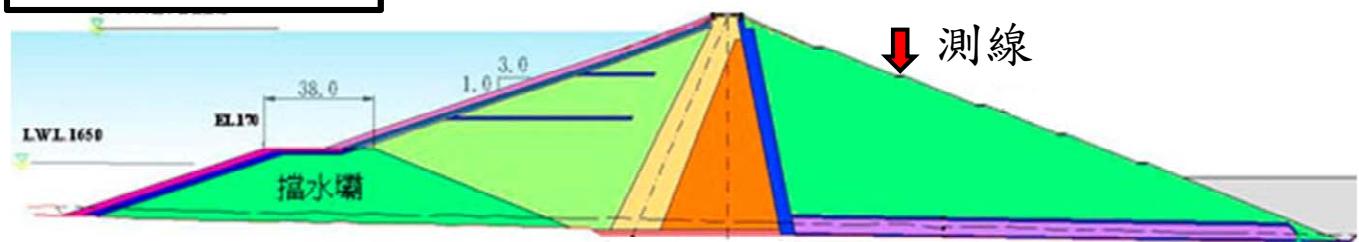


2D-ERT三維效應的來源

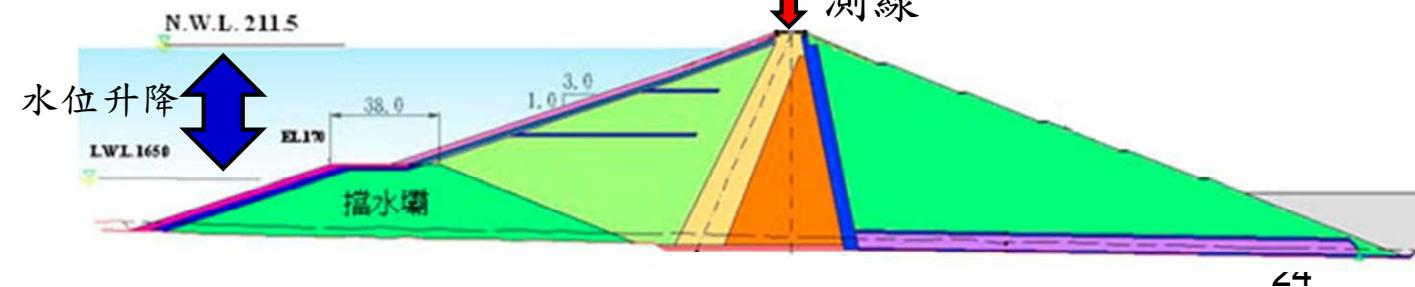
材料分區三維效應



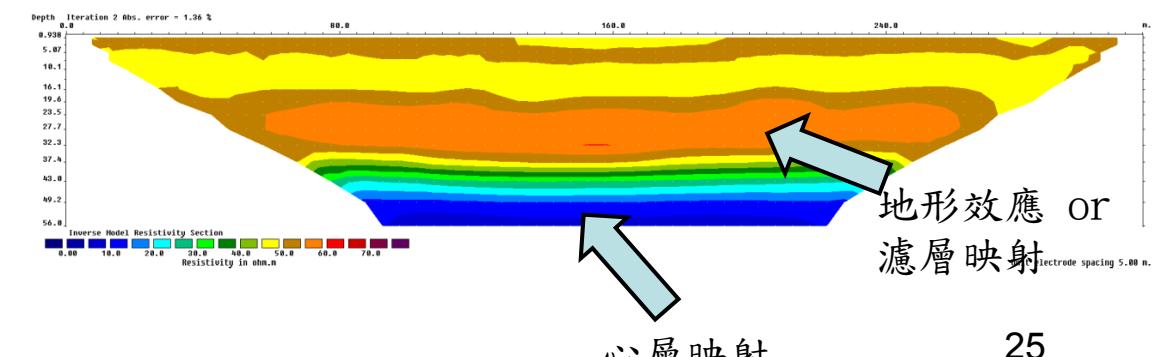
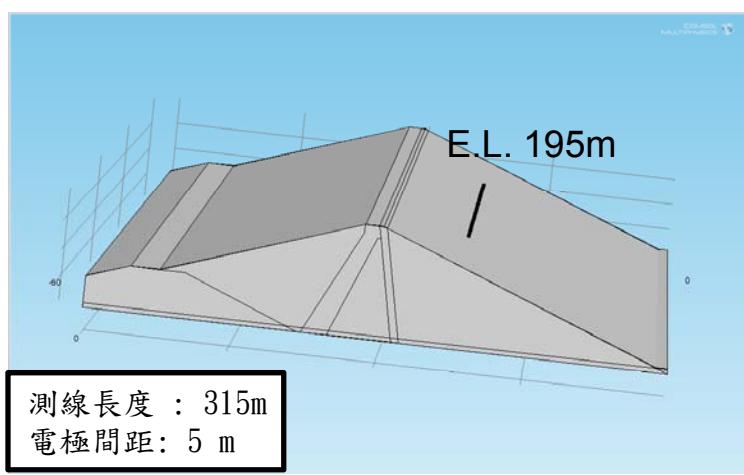
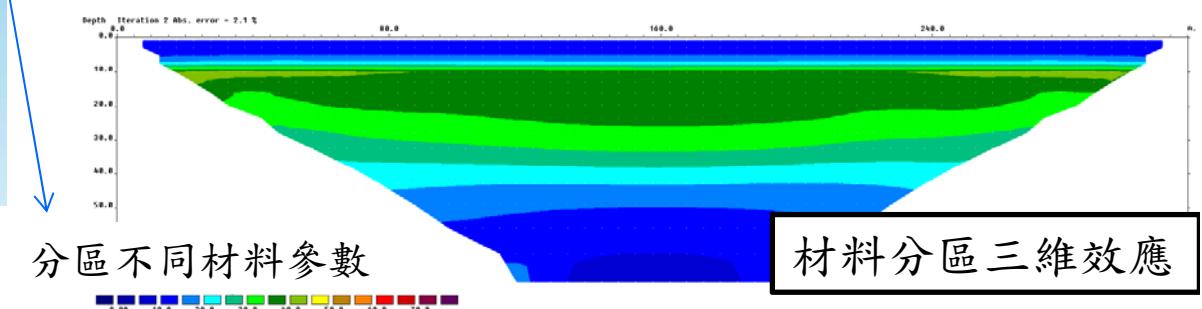
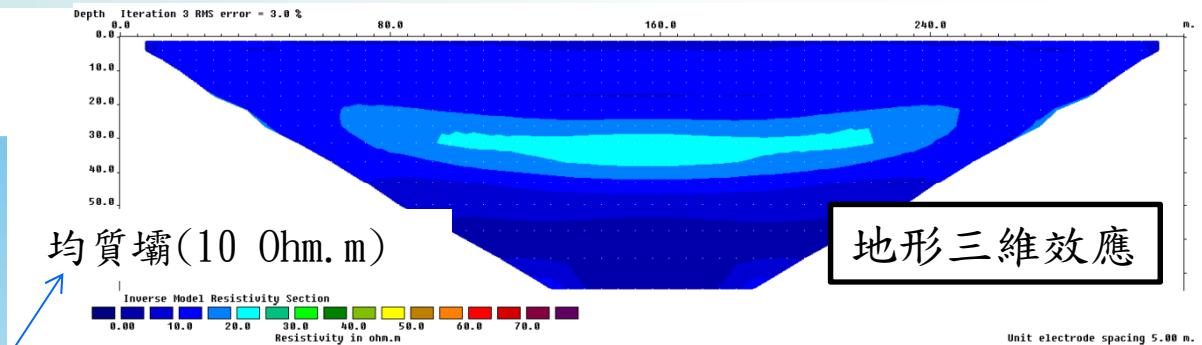
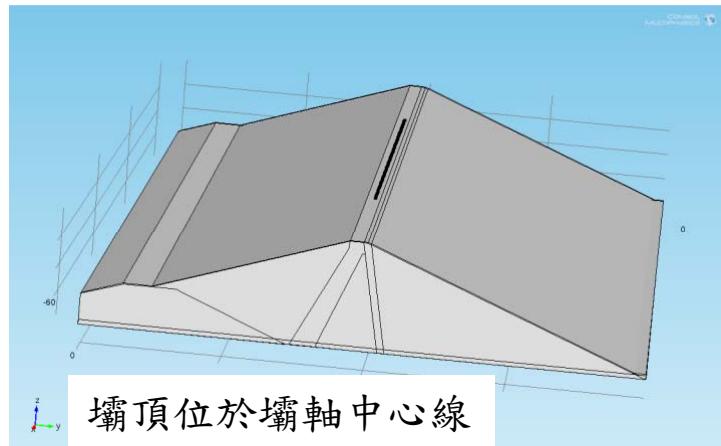
地形三維效應



測線

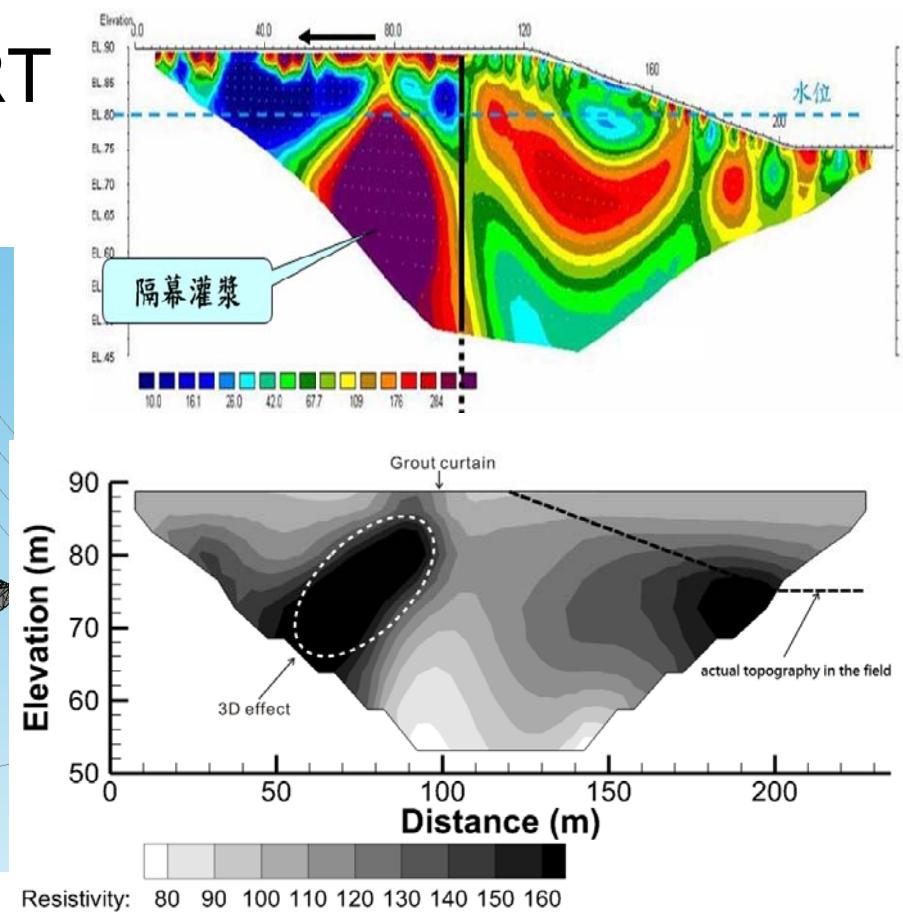
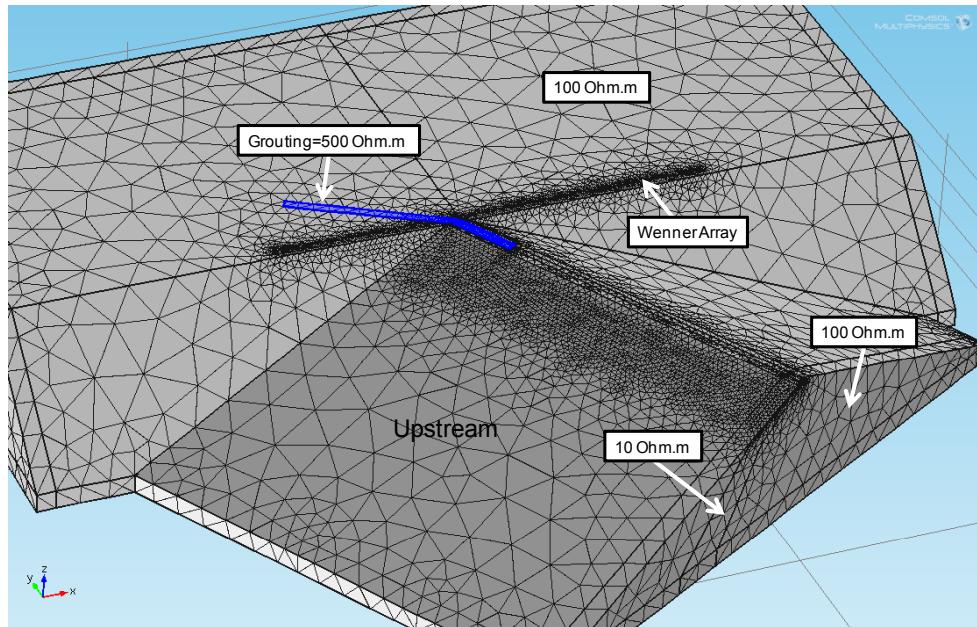


2D-ERT的三維映射效應



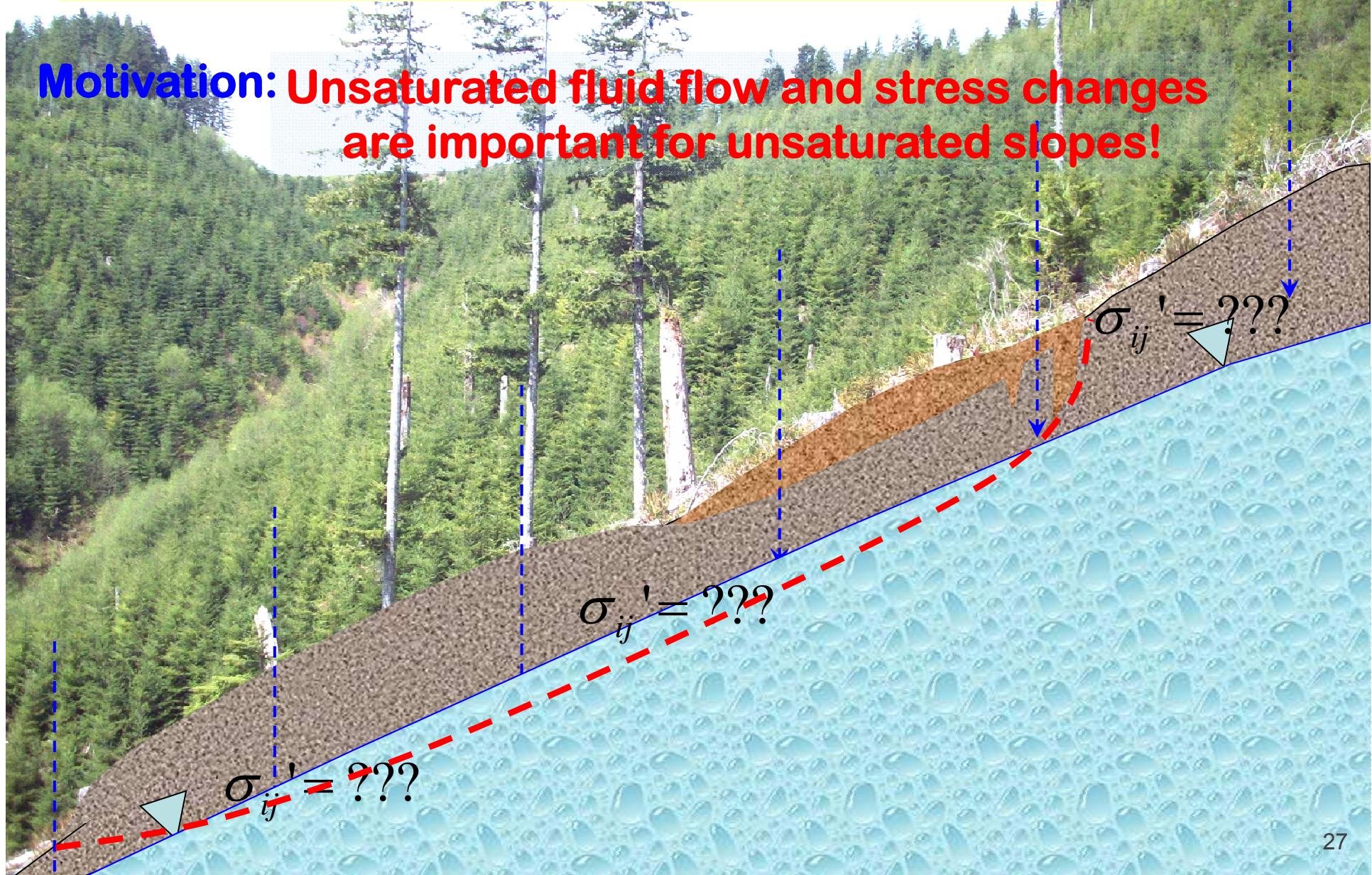
2D-ERT三維效應 - 對策

- 適當規劃測線，盡量與結構走向垂直
- 利用3D數模建構概念模式，驗證施測結果及探討可能受到三維效應的程度
- 3D-ERT或pseudo-3D ERT

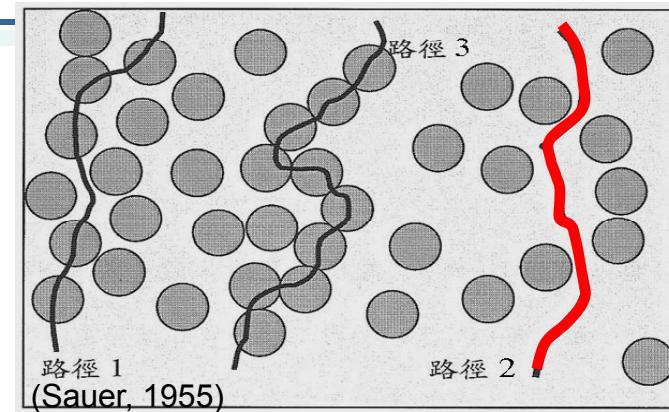
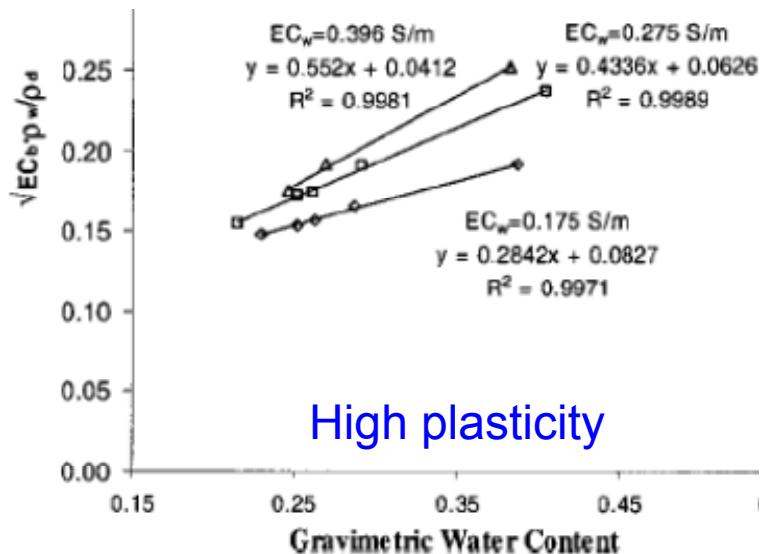
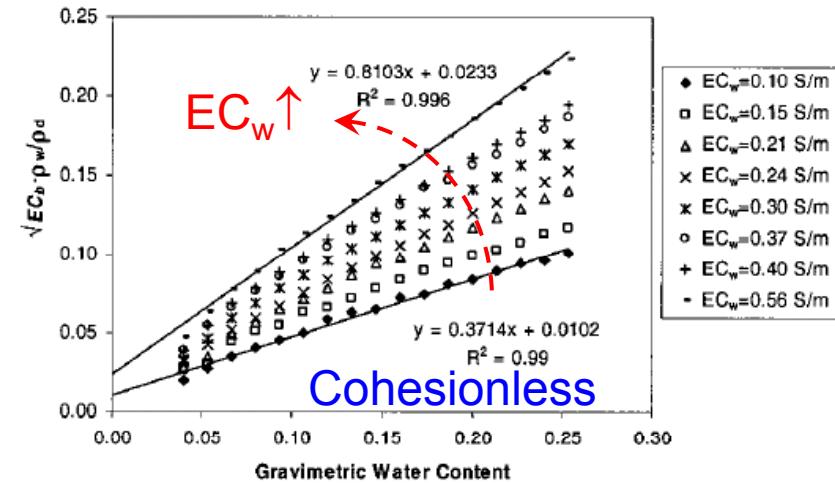


電探在坡地含水特性的量化分析

Motivation: Unsaturated fluid flow and stress changes
are important for unsaturated slopes!



電阻率與土壤組成



$$EC = f(\theta, \rho_d, A_{es}, EC_w)$$

Generalized Archie's law

$$EC = aEC_w \theta^n$$

(Archie, 1942; Shan and Singh, 2005)

Dielectric-analogous model

$$\sqrt{EC} \rho_w / \rho_d = c(A_{es}) + d(EC_w)w \quad (\text{Lin, 1999})$$

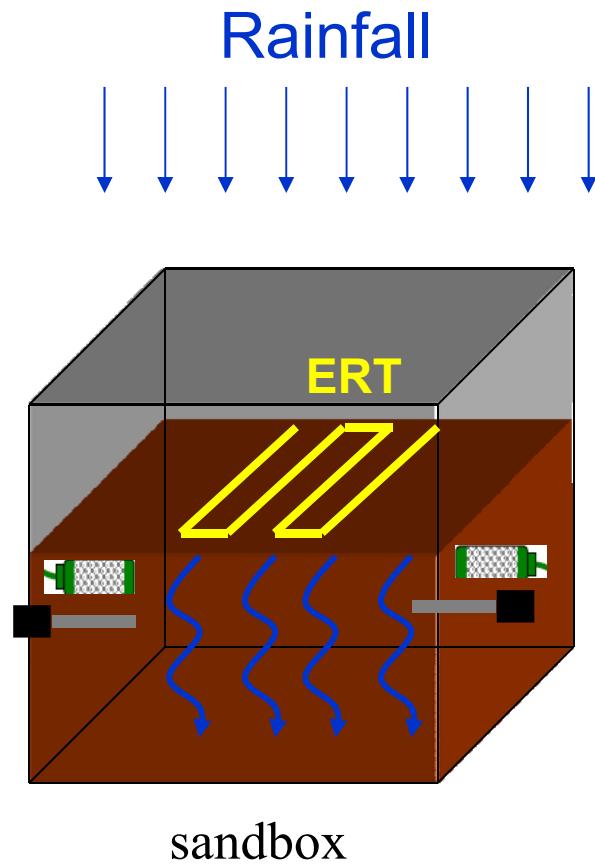
$$\equiv EC = \left(d^2 \right) \theta^2 + 2 \left(cd \frac{\rho_d}{\rho_w} \right) \theta + \left(c \frac{\rho_d}{\rho_w} \right)^2$$

Conductors in parallel model

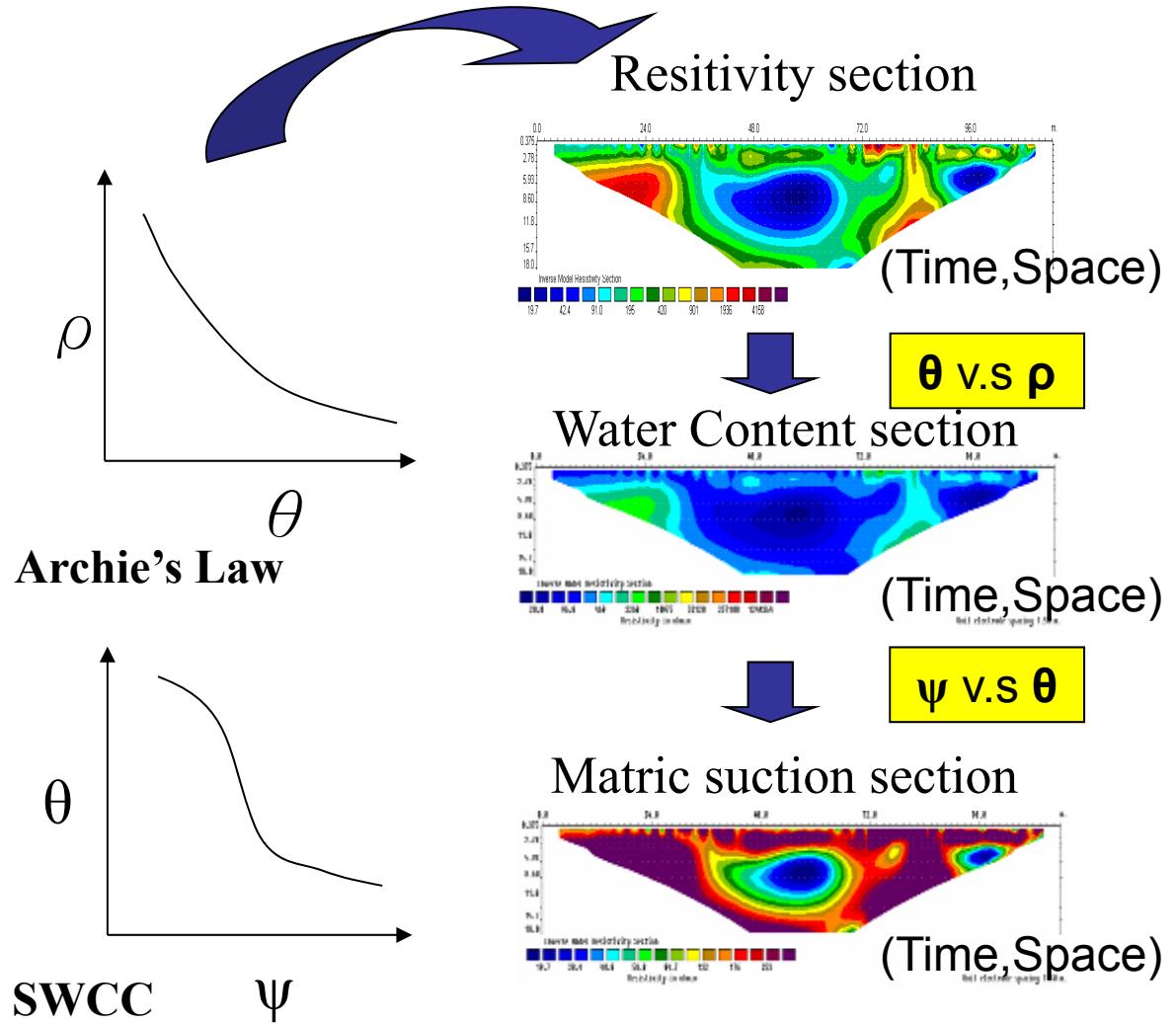
$$EC = a(EC_w) \theta^2 + b(A_{es}, EC_w) \theta + c(A_{es}, EC_w)$$

(Rhoades et al. 1976; Mojed et al., 2007)

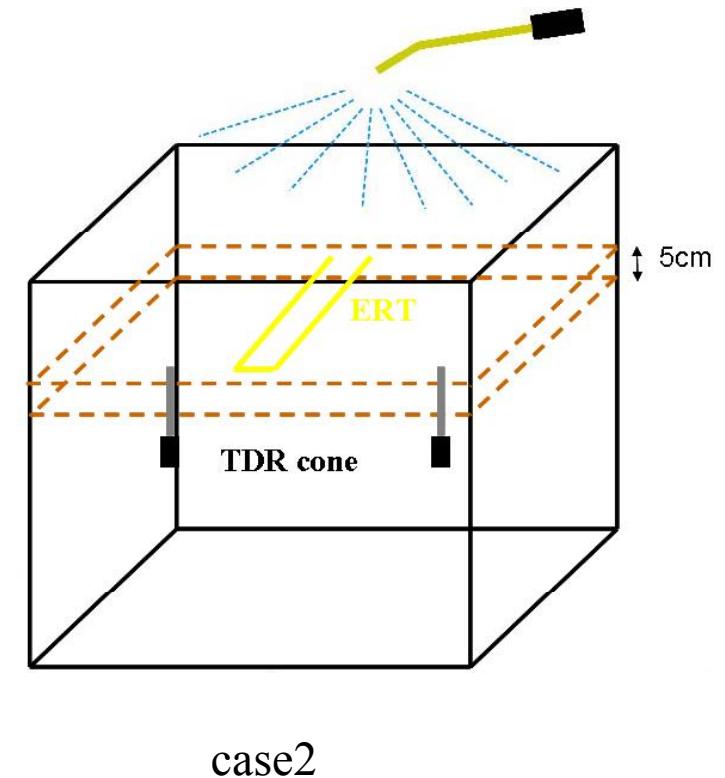
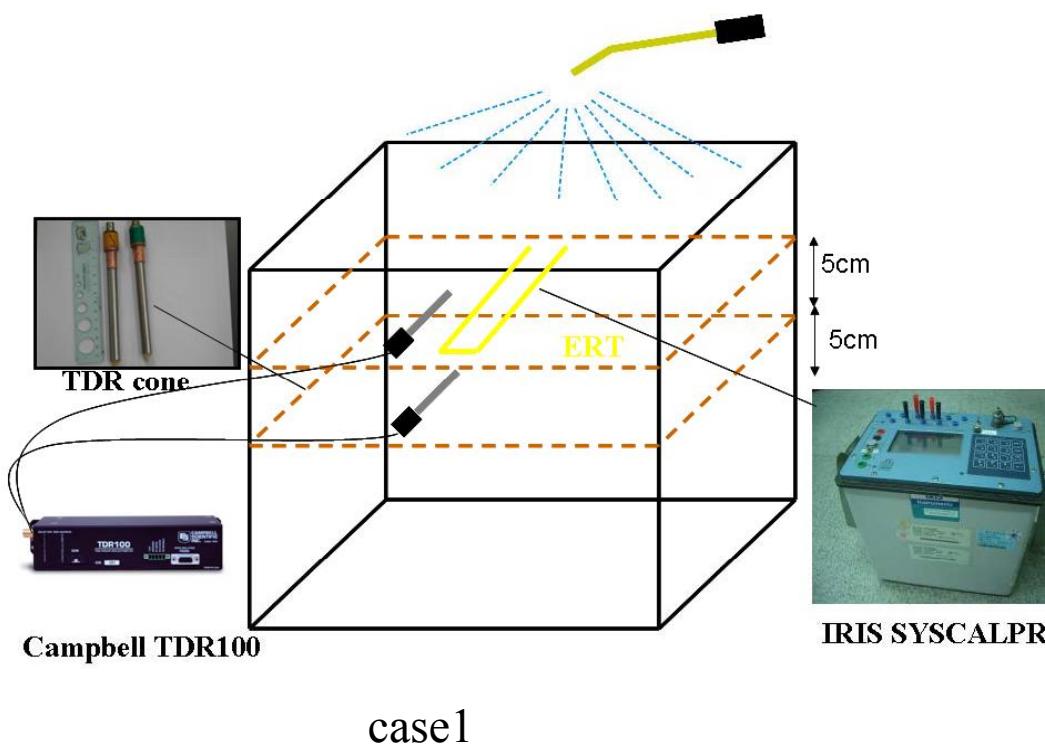
Proof of Concept for Moisture and Suction Imaging by ERT



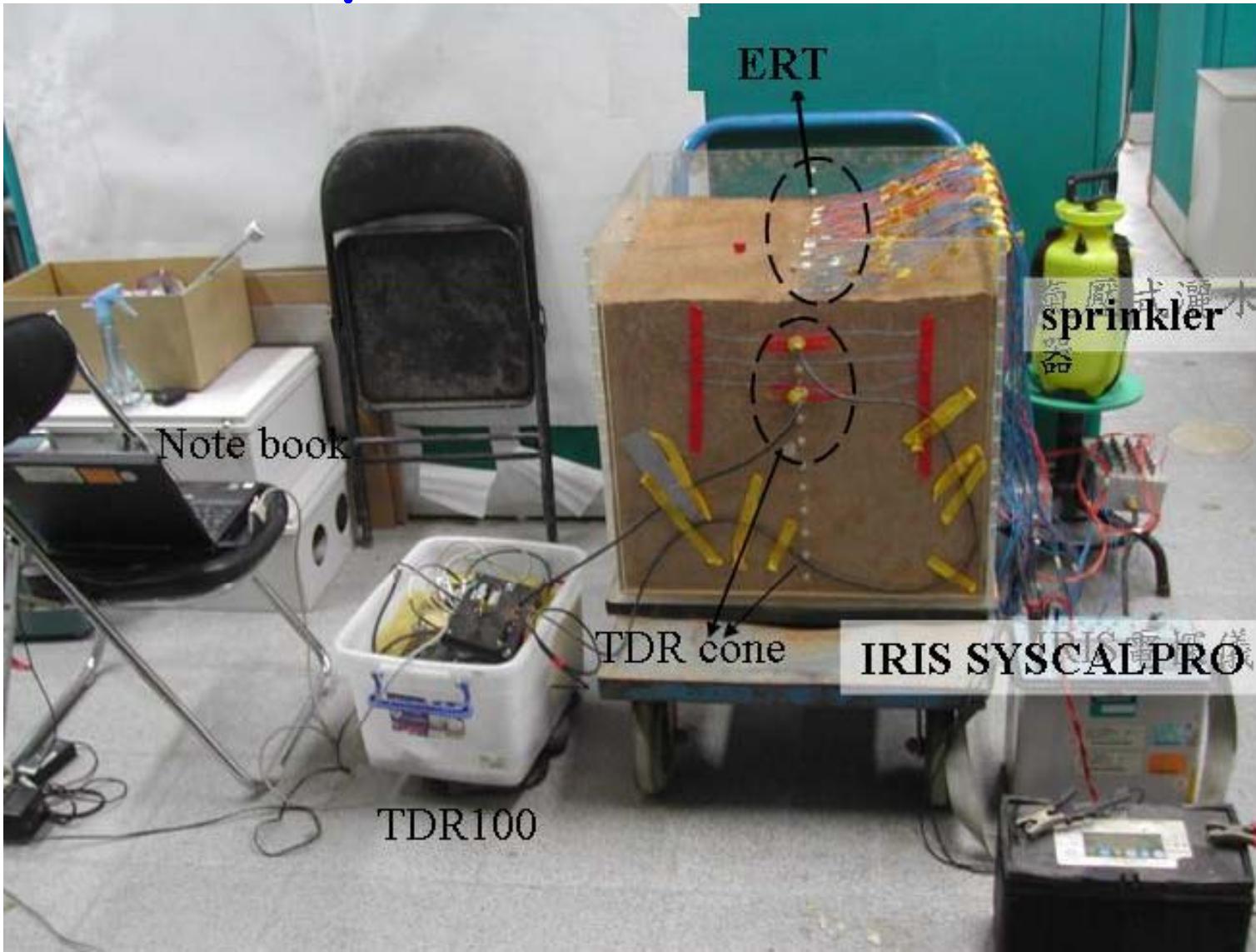
ERT resistivity + moisture and suction sensors for onsite calibration



Sandbox Experiment

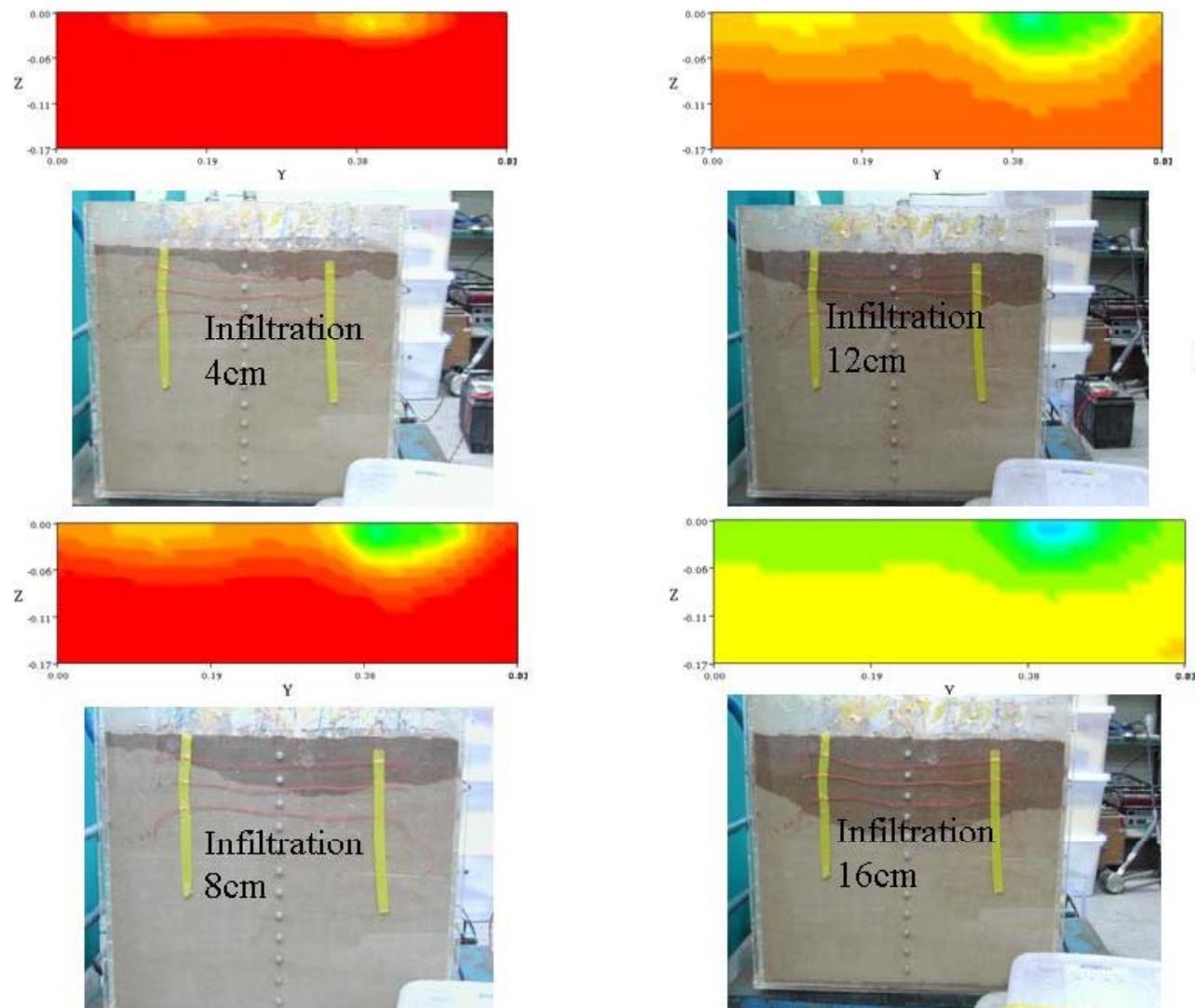
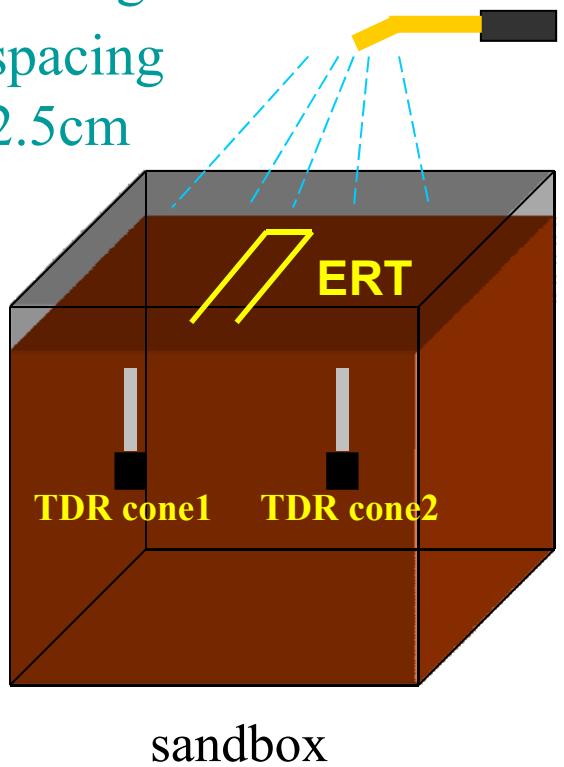


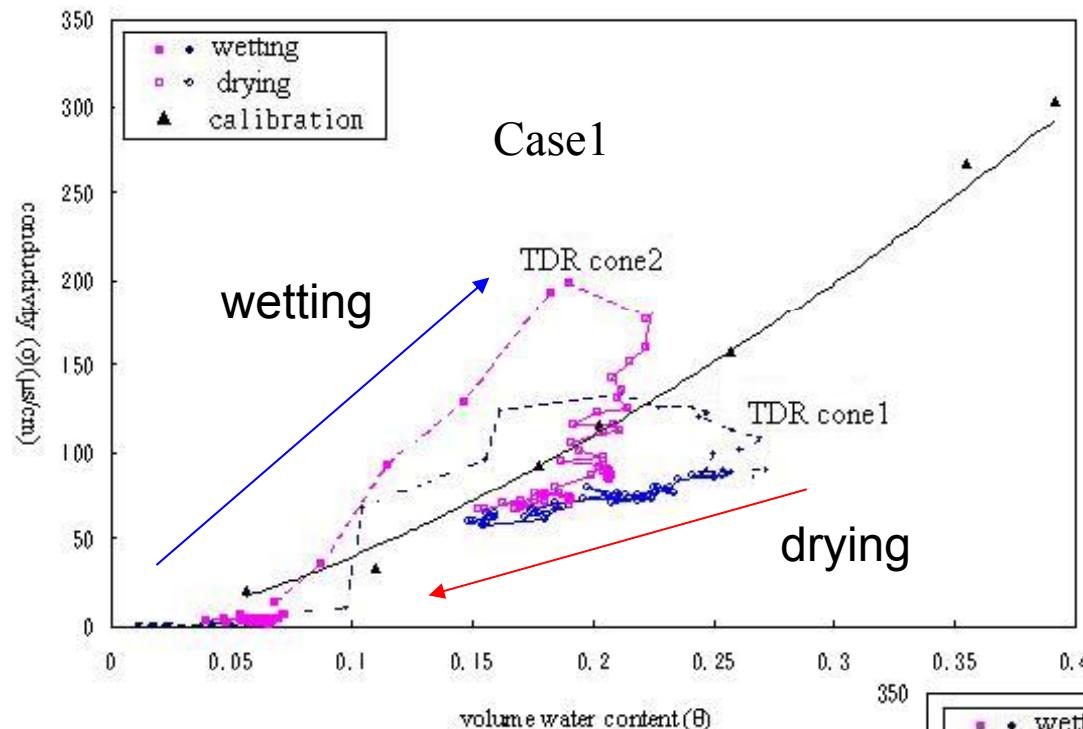
Sandbox Experiment



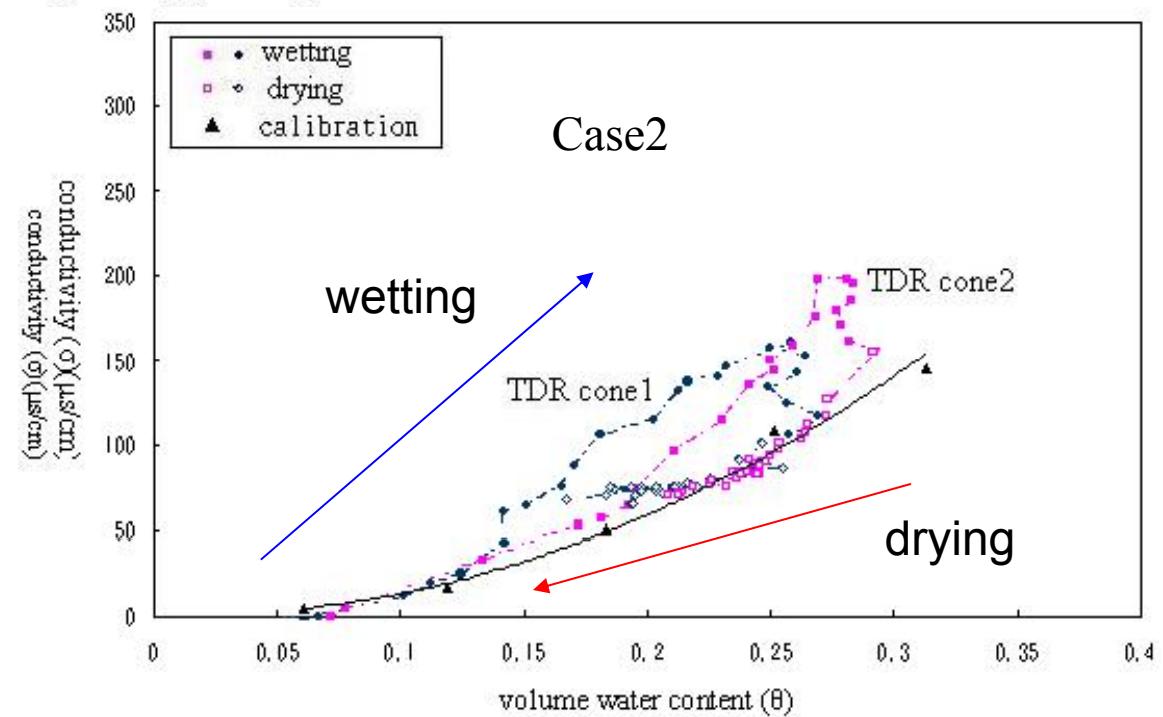
Sandbox Experiment

2*24 grids
spacing
2.5cm



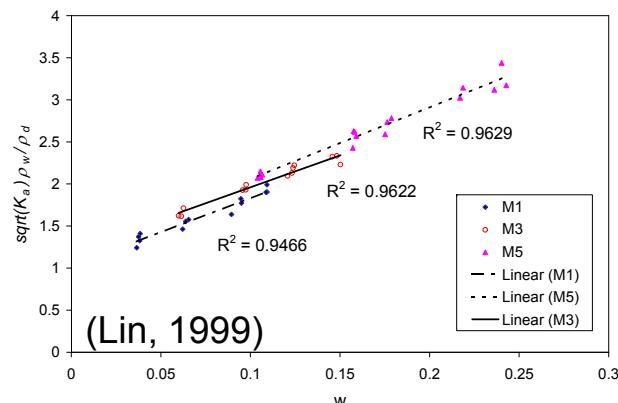


Hysteresis in ρ v. θ

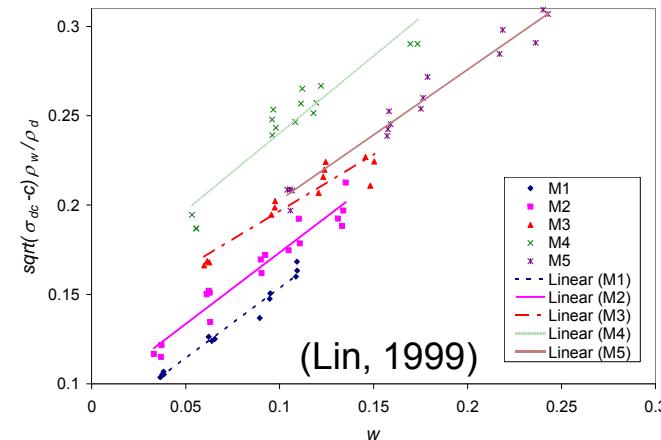


Soil Moisture vs. Dielectric/Ec

Dielectric



EC



- $\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$
(Topp et al., 1980)
- $\sqrt{K_a} = a_L + b_L \theta$
(Liedieu et al., 1986)
- $\sqrt{K_a} \rho_w = a \rho_d + b \theta$
 $\sqrt{K_a} \rho_w / \rho_d = a + b w$
(Siddique and Drnevich, 1995)

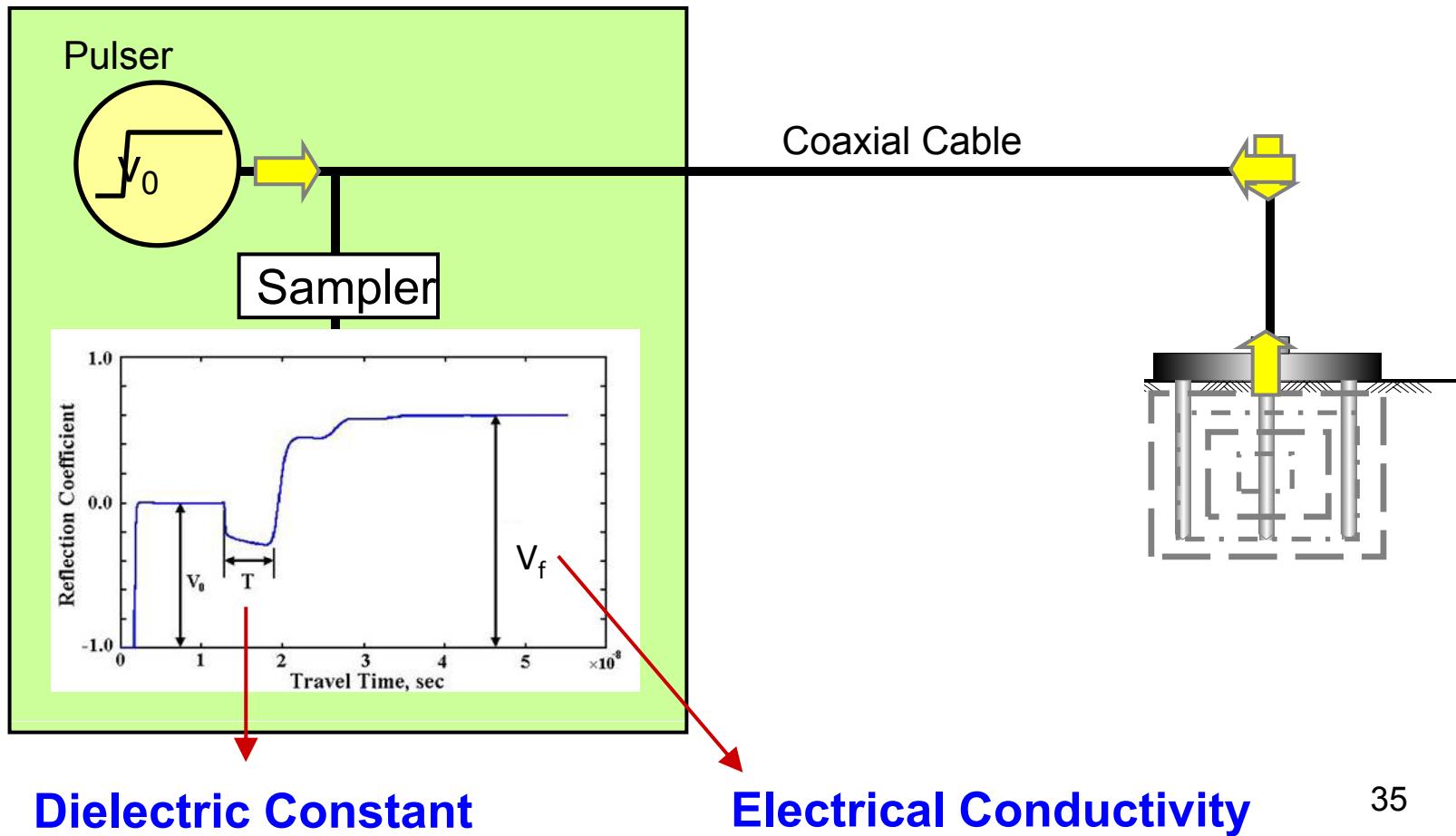
$$\sqrt{EC} \rho_w = c \rho_d + d \theta \quad (\text{Lin, 1999})$$

Dielectric = f(θ 、 ρ_d 、Soil Type)

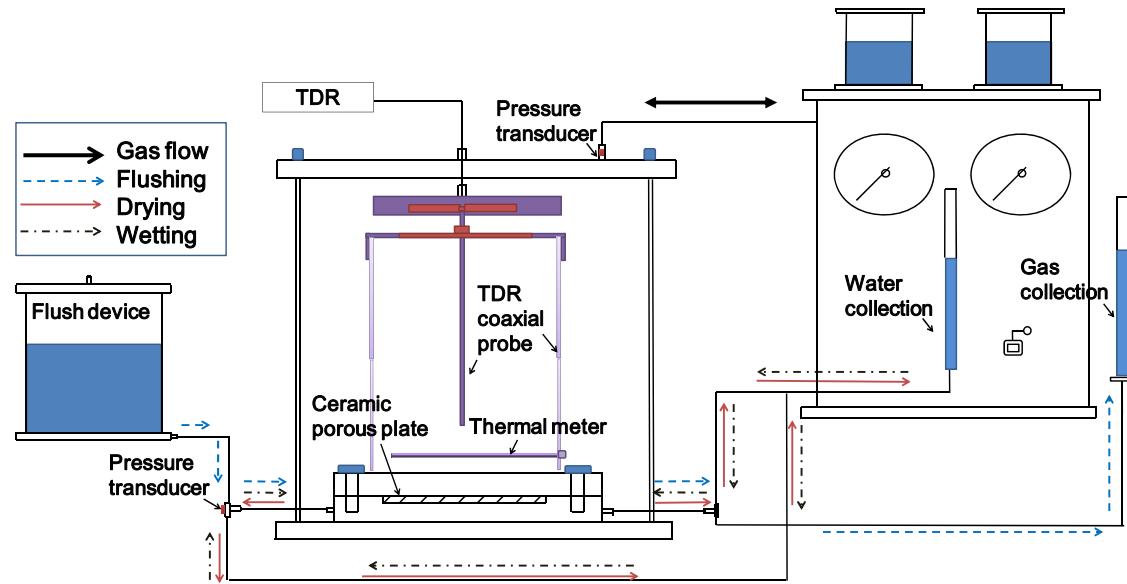
EC = f(θ 、 ρ_d 、Soil Type、 EC_w
Soil Structure、wetting/drying history)

Unsaturated Soil Water Content and Electrical Conductivity Characterization

Time Domain Reflectometry (TDR, cable radar)

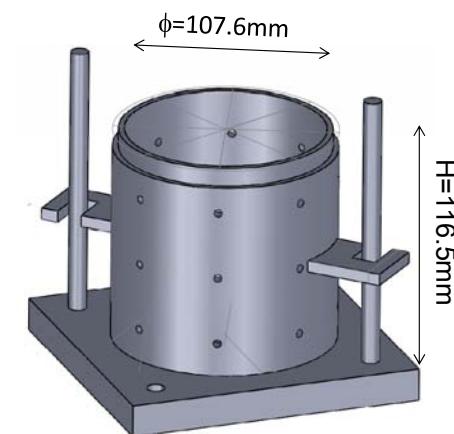
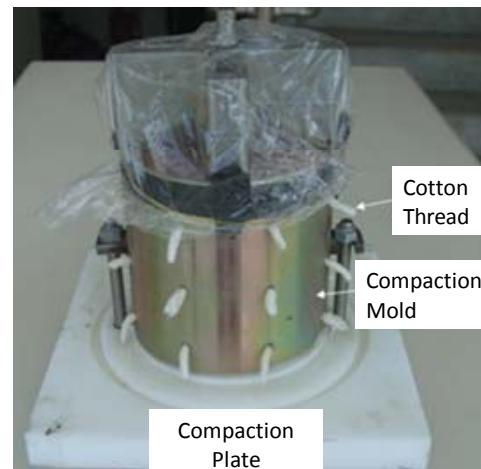


Laboratory Investigation

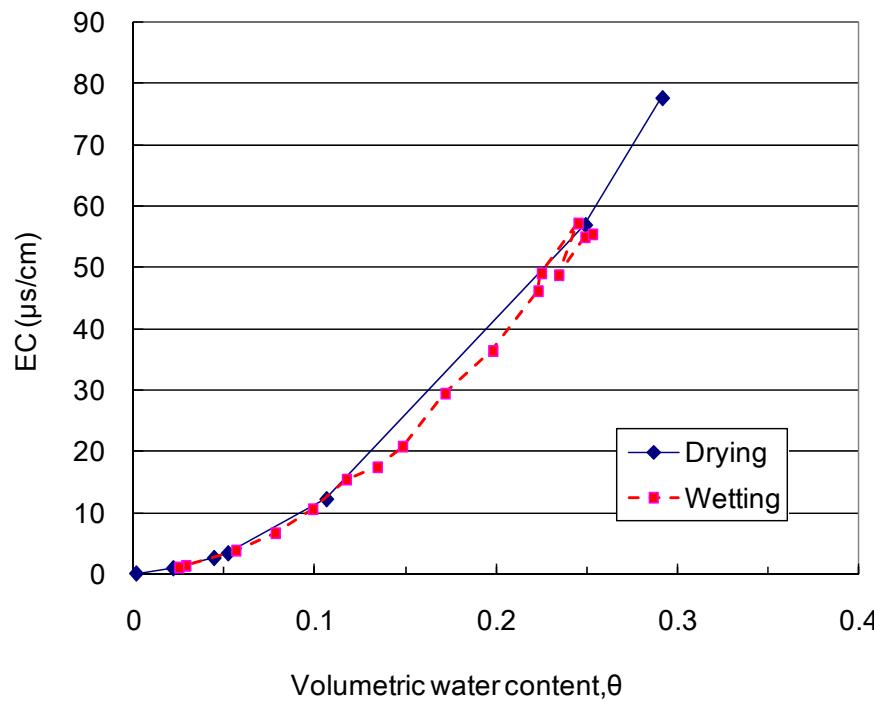


Pressure cell for slow wetting-drying

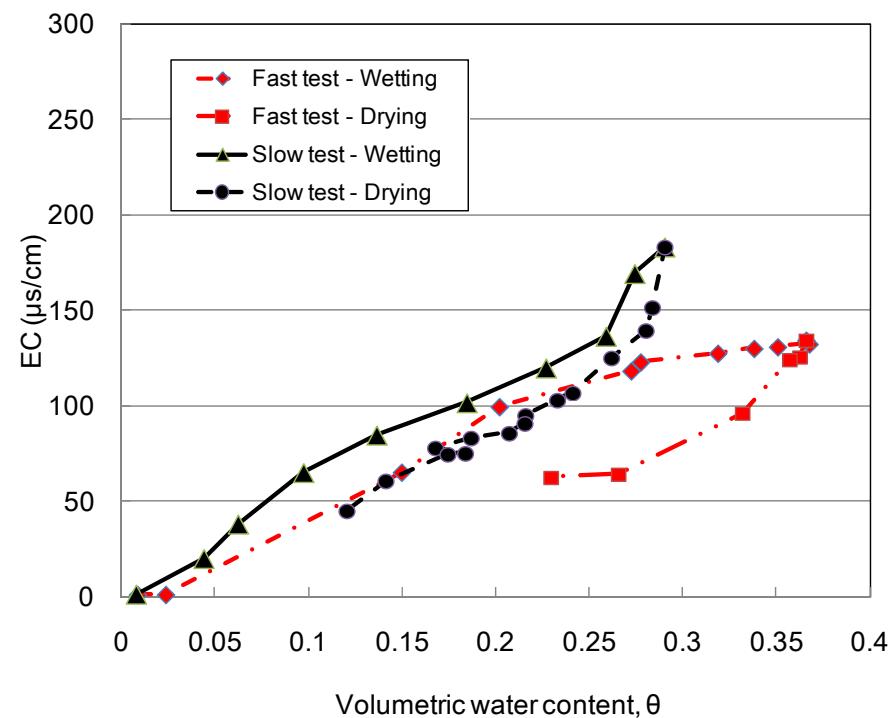
Apparatus for fast wetting-drying



Pressure Cell

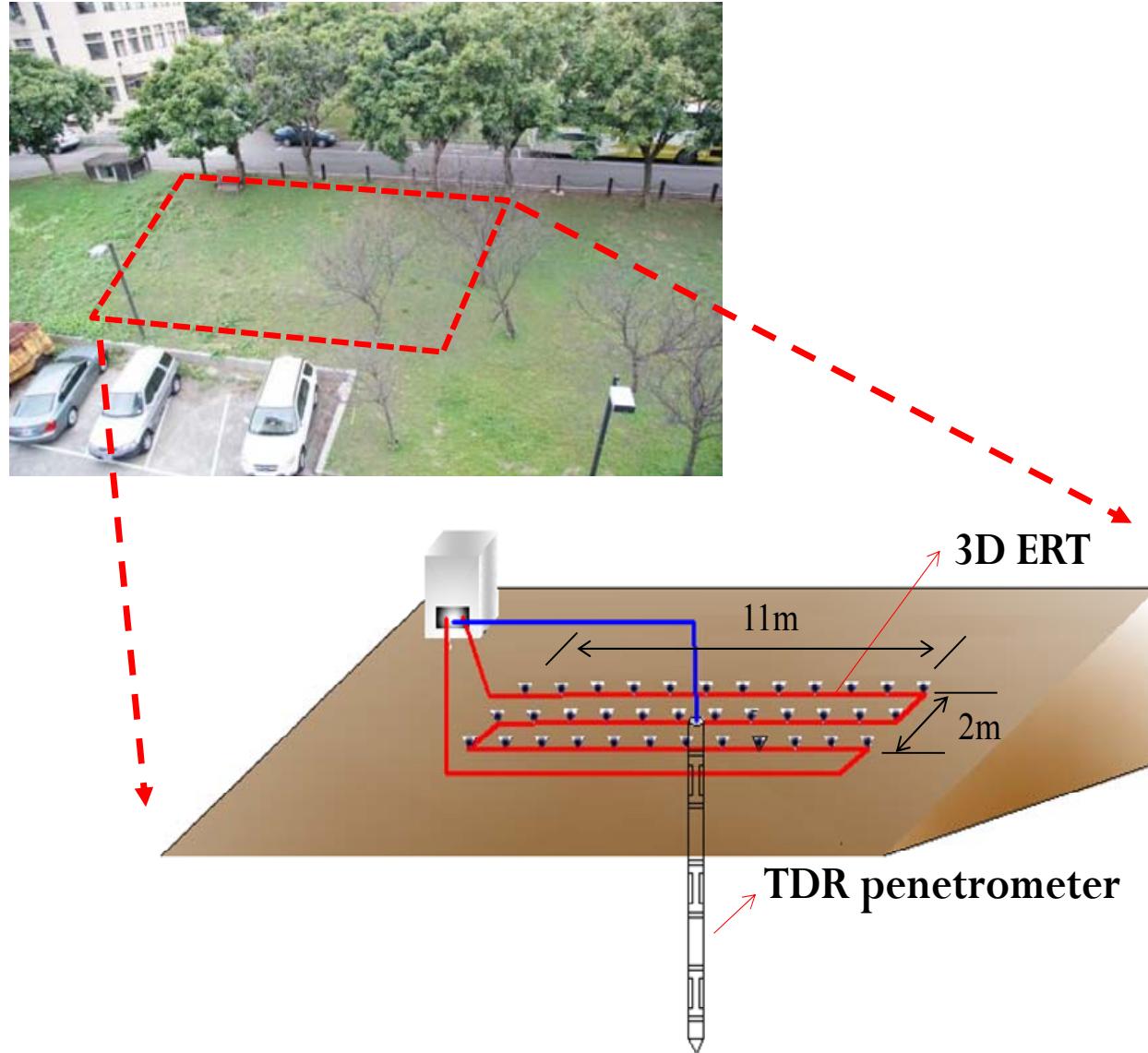


Fast wetting/drying apparatus

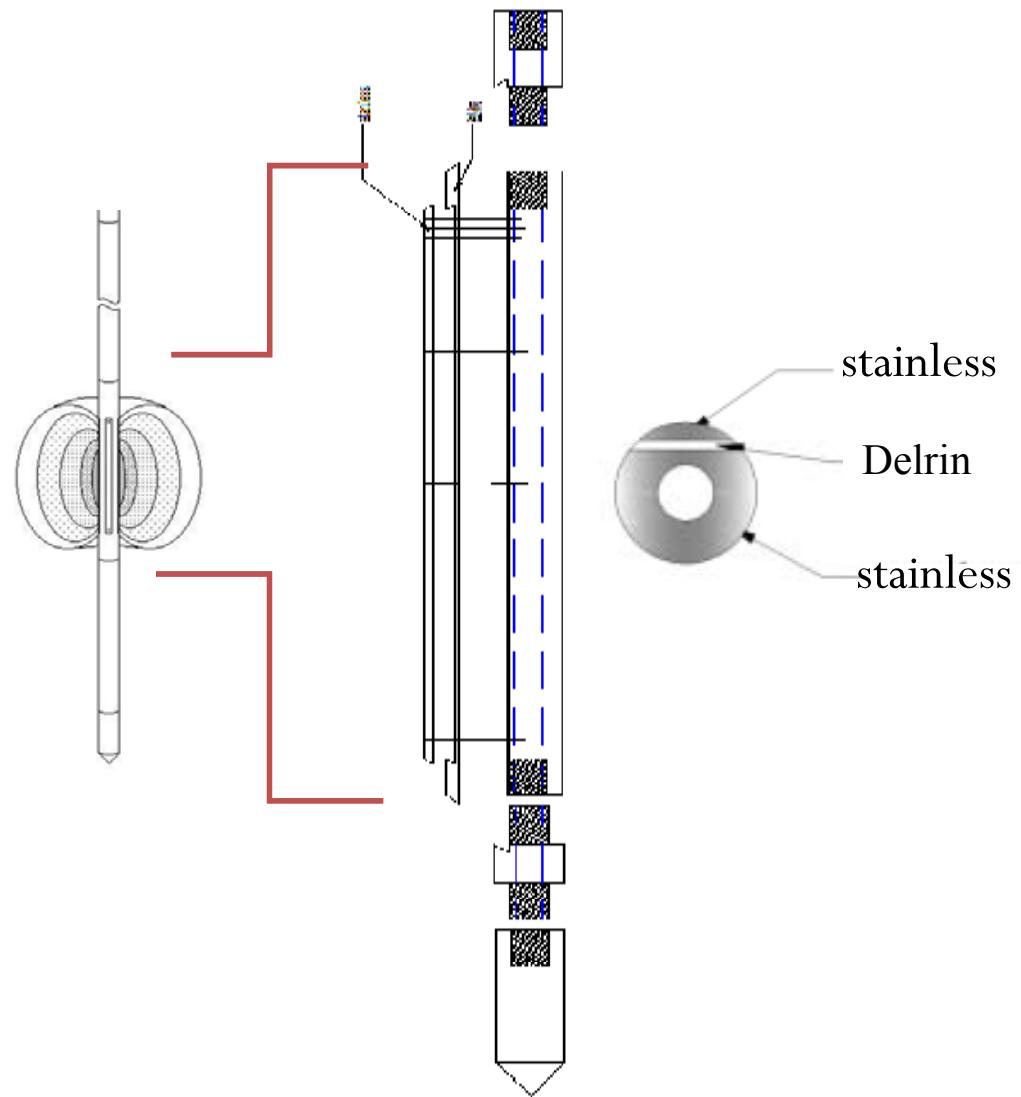


Hysteresis phenomenon between EC and θ intensifies as velocity of the wetting-drying process increases

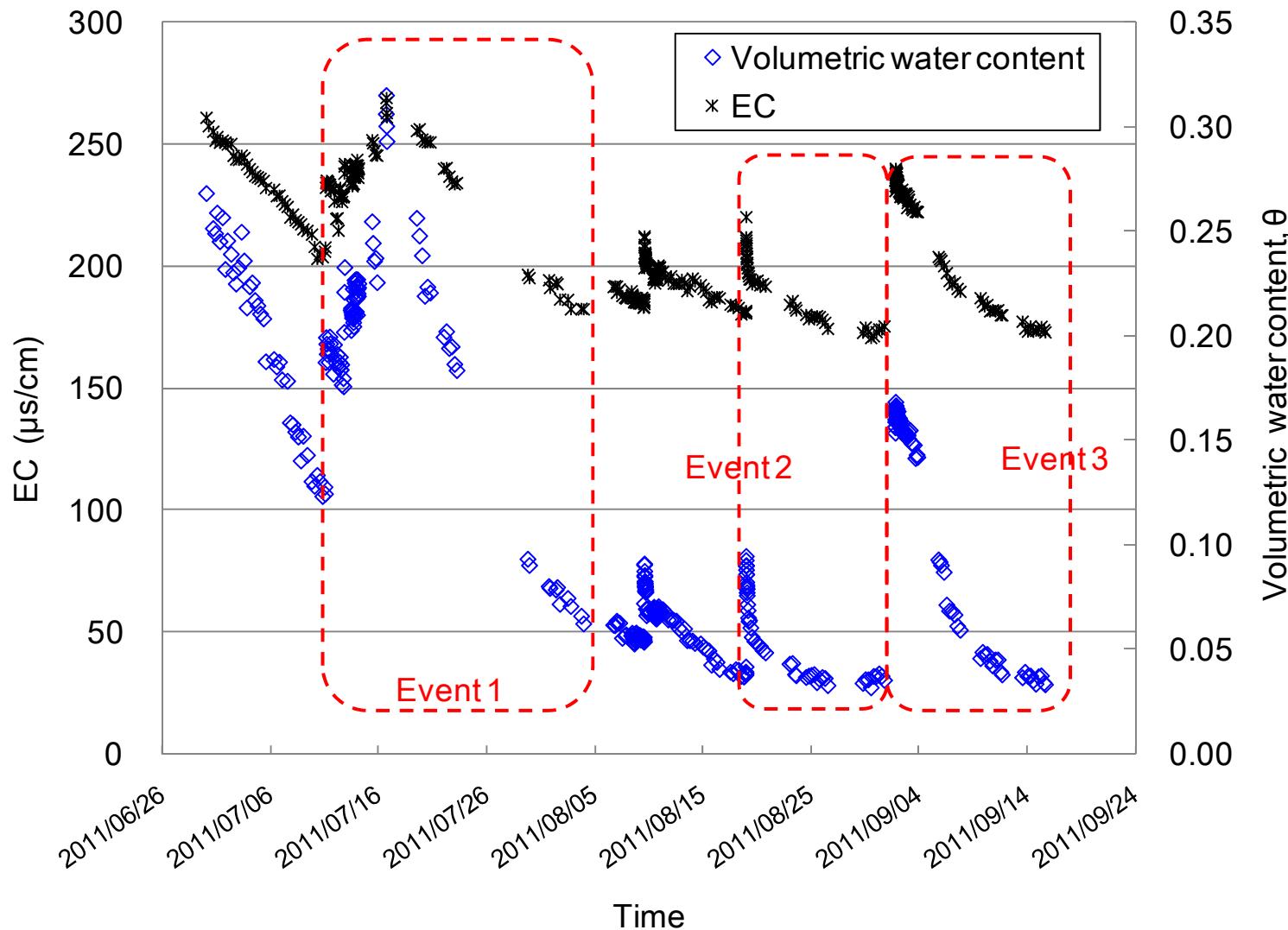
Field Observation



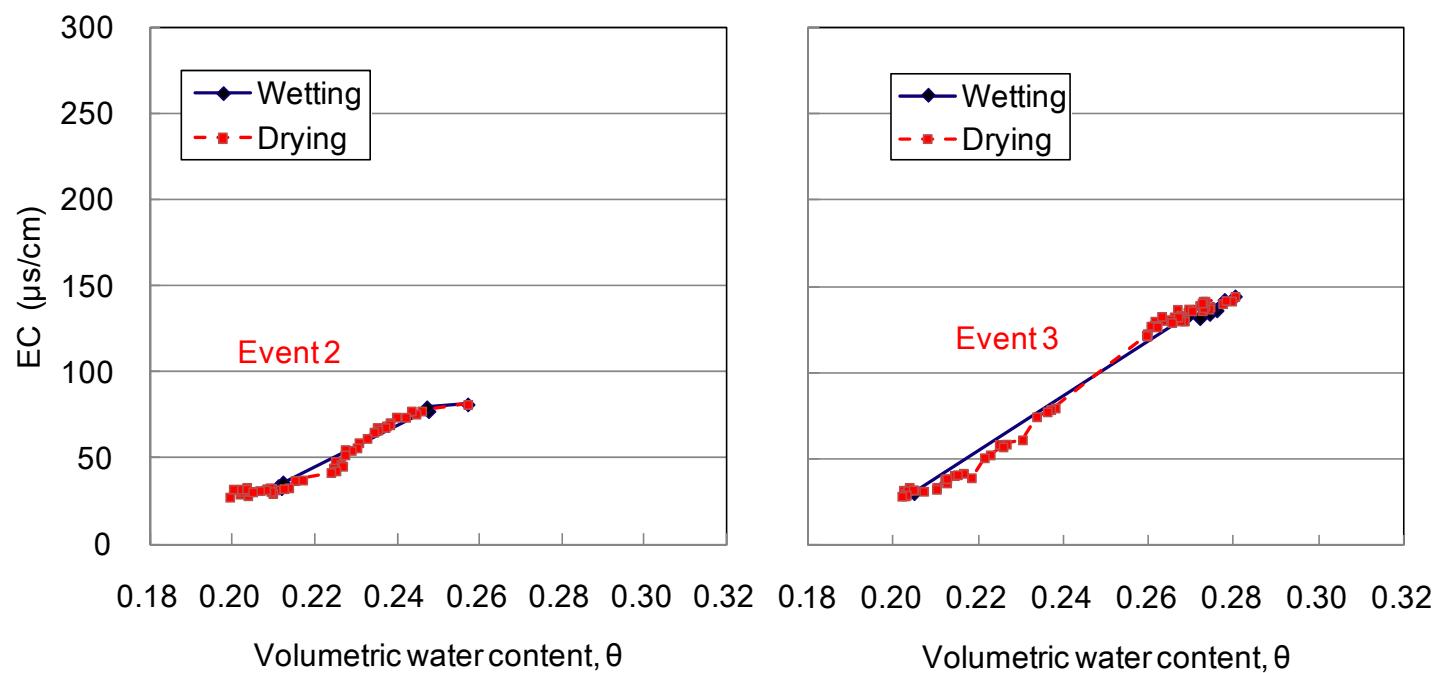
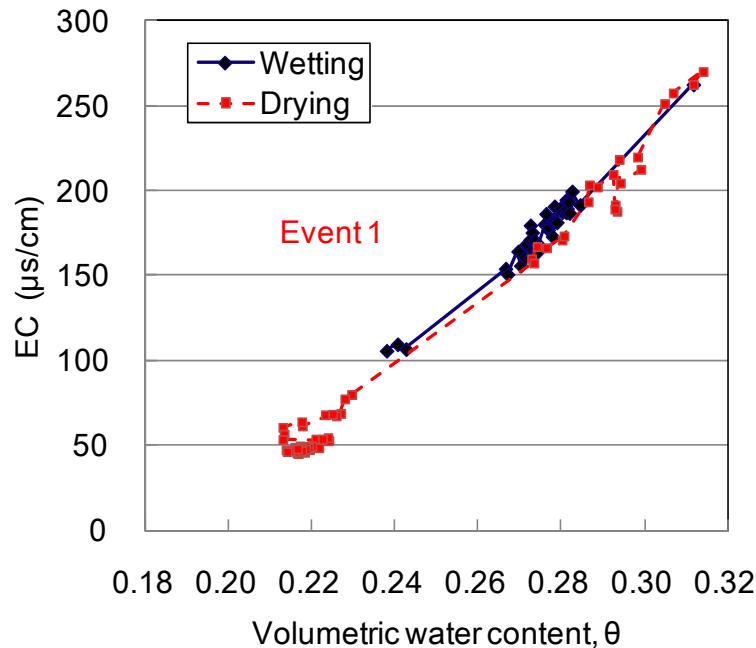
Probe Design



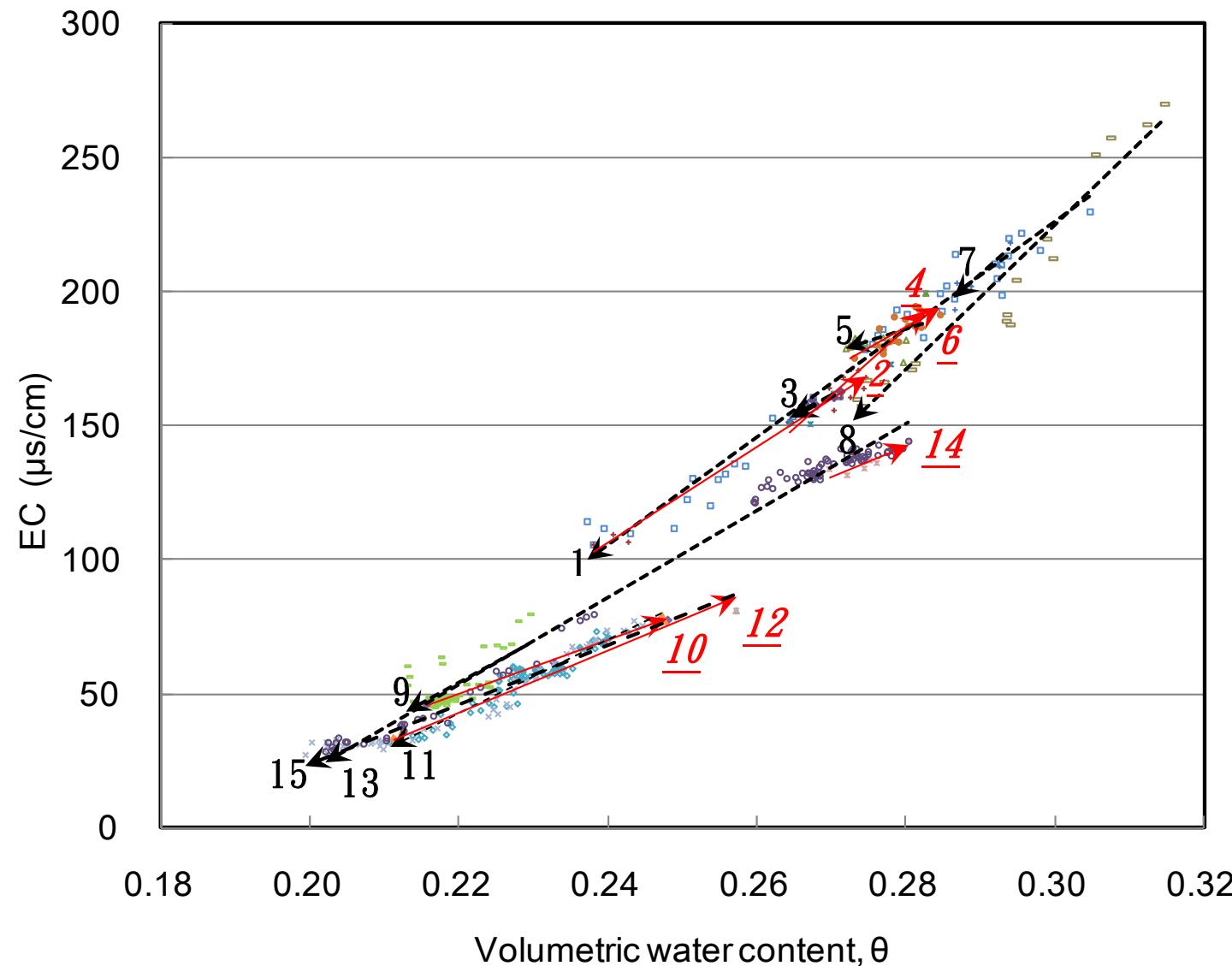
Results of Field TDR Monitoring @ 1m Depth



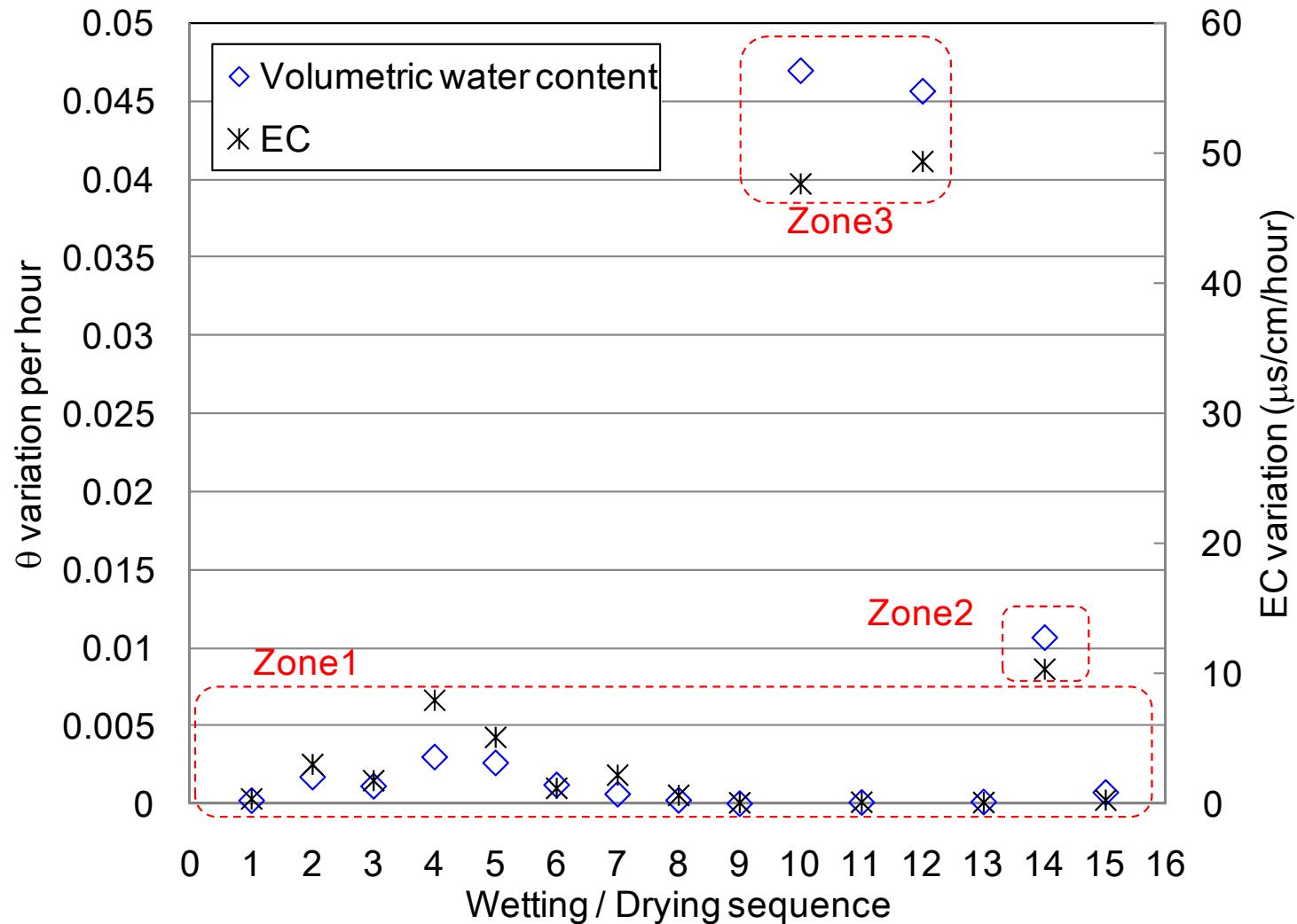
Field EC v. θ -Distinct events



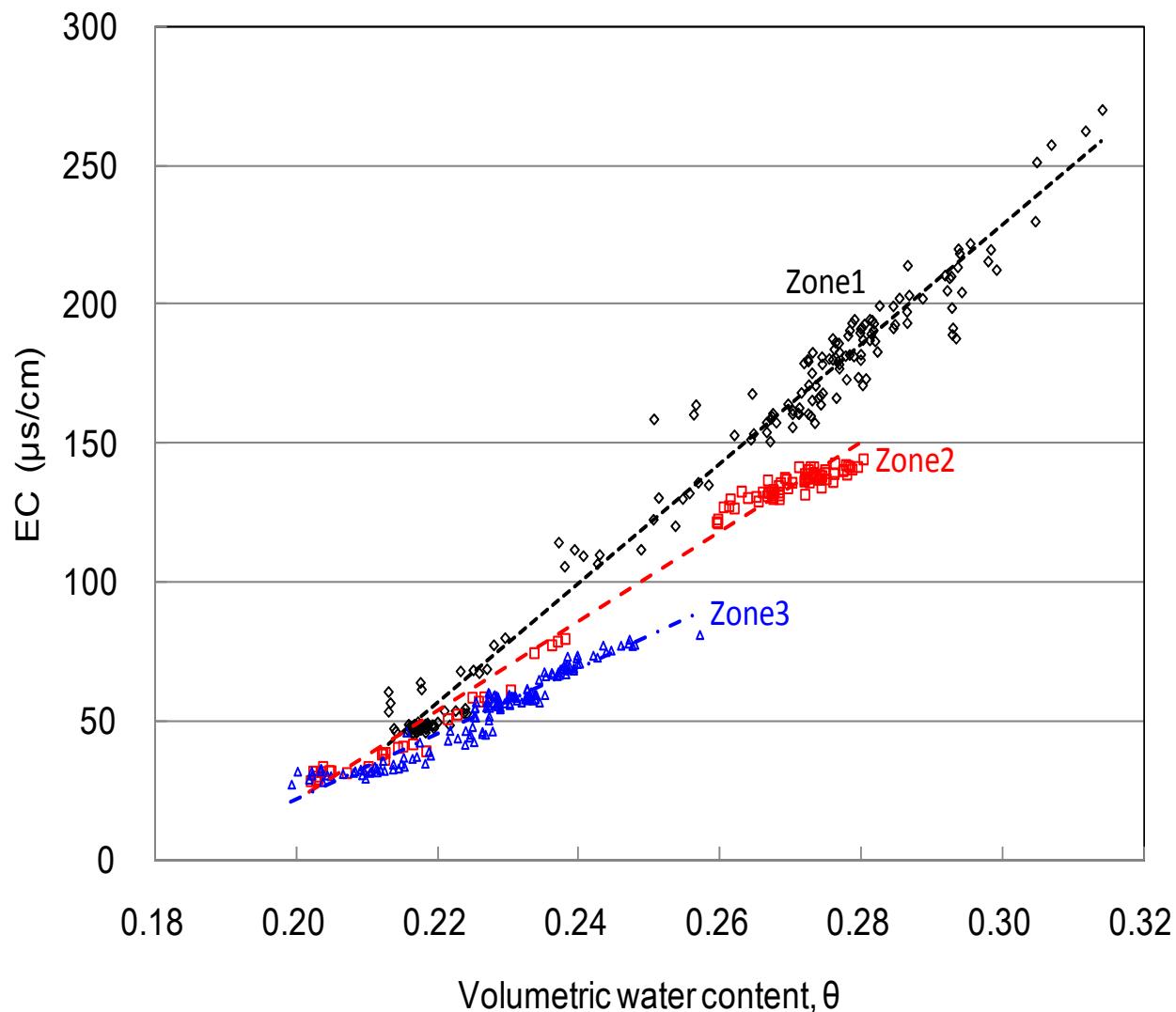
Wetting/Drying Sequence of EC v. θ



Groups of sequence by wetting/drying speed



EC- θ relation for groups of different wetting/drying speed



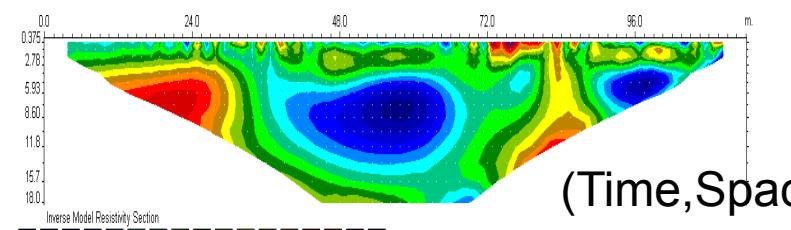
Combine ERT with TDR for θ Imaging



TDR

ERT

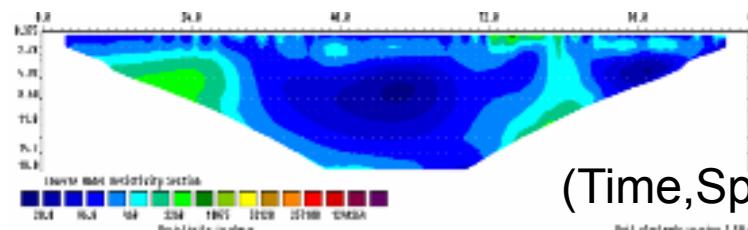
Resistivity section



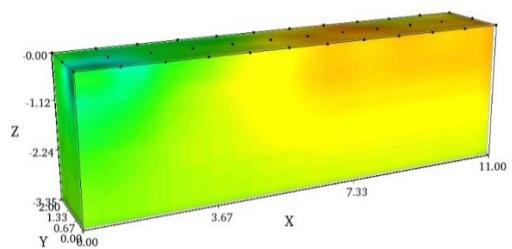
(Time,Space)

θ v.s ρ

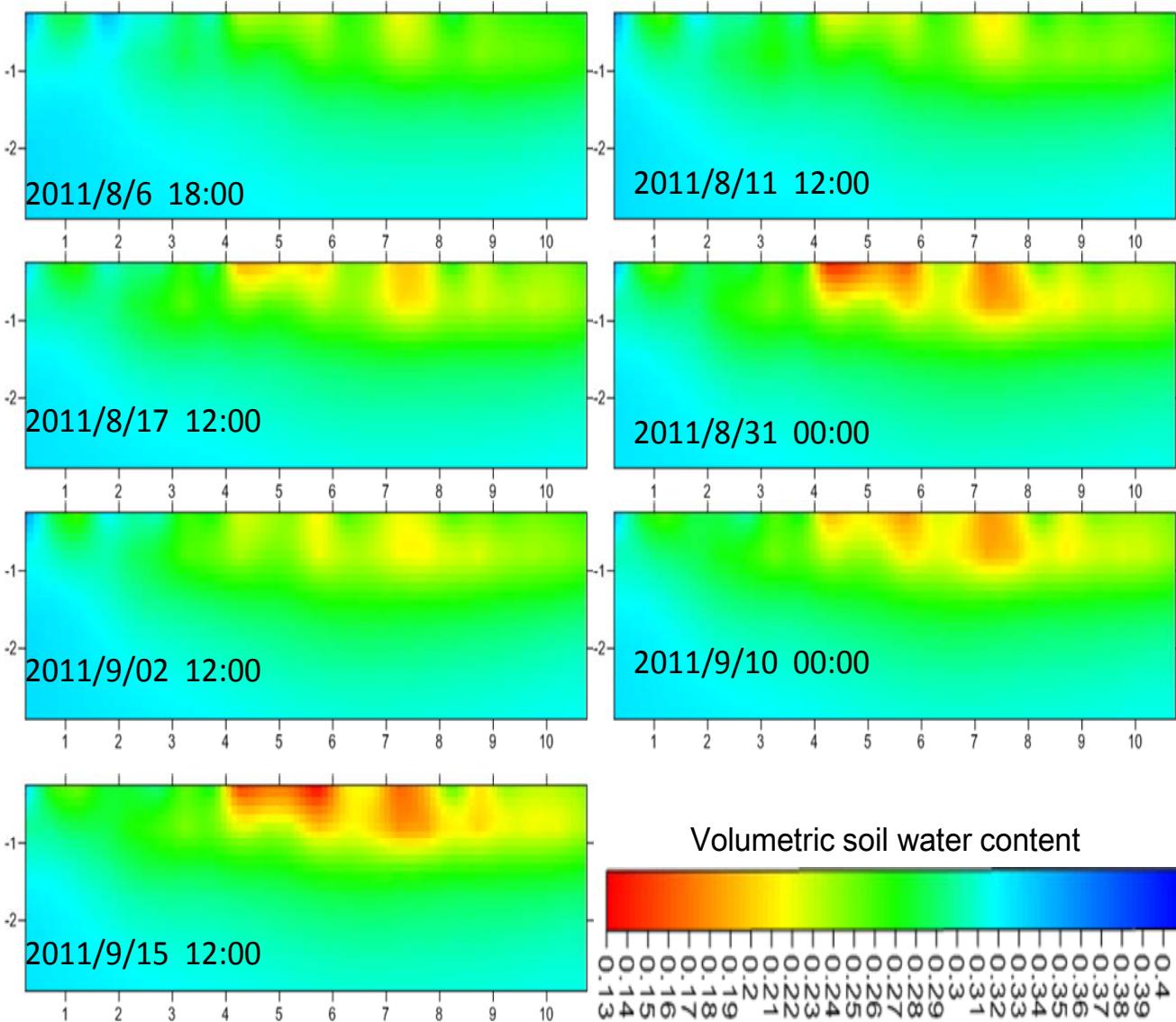
Water Content section



(Time,Space)



ERT+TDR θ Imaging



oil moisture profiler

1.



2.



3.



4.

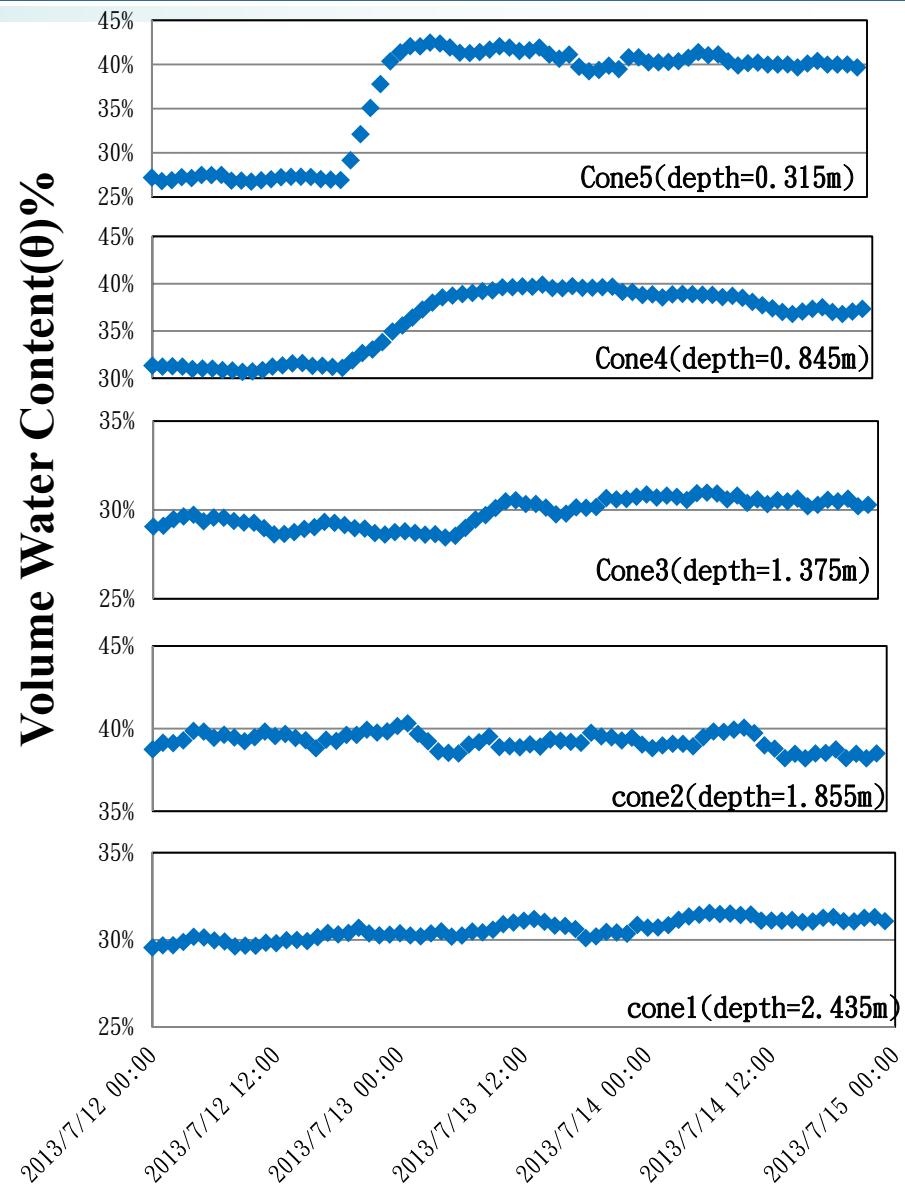
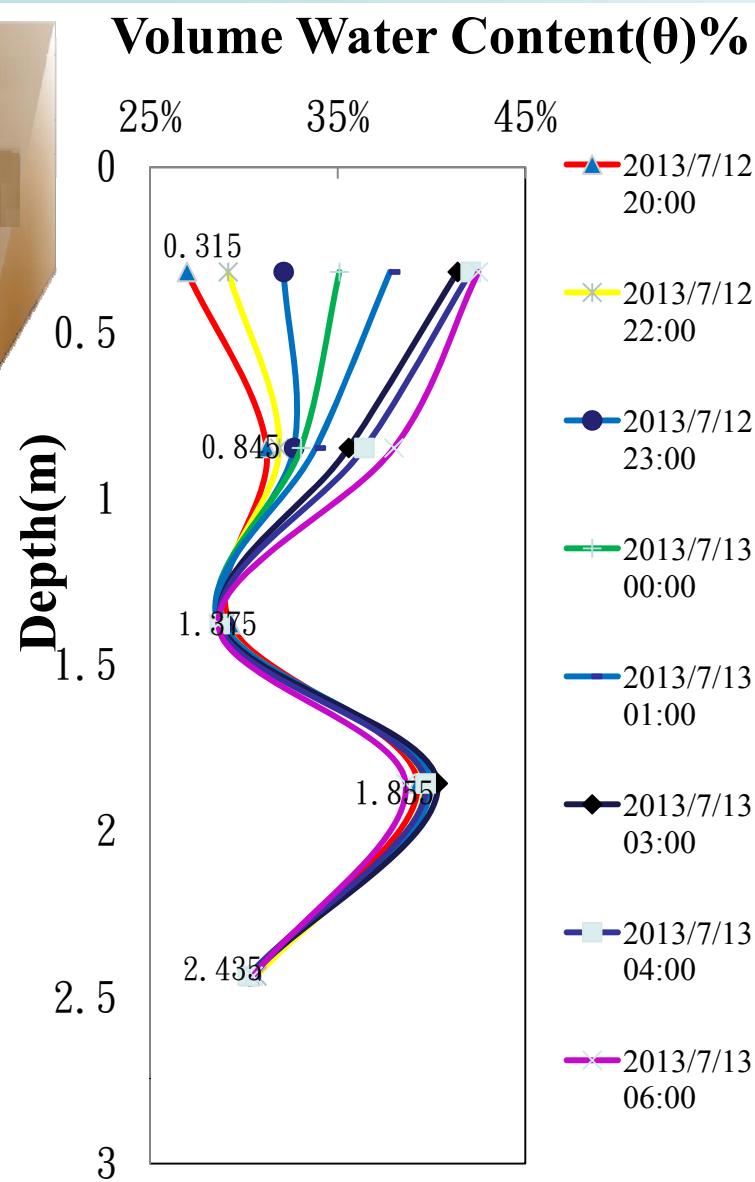
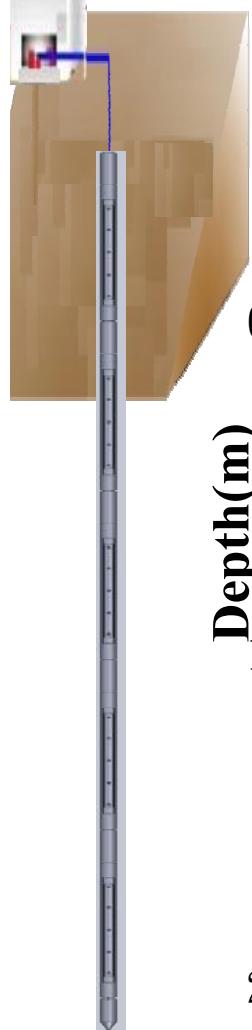


5.



oil

moisture rofiler



總結

- 電探探測深度佳，且能彈性的進行1D、2D、3D甚至4D的探測，使得它的應用越來越普遍。
- 但面上非破壞性施測的解析度隨深度增加降低甚快，且受到電阻率分佈的影響，另外需注意反算非唯一性及2D探測時的三維映射效應。
- 充分了解地物探測的可能限制，有助於降低其限制的影響，並避免錯誤的過度解讀；正算模擬可有效協助施測的規劃、探討施測可能限制及施測結果的解讀
- 在地文條件固定的情況下，電阻率反應含水特性，若透過如TDR監測技術提供場址率定，可將地物影像合理轉換成含水量影像。但除了含水量，需注意淺層電阻率可能受到入滲快慢與溫度的影響。

謝謝 !

geophysics

Colorado School of Mines

Summer 2012

