社團法人臺灣省土木技師公會
Taiwan Professional Civil Engineers Association

「透地雷達應用」研討會

國立雲林科技大學

營建工程系副教授兼大地防災與軌道技術研究中心主任

郭治平

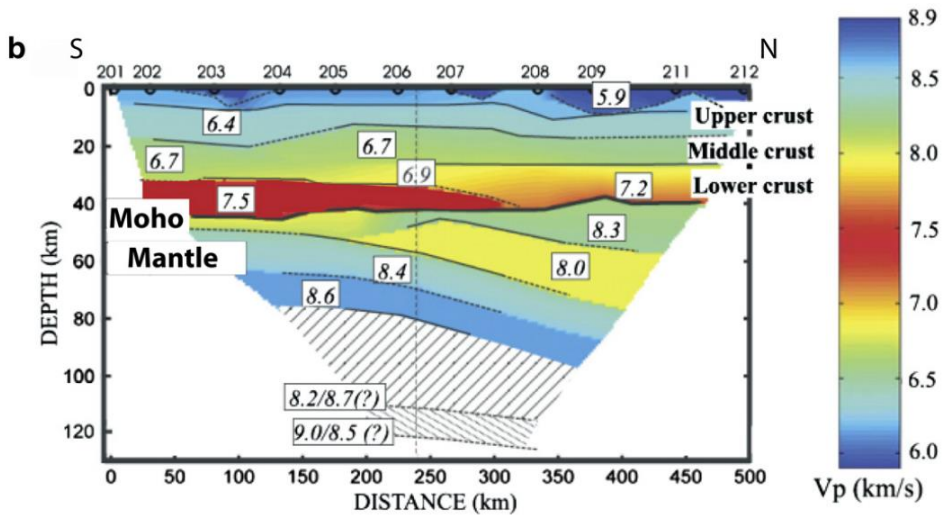
2023/12/16

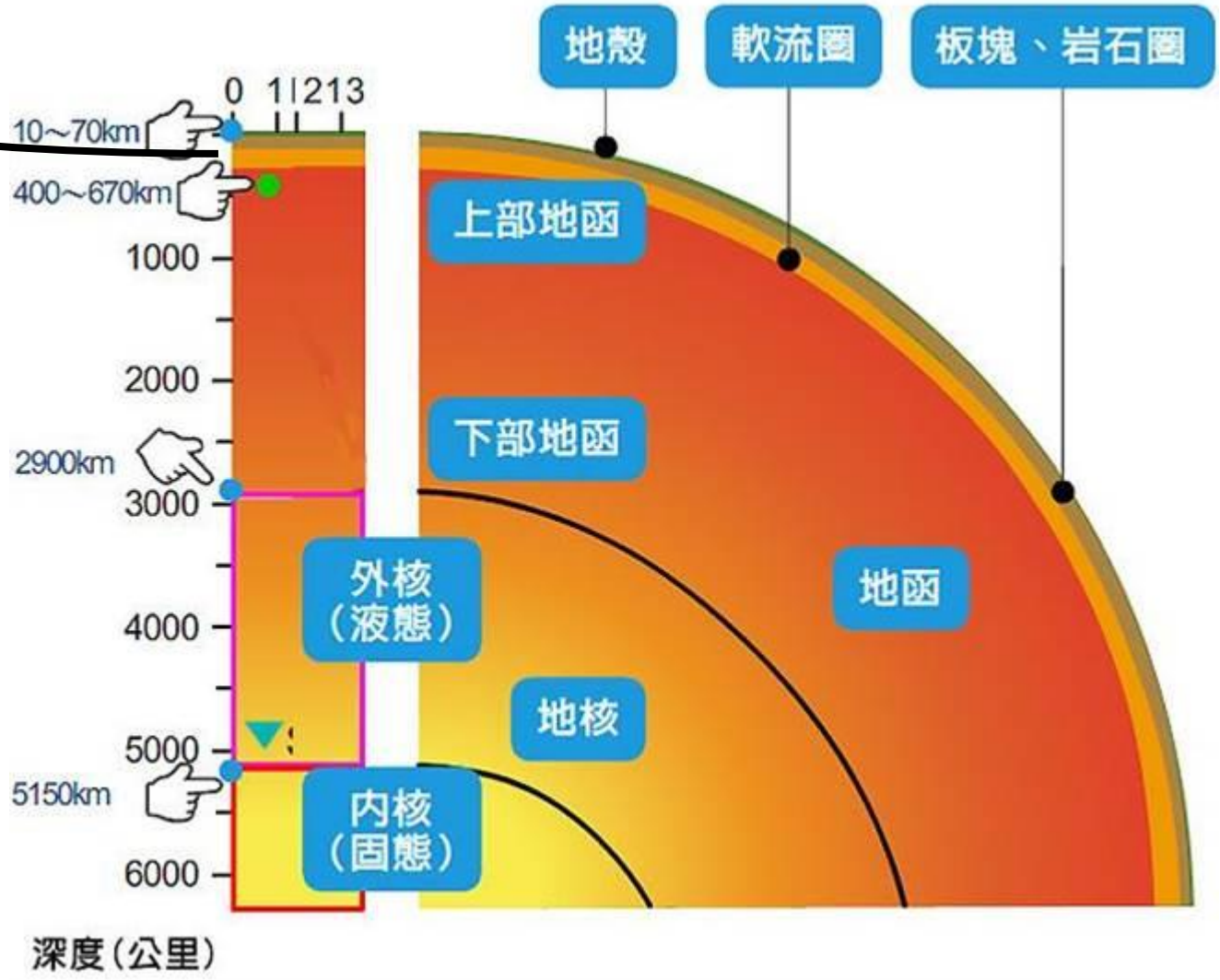
大綱

- 地球物理方法原理與非破壞性檢測
- 波傳在近地表探勘之應用
- 一般雷達原理
- 透地雷達原理
- 2D透地雷達之應用
- 3D透地雷達之應用
- 2D透地雷達操作注意事項概述

什麼是地球物理?

工程領域





西瓜質地探測?

實際應用

TVBS 新聞網 | 84.1k 人追蹤 ☆ 追蹤

天降「磁磚雨」！北市內湖737巷大小磁磚狂砸落 民眾掩頭躲

蘇憶歡 陳冠宇
2023年12月6日 週三 上午10:47

圖/TVBS

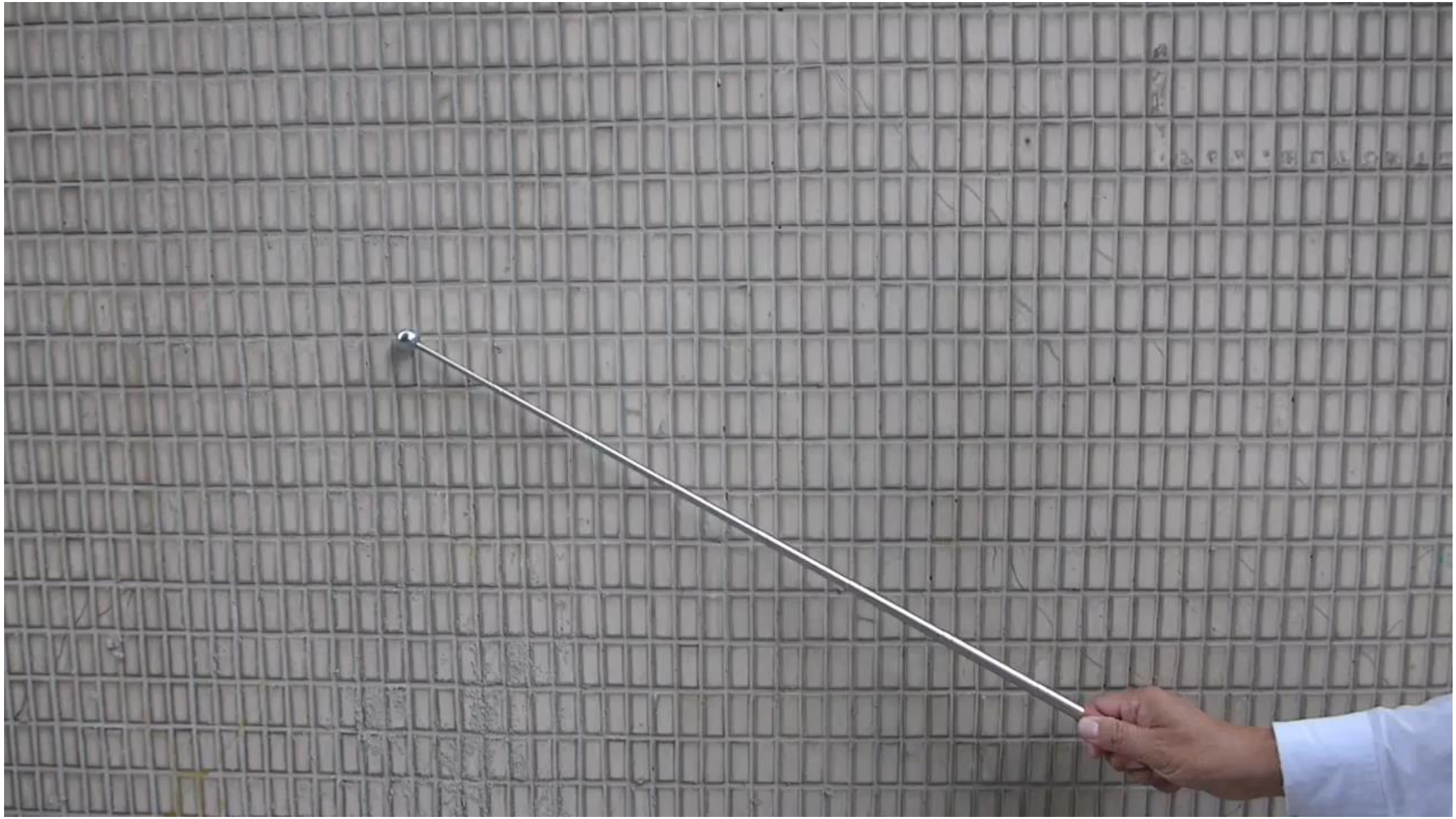
台北市內湖737巷美食街附近，昨（5）日晚間竟降下瓷磚雨！當時有民眾行經該處時，突然發現大樓外牆剝落、陸續掉落大小塊磁磚，嚇得紛紛掩頭快步閃避，同時報警處理。員警趕抵現場後，發現該處大樓磁磚仍有剝落風險，因此馬上於周邊拉起封鎖線，避免民眾靠近，確切原因為何仍待釐清。

板橋某大樓下起「磁磚雨」 新北工務局：最高可處30萬

2023-11-28 14:53 [illegible]

新北板橋一處舊大樓近日突然發生「磁磚雨」，讓附近居民人心惶惶；管委會趕緊修復。圖／新北工務局提供

新北板橋一處舊大樓近日突然發生「磁磚雨」，讓附近居民人心惶惶。新北工務局回應，接獲民眾通報後第一時間即到場確認情況，管委會也隔日就雇工修復；工務局提醒，管委會應依法管理，若未善盡管理責任，最高可處30萬元，以及相關民事及刑事責任。



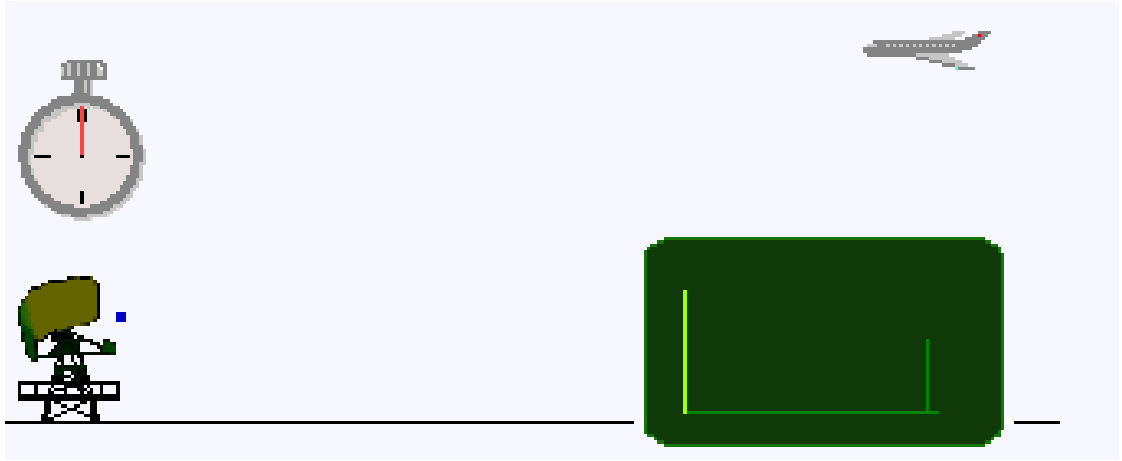
TechRentals

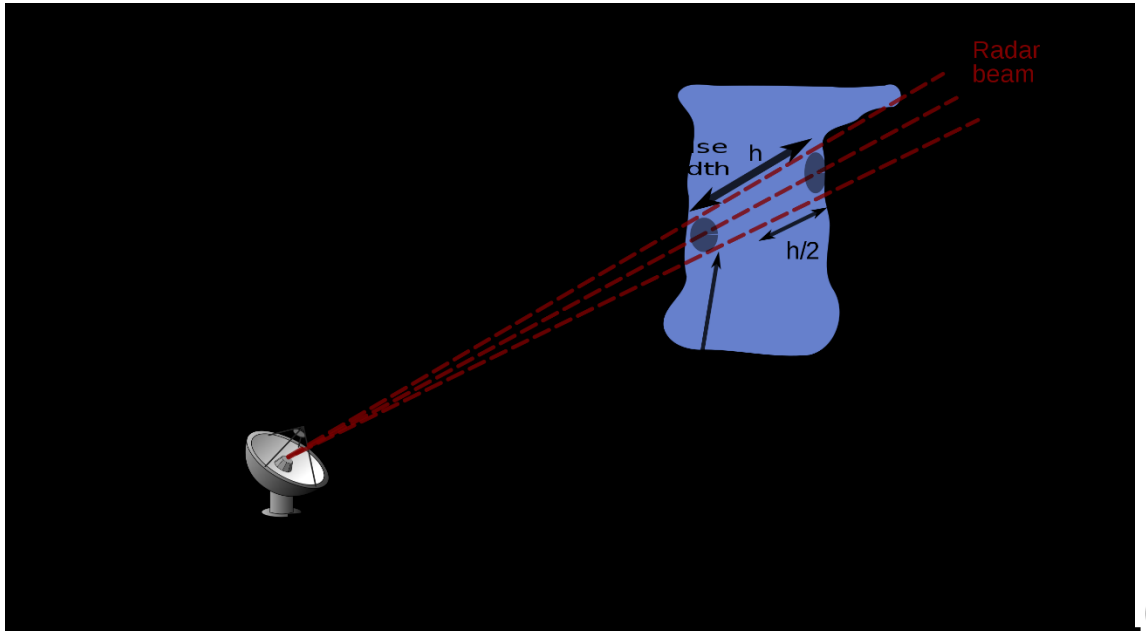
Determining Concrete Crack Depth using the Proceq PL-200PE

共詩作15次，
裂縫深從
2mm~200mm

何謂雷達

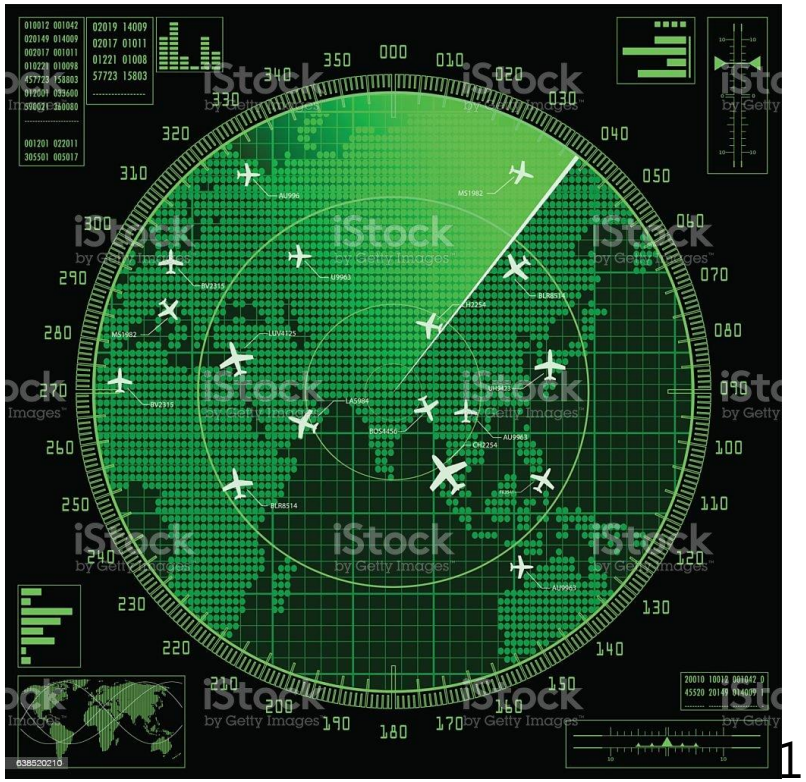
- Radar (originally acronym for radio detection and ranging) is a detection system that uses radio waves to determine the distance (ranging), angle, and radial velocity of objects relative to the site. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna (often the same antenna is used for transmitting and receiving) and a receiver and processor to determine properties of the objects. Radio waves (pulsed or continuous) from the transmitter reflect off the objects and return to the receiver, giving information about the objects' locations and speeds.





Doppler effect

- For waves that propagate in a medium, such as sound waves, the velocity of the observer and of the source are relative to the medium in which the waves are transmitted. The total Doppler effect may therefore result from motion of the source, motion of the observer, or motion of the medium. Each of these effects is analyzed separately. For waves which do not require a medium, such as electromagnetic waves or gravitational waves, only the relative difference in velocity between the observer and the source needs to be considered. When this relative velocity is not negligible compared to the speed of light, a more complicated relativistic Doppler effect arises.



Ground-penetrating radar

- **Ground-penetrating radar** (**GPR**) is a geophysical method that uses radar pulses to image the subsurface. It is a non-intrusive method of surveying the sub-surface to investigate underground utilities such as concrete, asphalt, metals, pipes, cables or masonry.[1] This nondestructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can have applications in a variety of media, including rock, soil, ice, fresh water, pavements and structures. In the right conditions, practitioners can use GPR to detect subsurface objects, changes in material properties, and voids and cracks.[2][3]
- GPR uses high-frequency (usually polarized) radio waves, usually in the range 10 MHz to 2.6 GHz. A GPR transmitter and antenna emits electromagnetic energy into the ground. When the energy encounters a buried object or a boundary between materials having different permittivities, it may be reflected or refracted or scattered back to the surface. A receiving antenna can then record the variations in the return signal. The principles involved are similar to seismology, except GPR methods implement electromagnetic energy rather than acoustic energy, and energy may be reflected at boundaries where subsurface electrical properties change rather than subsurface mechanical properties as is the case with seismic energy.

Ground-penetrating radar

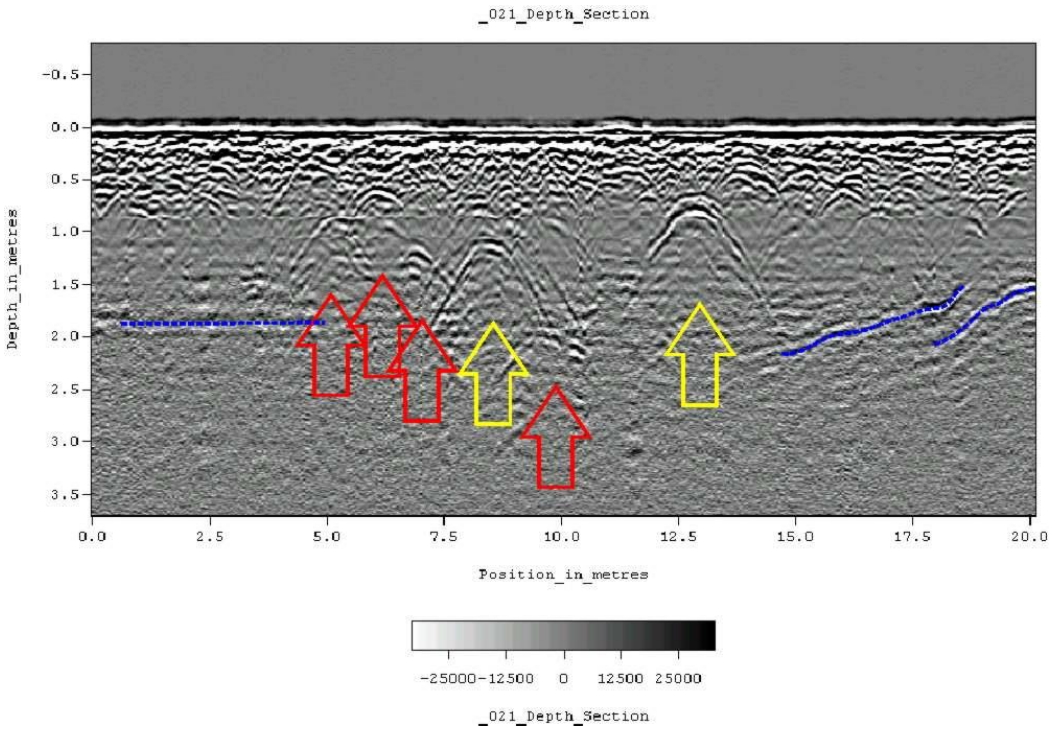
- The electrical conductivity of the ground, the transmitted center frequency, and the radiated power all may limit the effective depth range of GPR investigation. Increases in electrical conductivity attenuate the introduced electromagnetic wave, and thus the penetration depth decreases.
- Because of frequency-dependent attenuation mechanisms, higher frequencies do not penetrate as far as lower frequencies. However, higher frequencies may provide improved resolution. Thus operating frequency is always a trade-off between resolution and penetration.
- Optimal depth of subsurface penetration is achieved in ice where the depth of penetration can achieve several thousand meters (to bedrock in Greenland) at low GPR frequencies.
- Dry sandy soils or massive dry materials such as granite, limestone, and concrete tend to be resistive rather than conductive, and the depth of penetration could be up to 15 meters (49 ft).
- However, in moist or clay-laden soils and materials with high electrical conductivity, penetration may be as little as a few centimeters.
- Ground-penetrating radar antennas are generally in contact with the ground for the strongest signal strength; however, GPR air-launched antennas can be used above the ground.
- Cross borehole GPR has developed within the field of hydro geophysics to be a valuable means of assessing the presence and amount of soil water.


DitchWitch

透地雷達物理探測方法

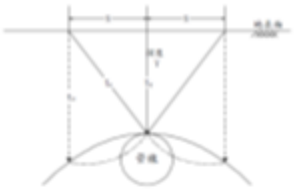
- **透地雷達地球物理探測是利用電磁波的理論**
- 1930年代 學者將電磁波用於**探測冰層之厚度**
- 1960年代 由美國麻省理工學院（MIT）開發出透地雷達的技術，主要是因應美國在越戰中需要**偵測越共地道**之用。
- 1970年代 透地雷達技術對外開放，使得學術界及工程界對透地雷達的研究有許多的重要成果
- 1972年代 第一間透地雷達設備生產公司Geological Survey System Inc.（GSSI）成立。
- 1980 年代中期，在國際透地雷達會議成立後，才有**標準化之制定**，成為專指利用電磁波(雷達波)探測地下物之方法。
- **1990年代台灣開始引進，學界及工程界亦陸續加以應用。**

- **土木結構**
  - 管線探測
  - 鋼筋探測
  - 混凝土結構
  - 空洞探測
- **環保問題**
  - 地下掩埋場位置探測
  - 地下油槽位置探測
  - 油槽漏油偵測
  - 管線滲漏偵測
  - 污染範圍偵測
- **大地工程**
  - 河床、湖底地形的描繪斷面探測
  - 地下管線探測
  - 地層探測
  - 空洞探測
  - 地下水探測
  - 地下礦體探測
- **交通運輸**
  - 道路瀝青厚度探測
  - 鐵路路基探測
- **考古**

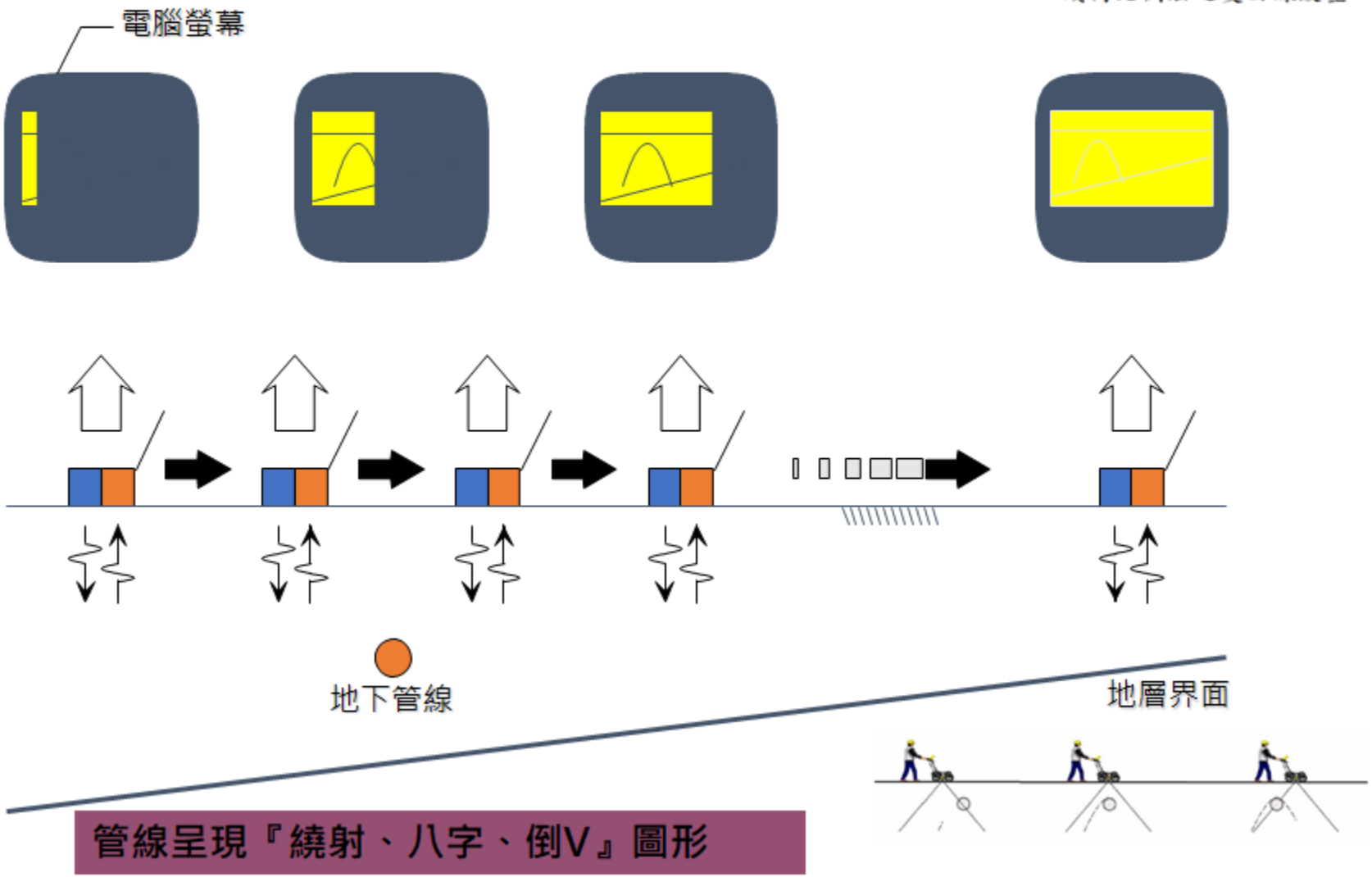


主要探測目的為瞭解目標物和位置

透地雷達探測技術_施測示意

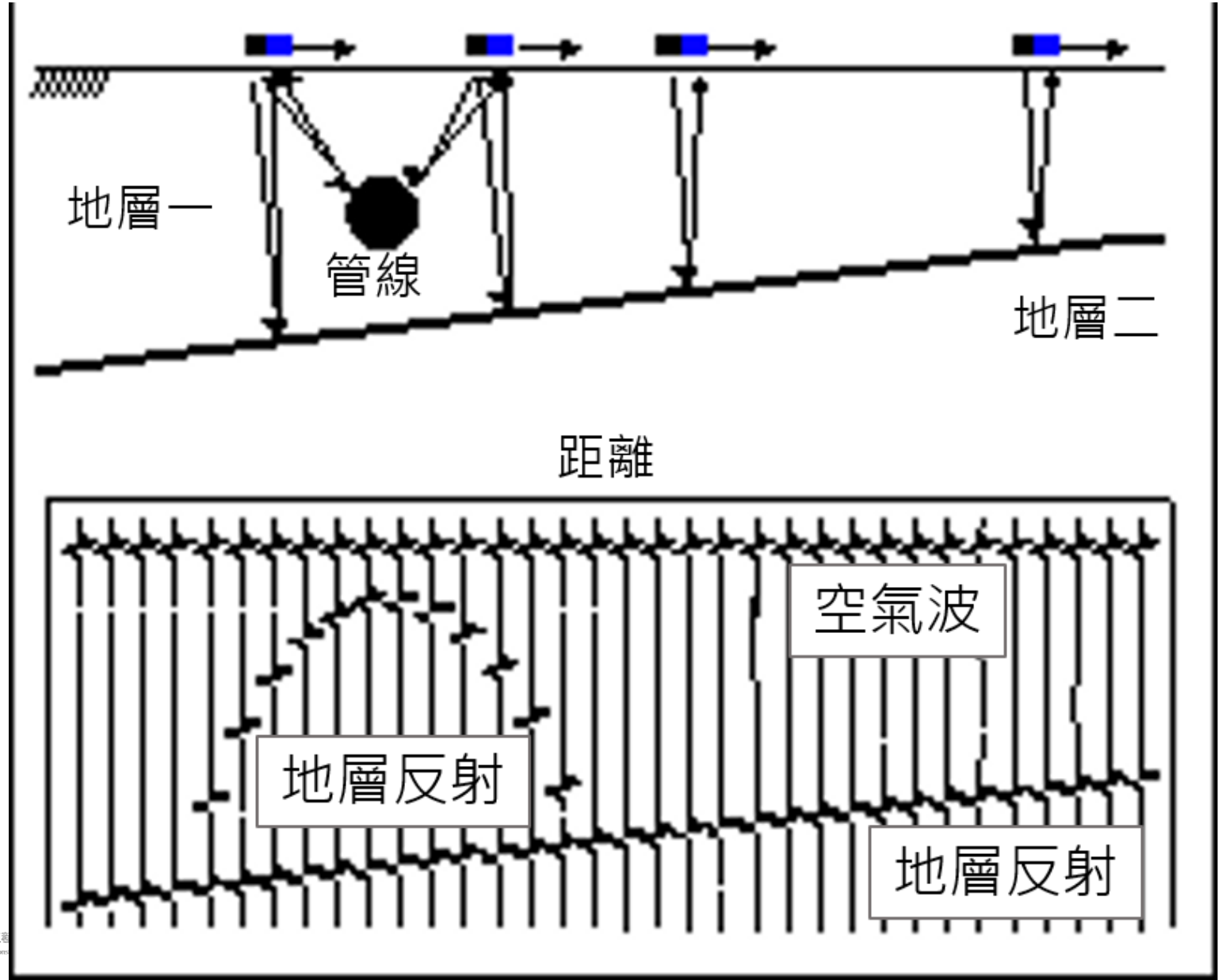


幾何比例法之雙曲線波型

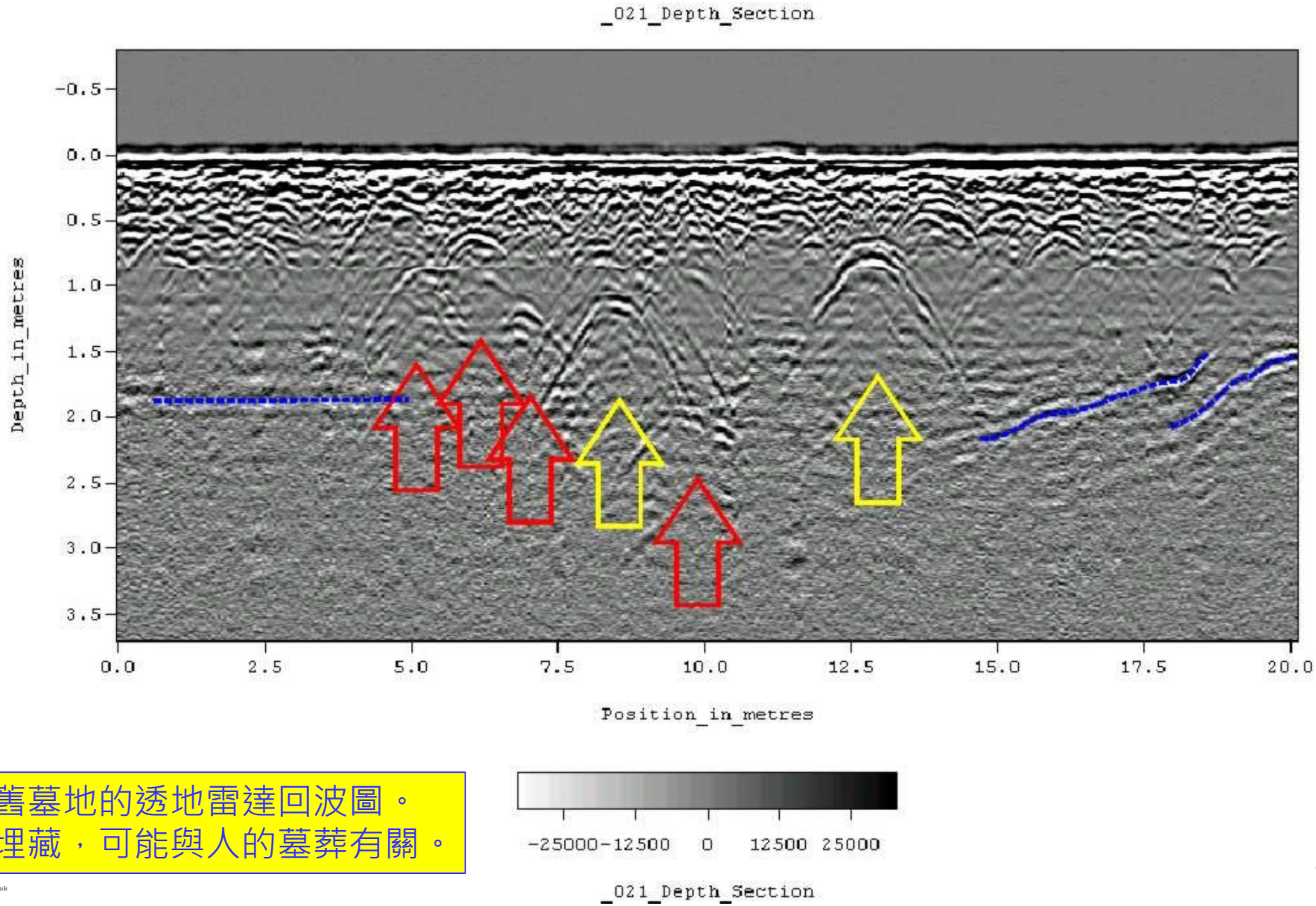


管線呈現『繞射、八字、倒V』圖形

透地雷達



維基百科上的案例



在美國阿拉巴馬州探測到地下舊墓地的透地雷達回波圖。雙曲線反射波代表地下有物體埋藏，可能與人的墓葬有關。

透地雷達探測原理

- 透地雷達主要係藉由電磁波天線罩向地下或結構體內發射出電磁波束
- 此電磁波經地層或結構體之傳遞，遇到目標體、異常體或層面處發生反射現象而傳回電磁波天線罩接收，由發射與接收得之電磁波信號時間差、以及介質之電磁波速度得以計算出目標體之深度，同時由接收得之電磁波信號之強弱亦得以判釋目標體之材質，因透地雷達能產生連續之高頻電磁波，因此能探測出地下或結構體內連續之高解析度剖面。
- 地表探測雷達所使用的原理與反射震測非常相似，反射波能量的大小與**地層介電常數（*Dielectric Constant*）**的差異程度有關，在一般自然界的地層情況下，地層電性介面的反射係數可以下式表示：

$$\gamma = \frac{\sqrt{(\varepsilon 1)} - \sqrt{(\varepsilon 2)}}{\sqrt{(\varepsilon 1)} + \sqrt{(\varepsilon 2)}}$$

- **γ代表反射係數，*ε1*、*ε2*則分別代表上、下層的介電常數。**

- 反射訊號的傳遞時間與地層界面的深度大小成正比，與地層中電磁波傳遞之波速成反比。

$$T = \frac{2d}{V}$$

- **T：反射訊號傳遞時間**
- **d：界面深度**
- **V：電磁波波速**

透地雷達探測原理

介 質	介電常數（ε_r）	電磁波速（m/μs）
空氣	1	300
混凝土	4-10	150
砂	4-30	55～150

*濕紅土礫石層波傳速度約：0.106 (m/nS)

*乾紅土礫石層波傳速度約：0.077 (m/nS)

Material	Velocity (m/ns)	Attenuation (dB/m)
Air	0.30	0
Ice	0.16-0.17	0.01
Dry Soil	0.15	
Dry Sand	0.15	0.01
Granite	0.13	0.01-1.0
Dry Salt	0.13	0.01-1.0
Dry Rock	0.12	
Limestone	0.12	0.4-1.0
Wet Rock	0.10	
Concrete	0.08-0.12	
Pavement	0.10	
Shales	0.09	1-100
Silts	0.07	1-100
Wet Soil	0.06	
Wet Sand	0.06	0.03-0.3
Clays	0.06	1-300
Fresh Water	0.033	0.1
Sea Water	0.033	1000

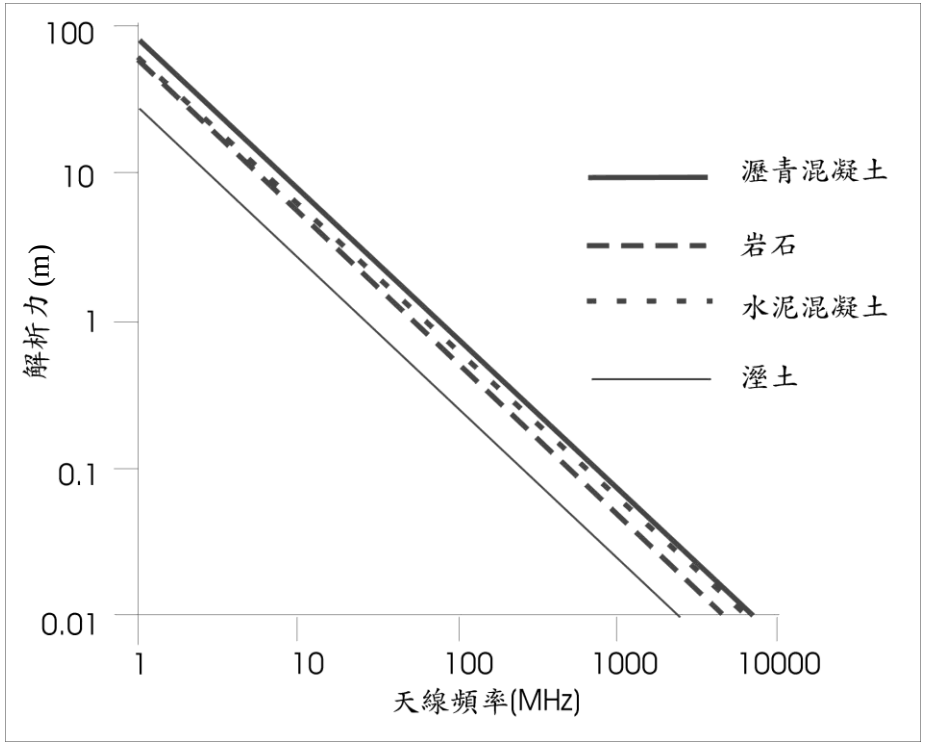
透地雷達有效深度

- 一般而言，透地雷達的天線頻率愈高(波長愈短)，其穿透力愈低(測深愈淺)，但解析度愈高。
- 透地雷達所能找尋之物體相當多，然其探測深度會因地質狀況等因素而有所變化。

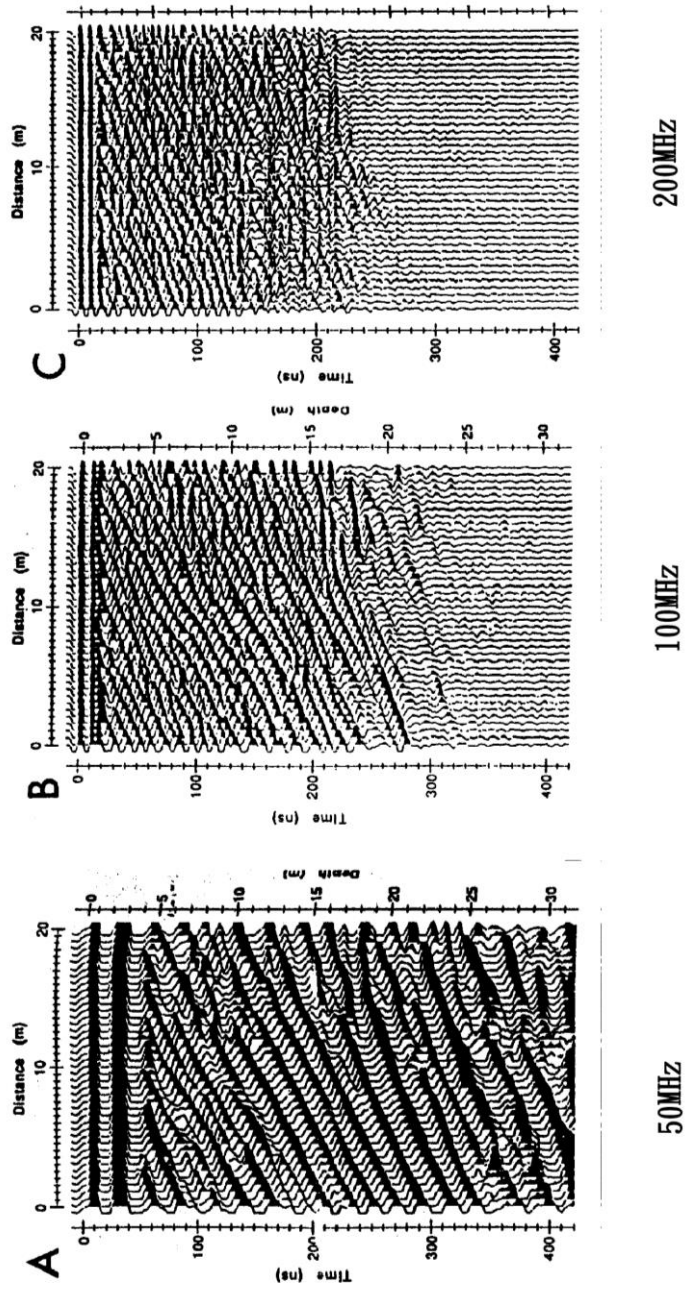
頻率 (MHz)	功　　能	概略測深 (m)
80	地下構造、地質探查	5-30
200	河堤淘空、地下水位面探查	3-12
400	河堤淘空、地下油槽、地下空洞探查	0.5-3
500	鋪面下空洞、埋設管線探查(淺層用)	0.5-2.5
900	混凝土厚度、背面空洞探查	0-1

透地雷達有效解析度

- 不同的天線頻率在岩石、濕土、瀝青混凝土及水泥混凝土等不同介質內的解析極限。
- 天線頻率愈高所能解析出的介質厚度愈小。
- 電磁波頻率愈高，其解析能力愈好，但探測深度愈淺
- 電磁波頻率愈低，其解析能力愈差，但探測深度則愈深。
- GPR探測深度淺可至幾公分以內，深則曾有過幾十公尺的紀錄。



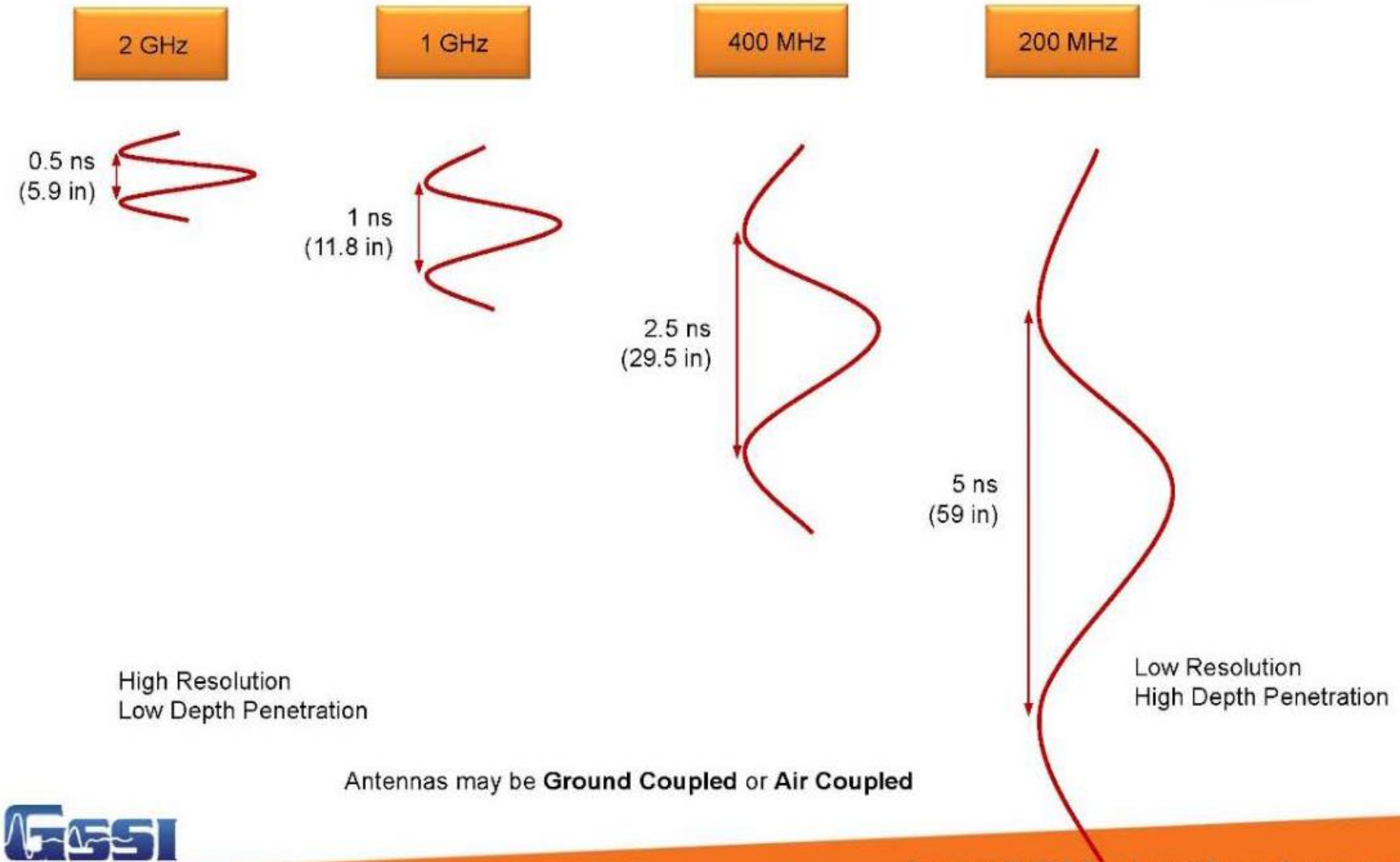
(修改自EKKO UPDATE，1996)



(Smithe &Jol ，1922)

Typical GPR Antenna Frequencies

(in air)



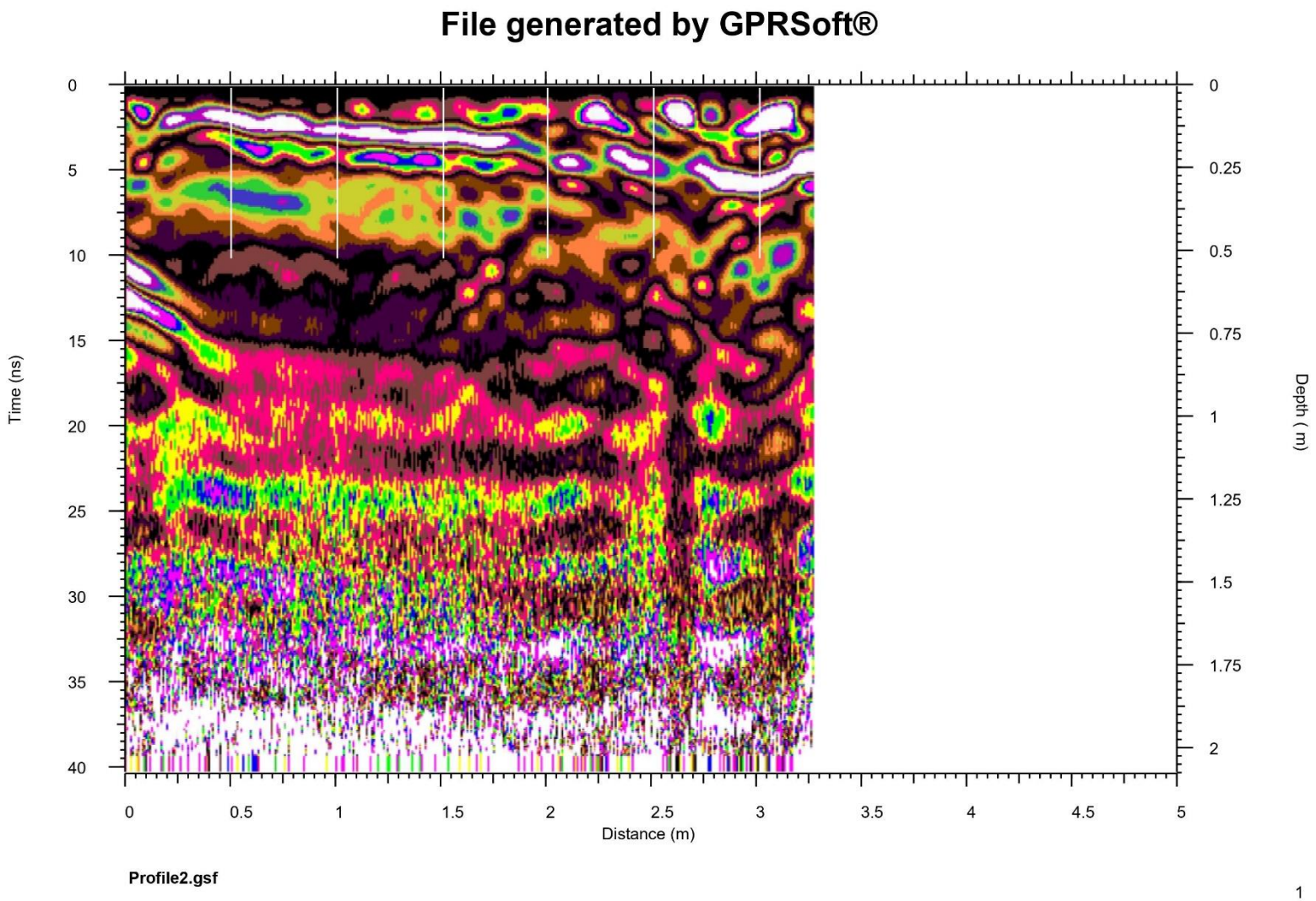
High Resolution
Low Depth Penetration

Low Resolution
High Depth Penetration

Antennas may be **Ground Coupled** or **Air Coupled**

透地雷達有效深度


A2
A1


File generated by GPRSoft®
Time (ns)
Depth (m)
Distance (m)
0
5
10
15
20
25
30
35
40
0.25
0.5
0.75
1
1.25
1.5
1.75
2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Profile2.gsf

透地雷達使用限制

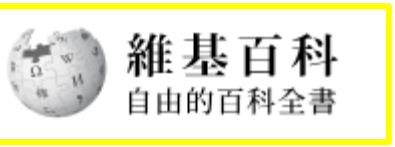
- 最常見的使透地雷達功能受到限制的環境是高電導率的物質，例如黏土質土壤和受到鹽分汙染區域。透地雷達在地下物質差異交界處（例如岩石和土壤之間）則會因為訊號被散射而大幅降低其探測能力。
- 其他目前使用的透地雷達系統還有如下限制：

➢ 雷達圖的判讀對於新手而言是不直觀的。

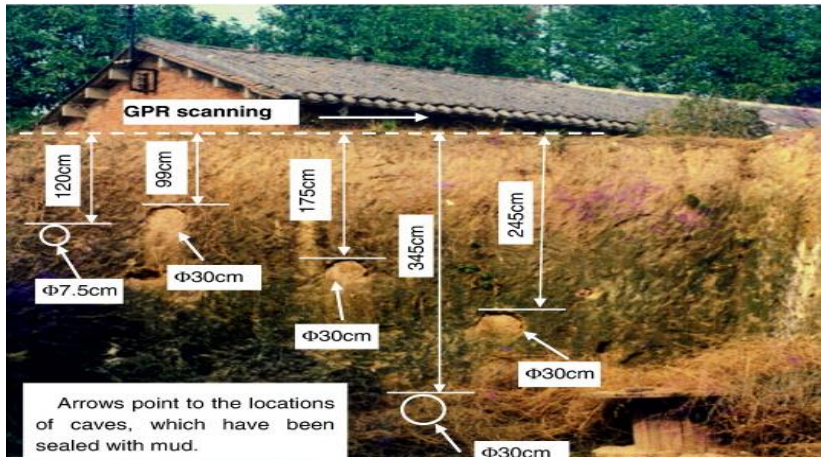
➢ 為了有效地設計、執行透地雷達調查和判讀其資料，必須要有一定的專業知識。

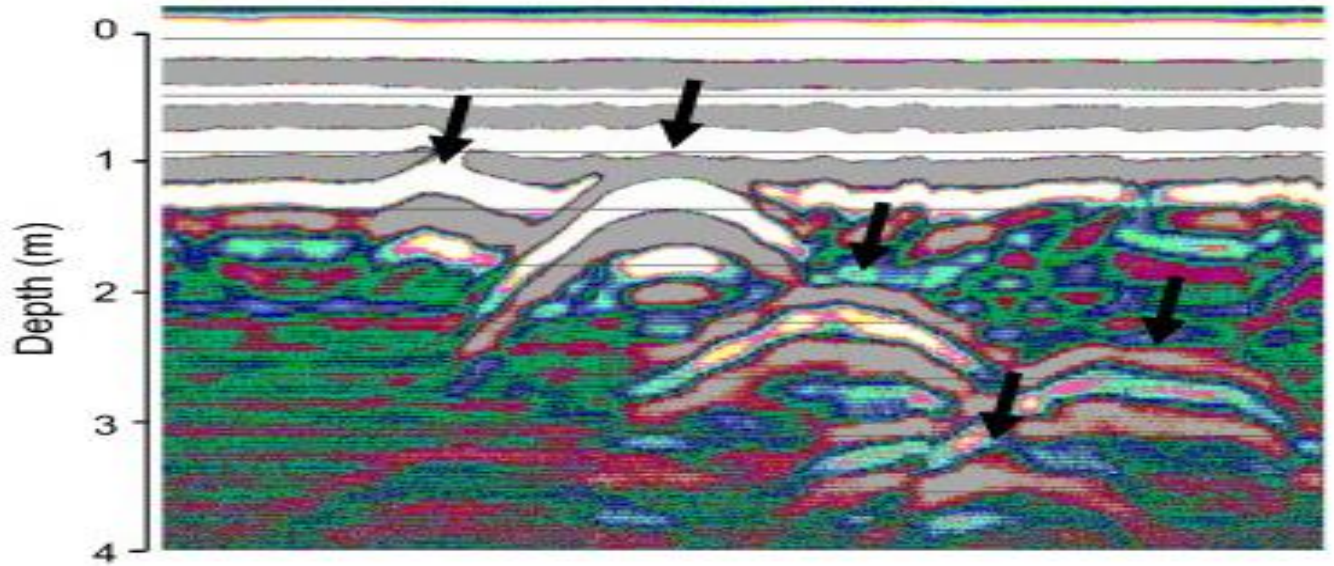
➢ 大範圍的透地雷達調查相當耗電等能源。

➢ 透地雷達的設備至今仍在不斷改進前述的限制中，並且未來的改進是可期待的。



- 在廣東省模擬洞穴之試驗場（五處不同深度洞穴）
- 採用天線頻率500MHZ（探測至2.45公尺）及300 MHZ（探測至3.45公尺）





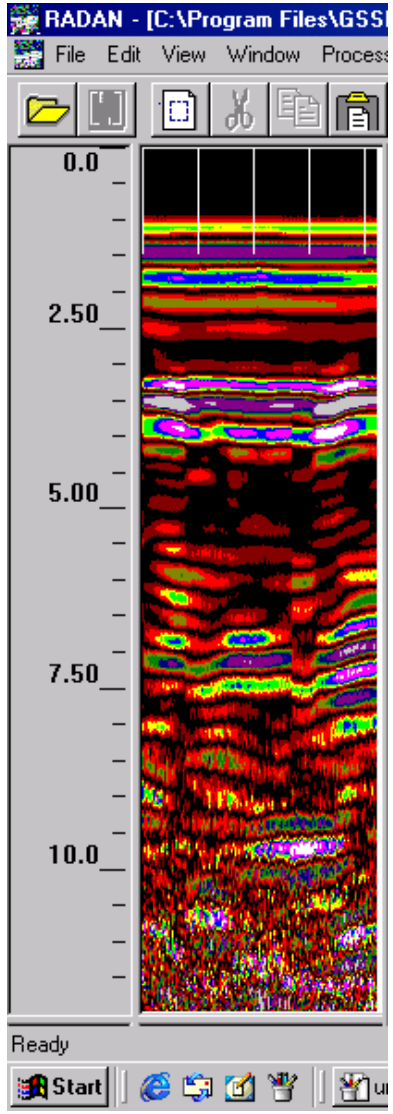
300 MHZ

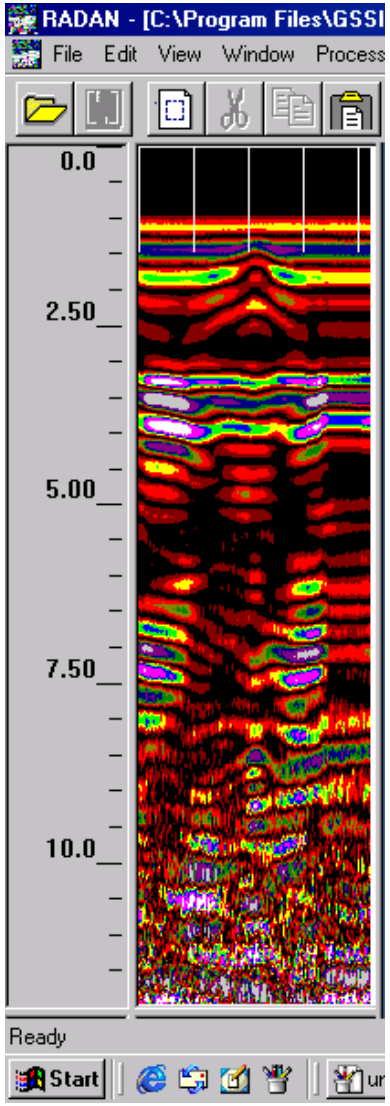
平均雷達波速度

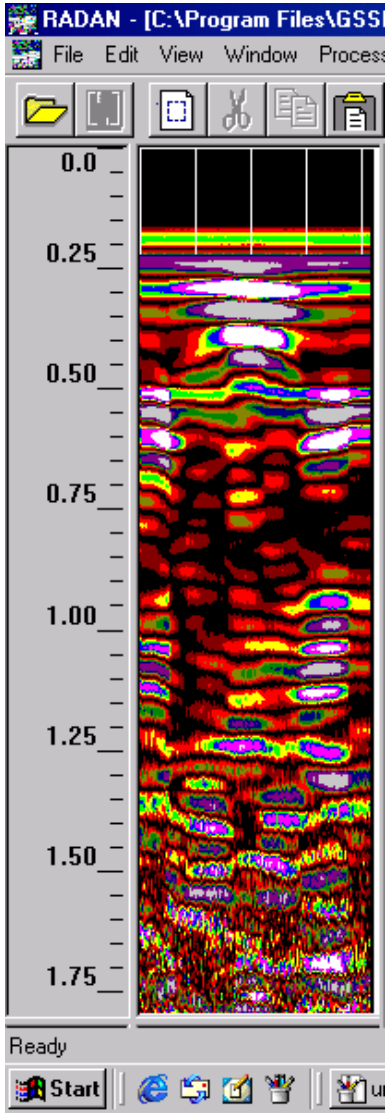
V=0.076 m/ns

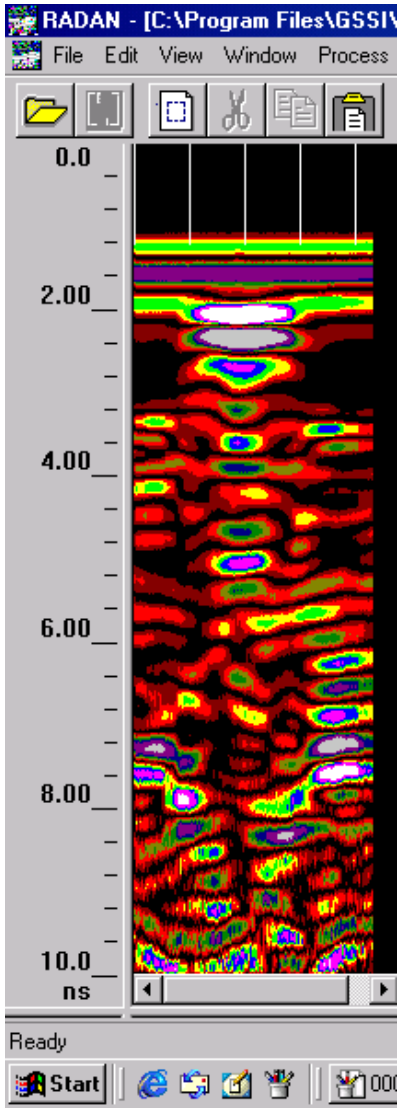
[Wang et al., 2006] and [Huang and Zhou, 2003])

找找看異物在哪


RADAN - [C:\Program Files\GSSI
File Edit View Window Process
0.0
2.50
5.00
7.50
10.0
Ready
Start

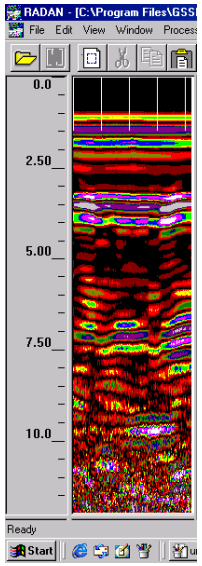

RADAN - [C:\Program Files\GSSI
File Edit View Window Process
0.0
2.50
5.00
7.50
10.0
Ready
Start

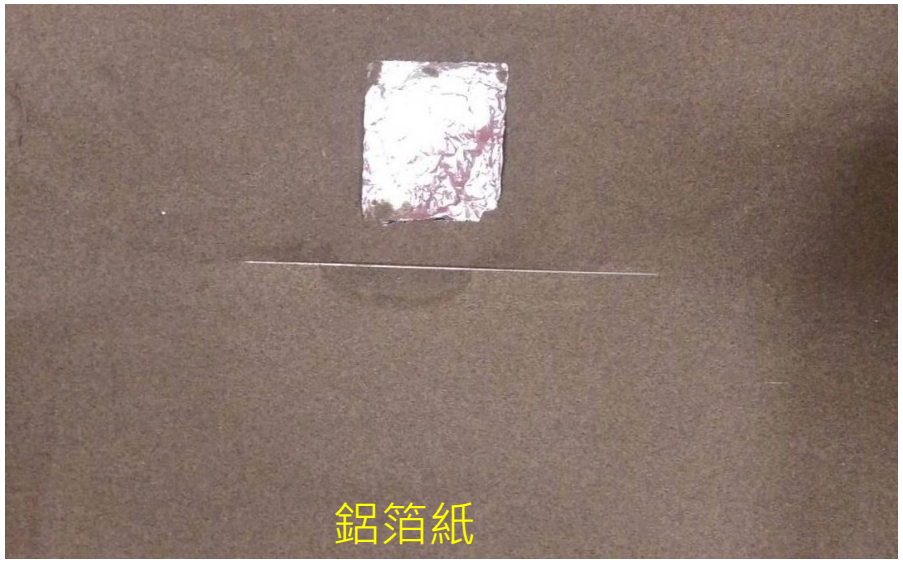

RADAN - [C:\Program Files\GSSI
File Edit View Window Process
0.0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
Ready
Start

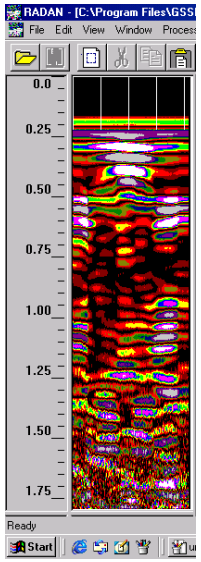

RADAN - [C:\Program Files\GSSI
File Edit View Window Process
0.0
2.00
4.00
6.00
8.00
10.0
ns
Ready
Start

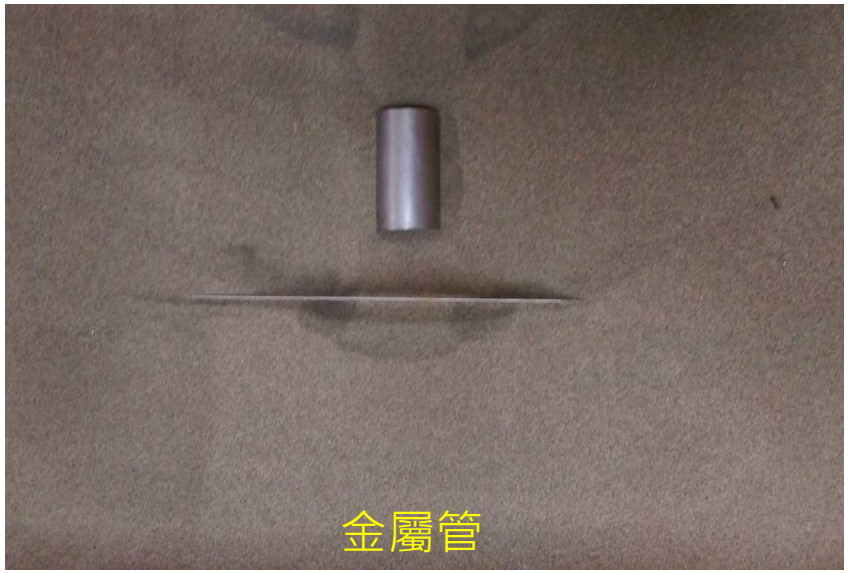
對了嗎?

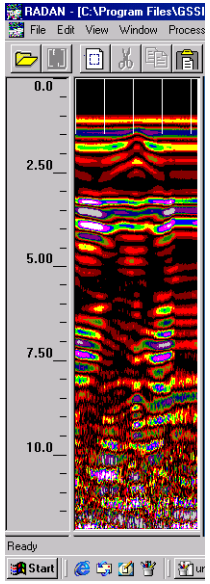

純砂

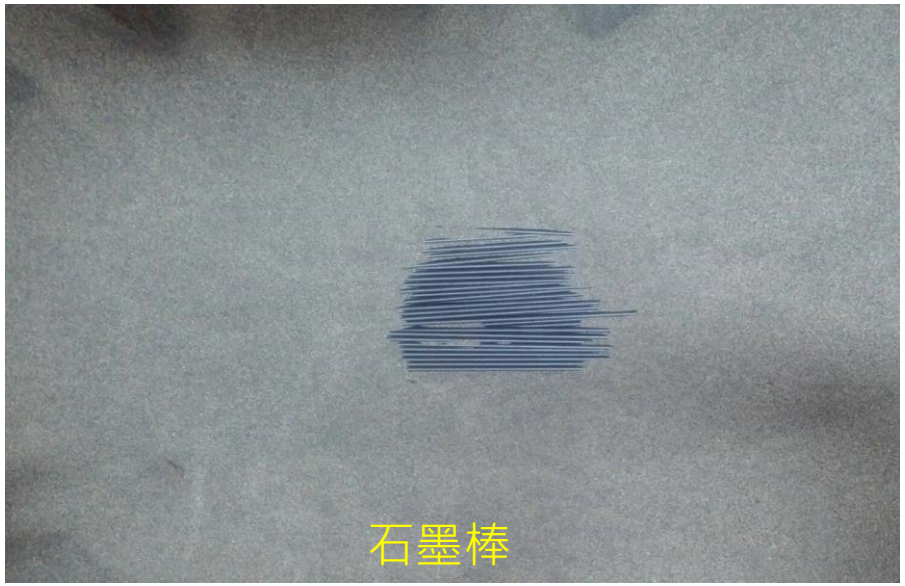

RADAN - [C:\Program Files\GSS
File Edit View Window Process
0.0
2.50
5.00
7.50
10.0
Ready
Start

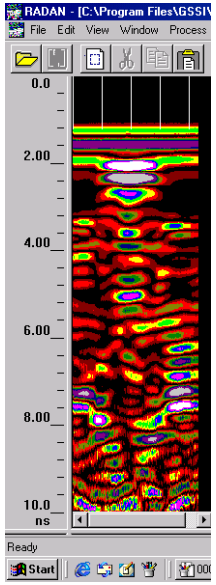

鋁箔紙

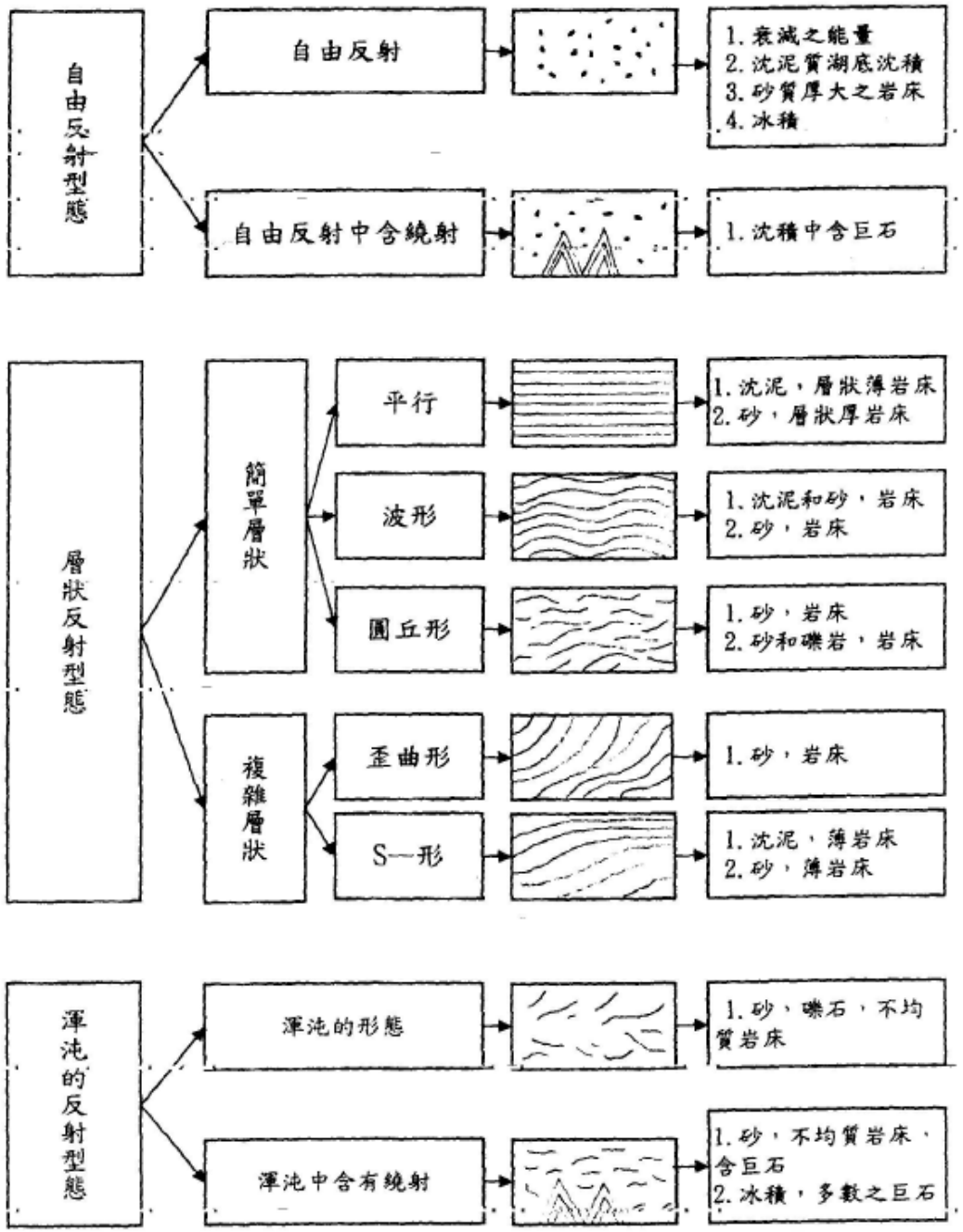

RADAN - [C:\Program Files\GSS
File Edit View Window Process
0.0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
Ready
Start


金屬管

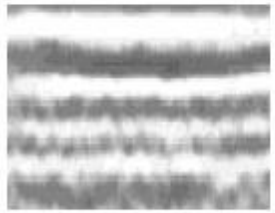
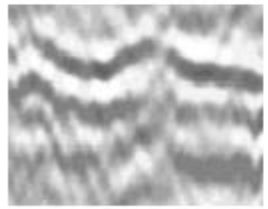
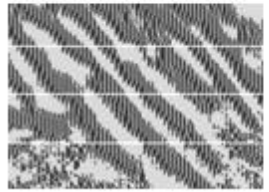
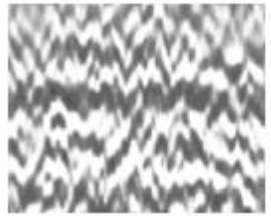
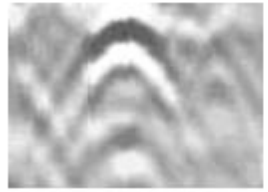

RADAN - [C:\Program Files\GSS
File Edit View Window Process
0.0
2.50
5.00
7.50
10.0
Ready
Start

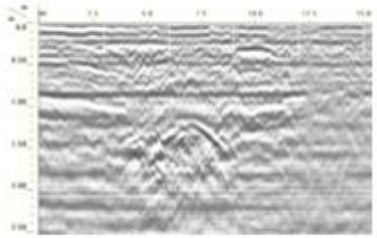
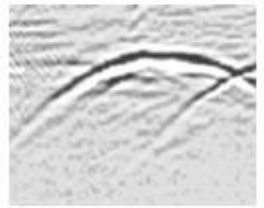
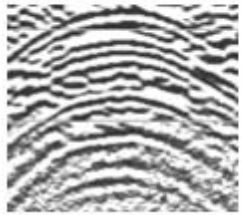
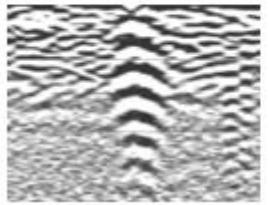
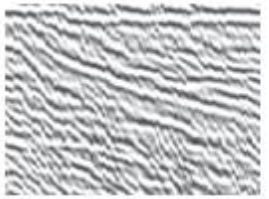

石墨棒

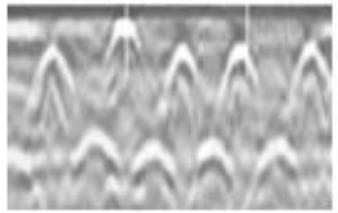
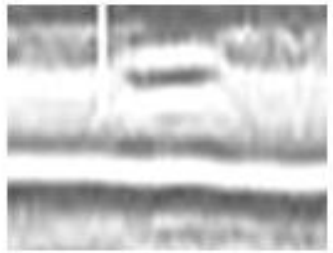
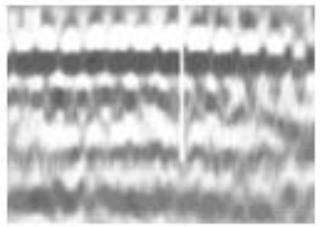
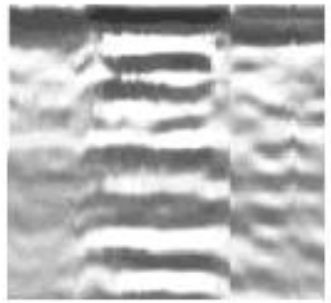

RADAN - [C:\Program Files\GSS
File Edit View Window Process
0.0
2.00
4.00
6.00
8.00
10.0
ns
Ready
Start

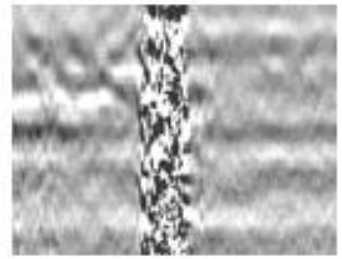
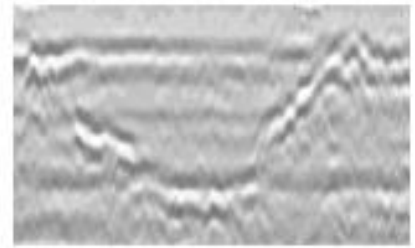
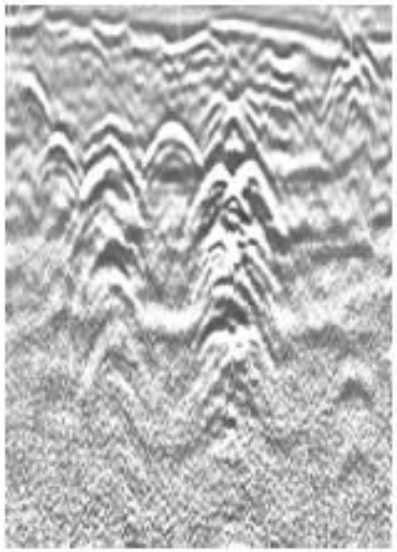


透地雷達反射波形之外貌參考圖（Milan, 1991）

常見反射型態	波形特徵	波形參考
層狀地層	連續層狀	
複雜層狀地層	不平整特徵呈波形層狀	
傾斜地層或構造	傾斜層狀	
礫石層或級配層	連續小且密集繞射	
地下管線	倒V或繞射特徵	

常見反射型態	波形特徵	波形參考
異常反射特徵	異常強烈反射、能量衰減、波幅變化	
地表上結構干擾：如屋頂、高壓電塔、管架	雙曲線繞射(通常電磁波速 > 0.2m/ns)	
導電差的塑膠材料	電磁波能量上下震盪造成類似重覆反射	
導電佳的金屬管線	金屬物質遮蔽造成重覆倒V強反射現象	
金屬結構側向反應	類似地層傾斜波幅形狀	

RC 鋼筋結構	等間距 繞射波幅	
混凝土鋪面 裂隙	強反射波幅 形狀	
鋼筋網鋪面	連續鋸尺狀 繞射波幅	
金屬水溝或 金屬人孔	平面重覆 反射波幅	

電磁波干擾	不明強弱雜 訊波幅形狀	
地層疏鬆 與掏空	不連續強反 射發生邊界 有傾斜反射 特徵	
常見市區 道路管線	強反射繞射 分布複雜	

The true sign
of intelligence
is not knowledge
but
imagination.

~ Albert Einstein