



剪力波速液化潛勢評估法介紹



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- ▶ 剪力波速性質與量測方法
- ▶ 剪力波速液化評估法回顧
- ▶ 礫石砂土層液化評估
- ▶ 本土土壤適用性與案例
- ▶ 結論





土壤剪力波速(V_s)



- ▶ 土壤小應變下之力學特性： $G_{\max} = \rho V_s^2$
- ▶ 反應土壤組成、微觀構造、應力歷史及應力狀態

$$G_{\max} = 1230 \frac{(2.973 - e)^2}{(1 + e)} (OCR)^K (\sigma'_m)^{0.5} \quad (\text{Hardin \& Drenvich 1972})$$

$$V_s = A(\sigma'_m)^n \quad n \leq 0.25 ; \quad V_s = C(\sigma'_a)^{na} (\sigma'_b)^{nb} \quad na \leq nb \leq n/2$$

- ▶ 地盤反應分析及地工數值模擬所需彈性參數
- ▶ 簡易液化評估之方法之一

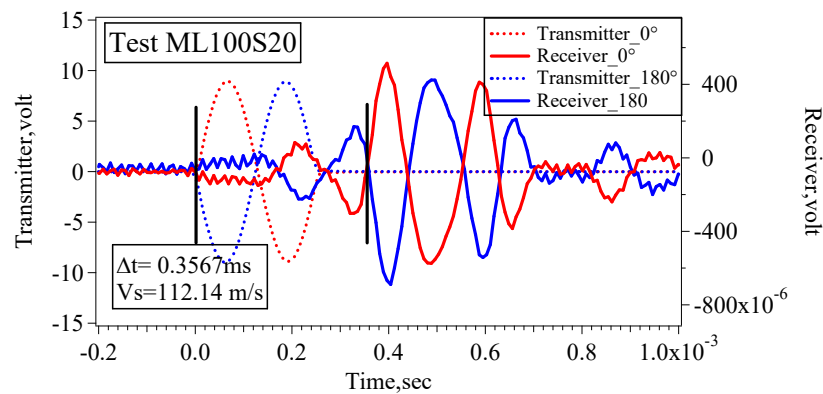
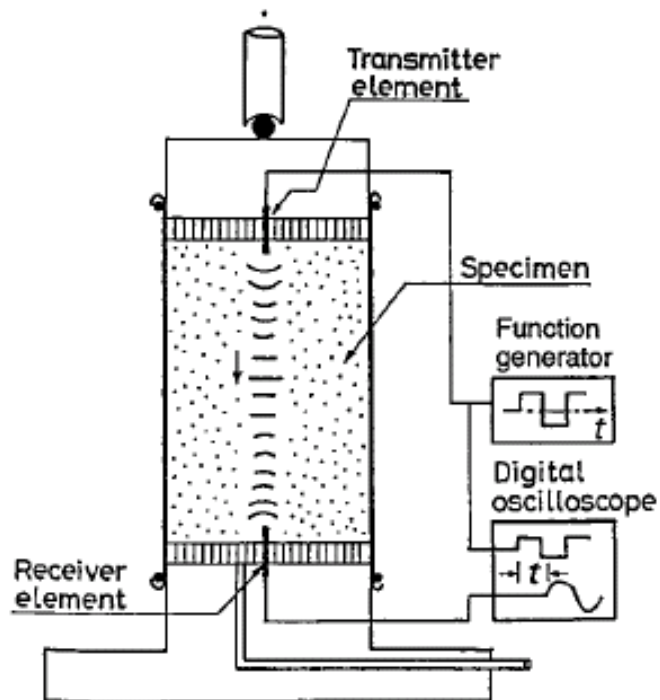




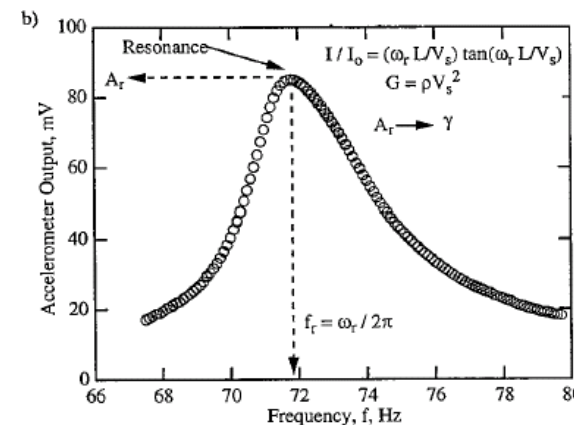
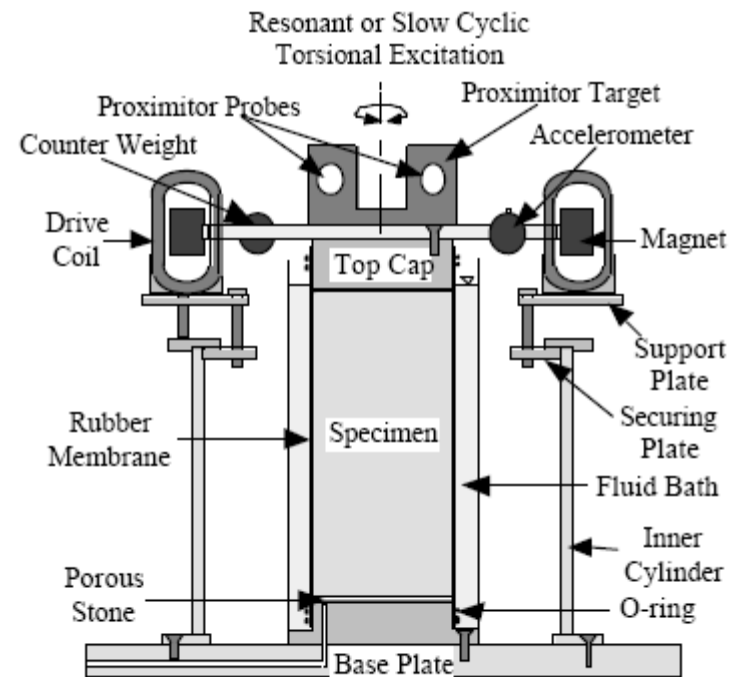
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室內剪力波速量測方法



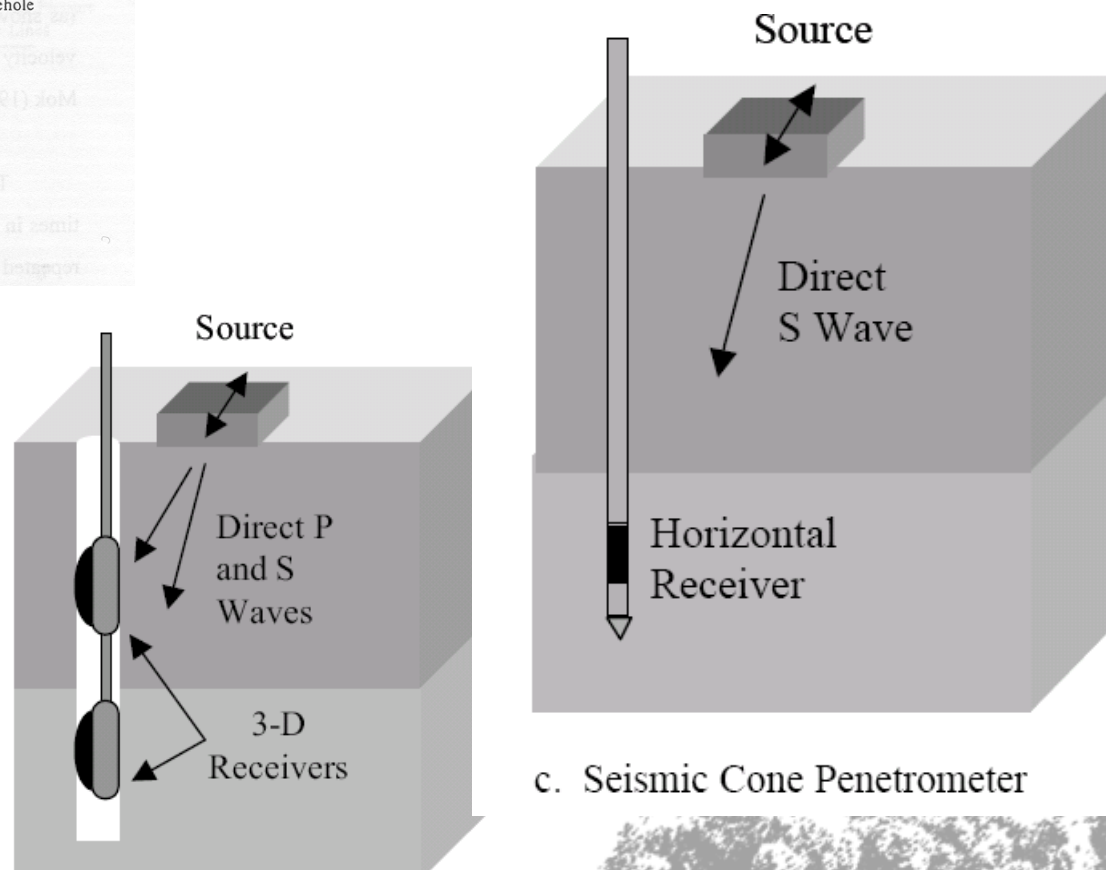
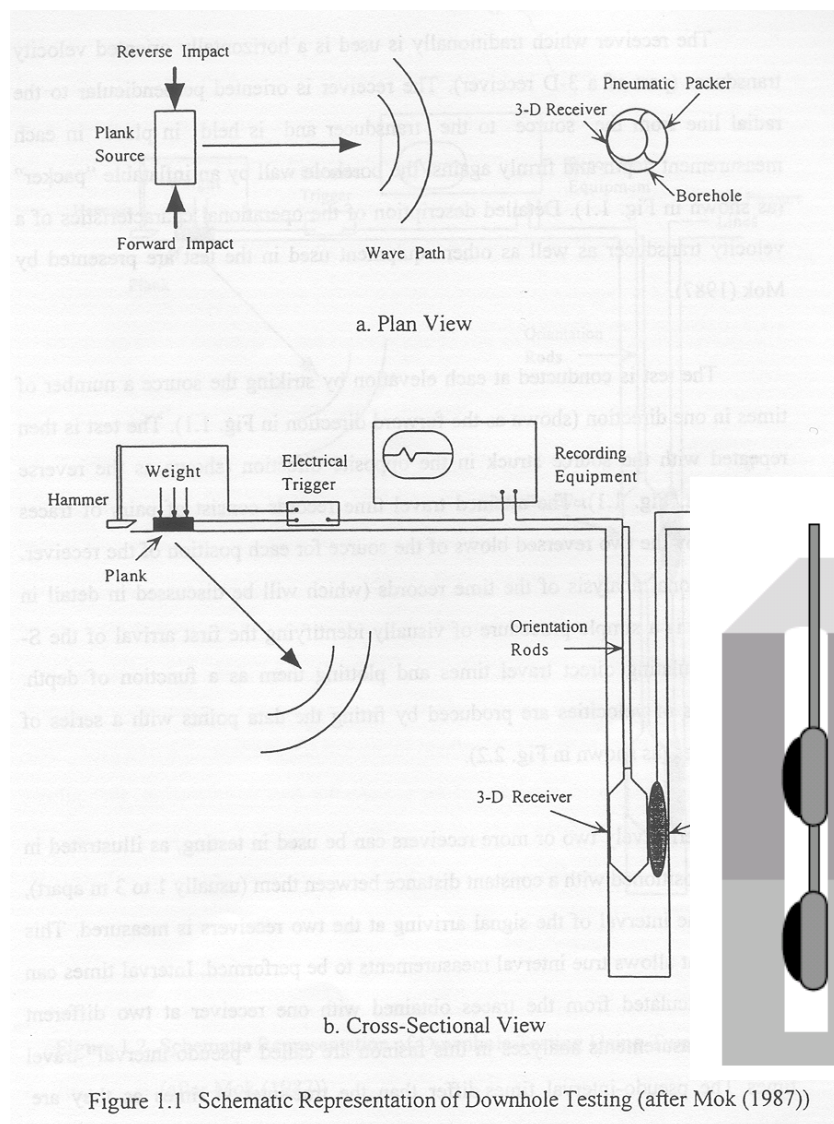
Bender Element



Resonant Column Test



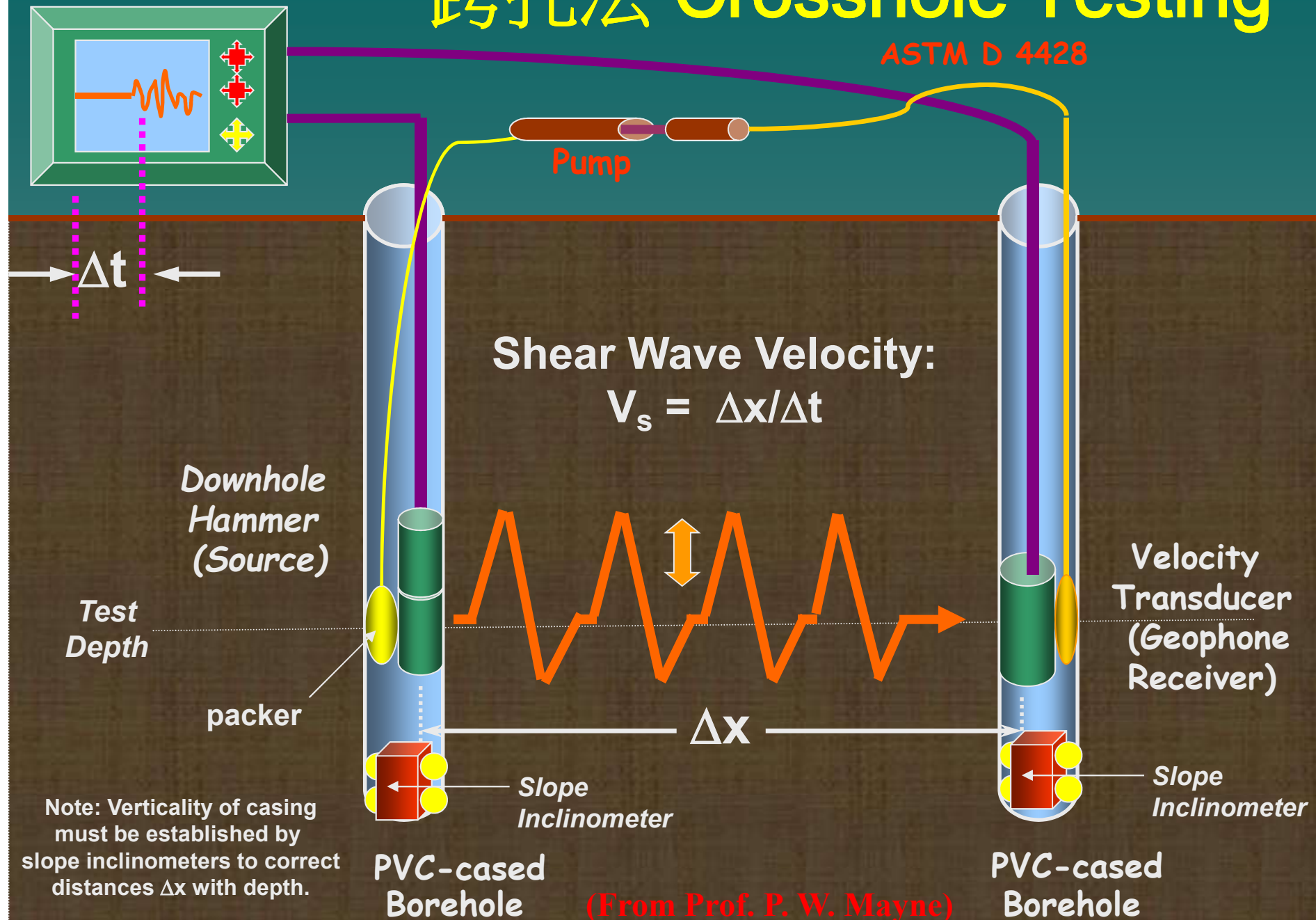
現地剪力波速量測法(1/5)



下孔法(Downhole Testing)

跨孔法 Crosshole Testing

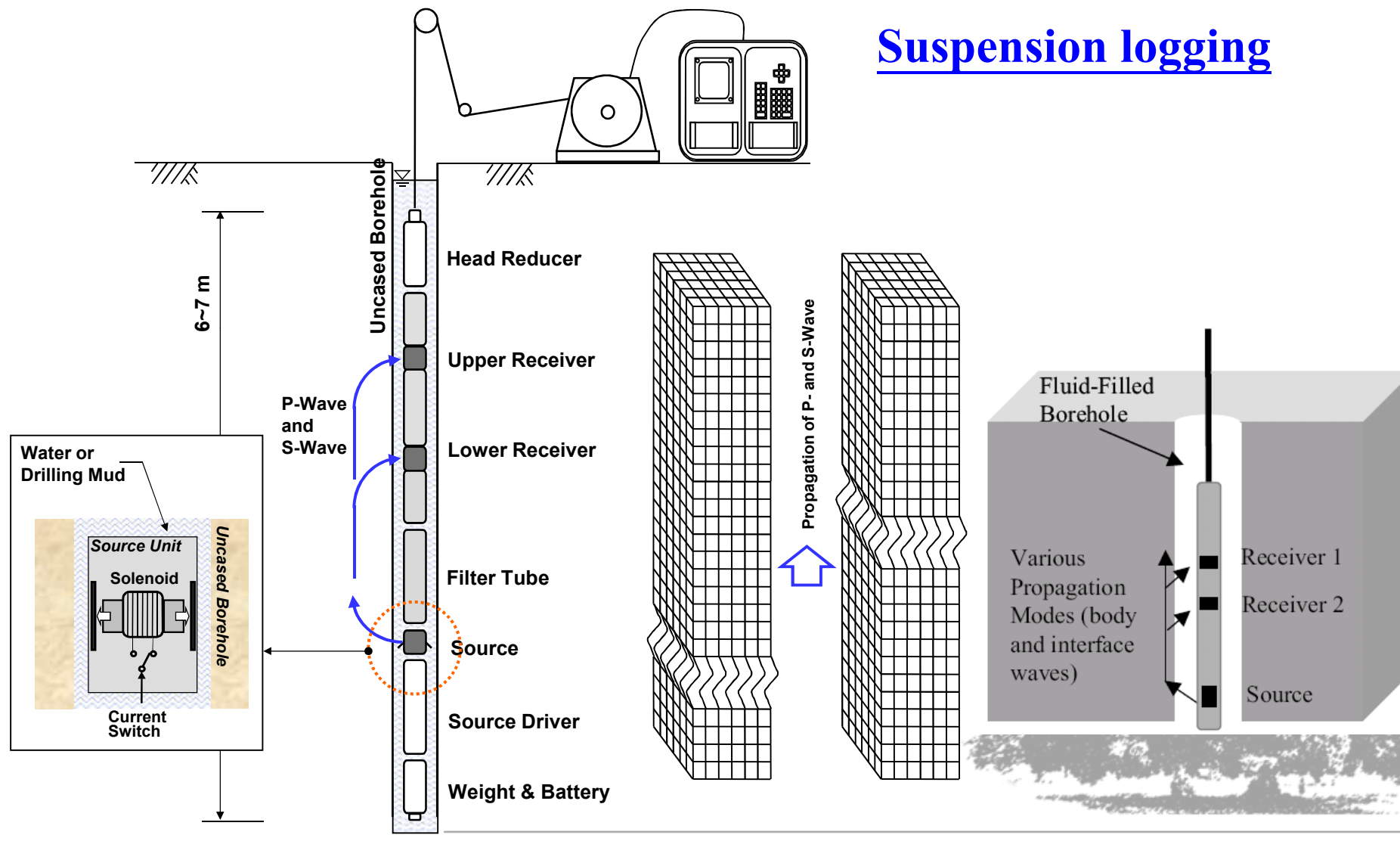
ASTM D 4428



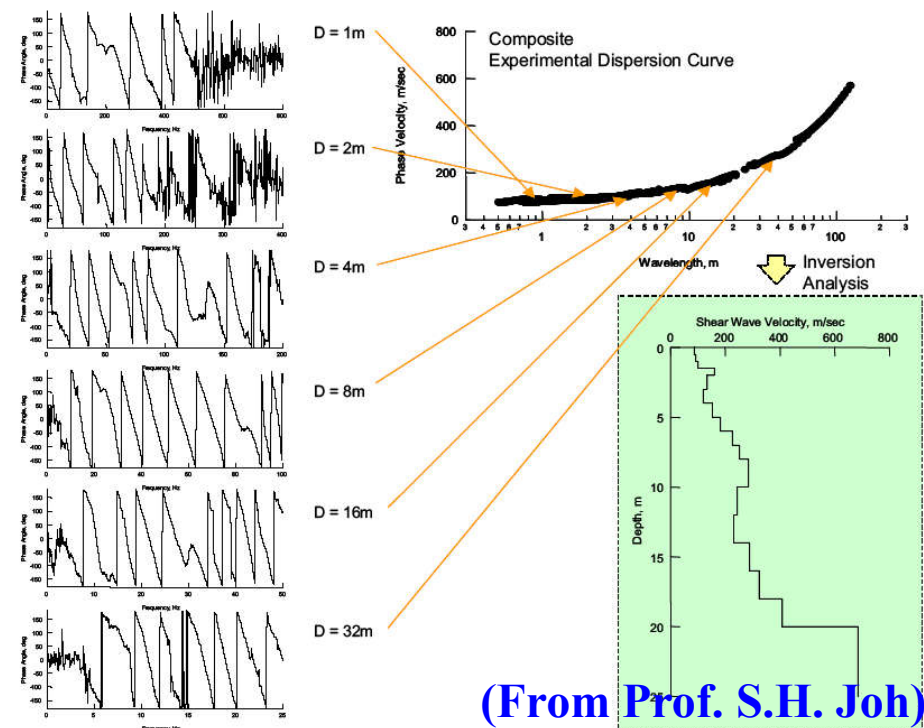
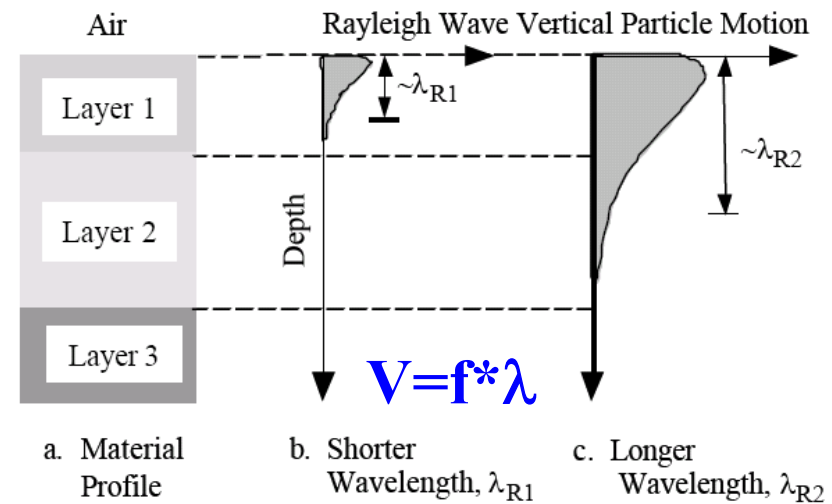
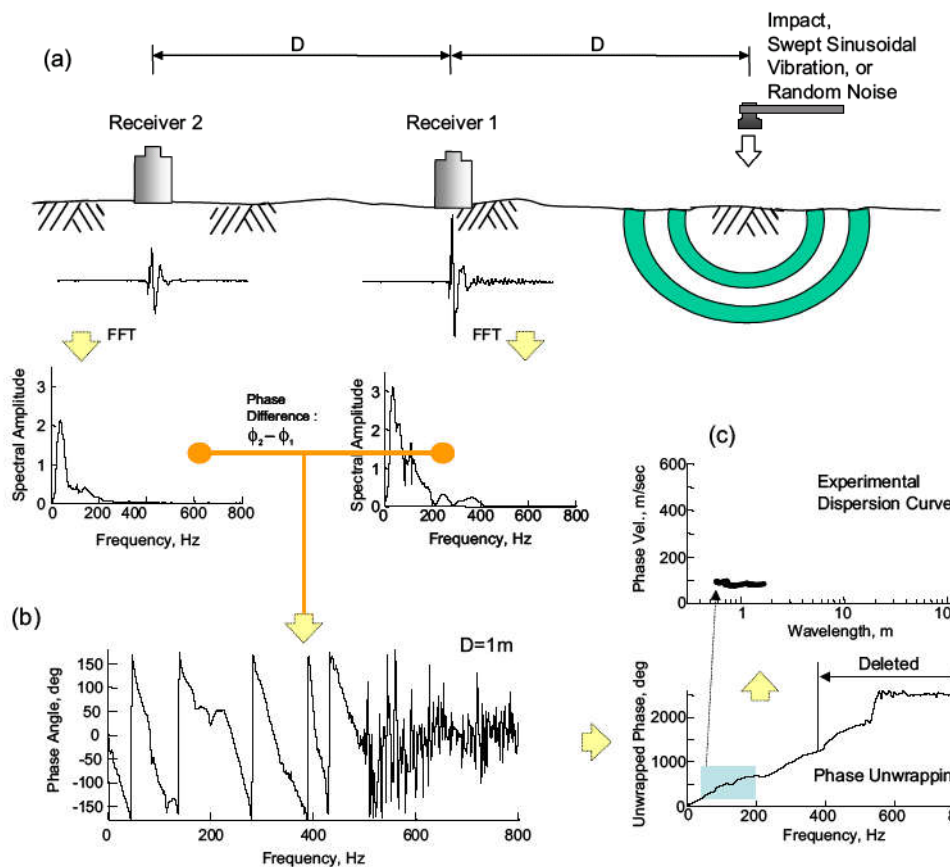


現地剪力波速量測法(3/5)

Suspension logging



表面波譜法(SASW)

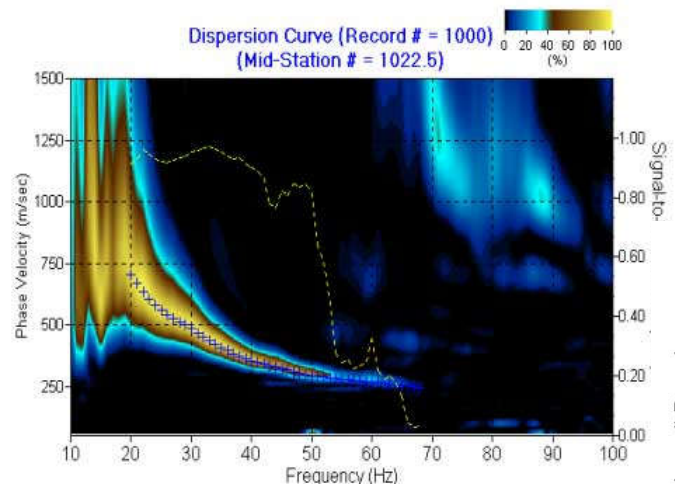
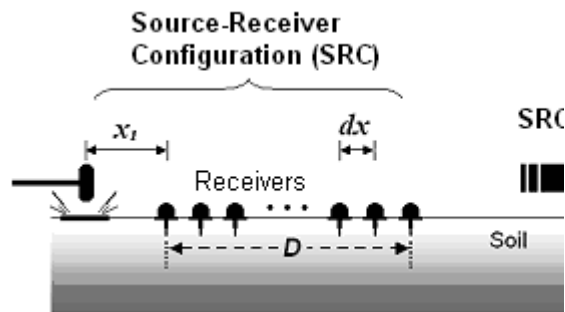


(From Prof. S.H. Joh)



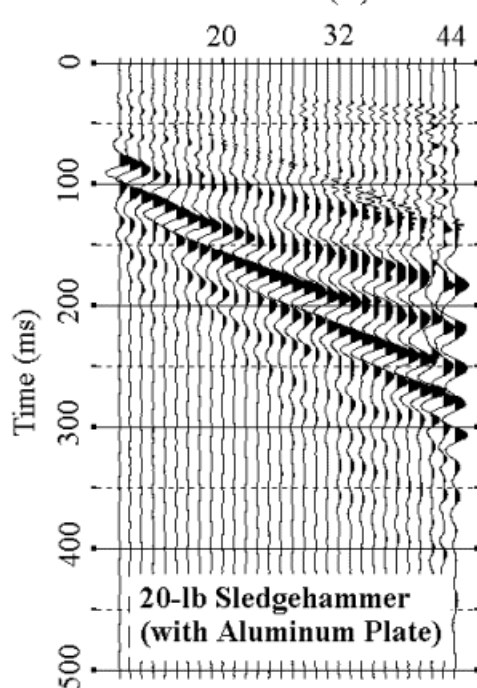
現地剪力波速量測法(5/5)

2. Dispersion Curve Extraction--Frequency-Phase Velocity

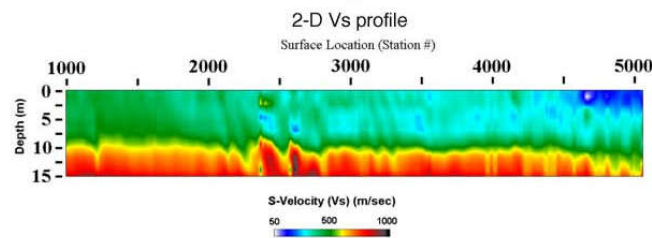
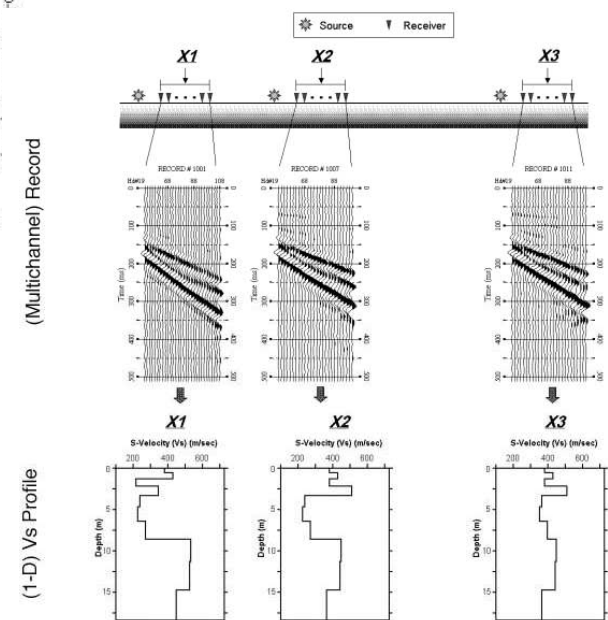
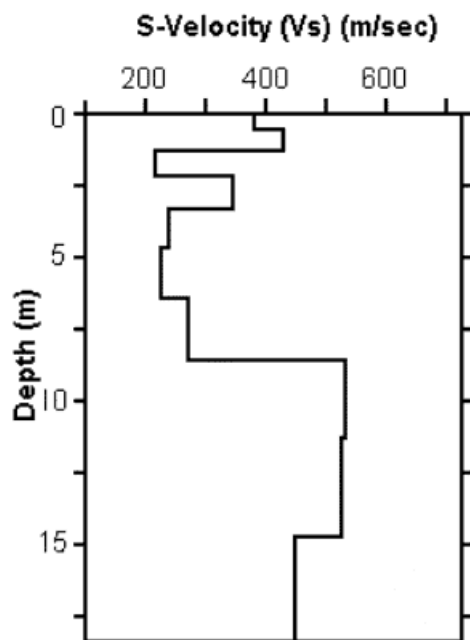


多通道表面波譜法 (MASW)

1. Acquisition--Time-Space



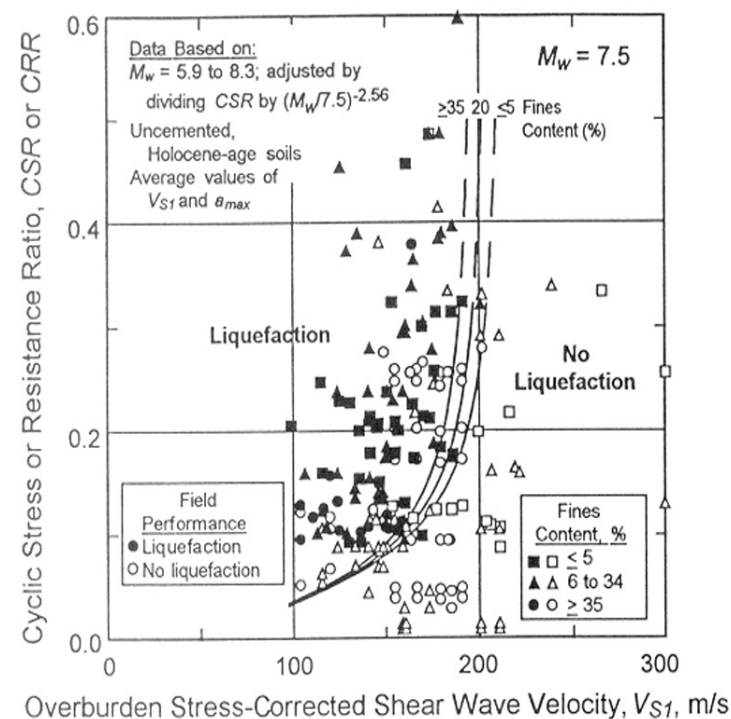
3. Inversion--Depth-Vs



(From KGS website)

簡易液化評估法特點

- ▶ 基於過往震後案例分析結果
- ▶ 建立土壤液化阻抗(CSR_{LF})與現地試驗參數之關係式
 - ▷ Corrected SPT- $N_{1,60}$
 - ▷ Normalized CPT- q_{c1}
 - ▷ Normalized shear wave velocity V_{s1}
- ▶ 因程序簡易而廣為工程界使用
- ▶ 準確性？



$$V_{s1} = V_s \left(\frac{Pa}{\sigma_v'} \right)^{0.25}$$

土壤液化阻抗影響因子與現地試驗參數關聯



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因子	液化阻抗	SPT-N	Vs	土壤取樣影響
相對密度, D_r (void ratio, e)	+	+	+	Significant
土壤微觀結構 (fabric effect)	+	+	+ (minor)	Significant
前震效應 (pre-shaking effect)	+	+ (?)	--	Significant
應力歷史 (K_0 & OCR)	+	+	--	?
時間效應 (aging effect)	+	+	--	?
有效應力 (Effe. Stress)	--	+	+	?

(Ladd et al. 1989)



不同現地參數液化阻抗評估比較

特點	SPT	CPT	BPT	Vs
案例數量	最多	次之	有限	較少
試驗時之應變範圍 與排水	大應變、 部分排水	大應變、 排水/部分排 水	大應變、 部分排水	小應變、 不排水
試驗重複與一致性	差->好	優	差	好->優
土壤變異判釋	好	優	良	良
適用土層	非礫石土層	非礫石土層	礫石土層	各種土層
土壤取樣	可	無	無	無
參數本質	Index	Index	Index	Eng. prop.

Vs-based 方法優缺點

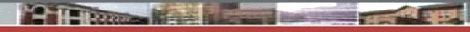
(Youd et al. 2001)

優點:

量測土壤工程性質、可用於礫石土層、非侵入/非破壞檢測

缺點:

小應變性質、無取樣、無法反應膠結程度、受應力影響顯著



- ▶ Deterministic (定值分析)
 - ❑ Robertson et al. (1992)
 - ❑ Tokimatsu & Uchida (1990)
 - ❑ Kayen et al. (1992), (2013)
 - ❑ Lodge (1994)
 - ❑ Andrus and Stokoe (2000)
 - ❑ Zhou and Chen (2007)
 - ❑ Chang (2016) (for gravel)
- ▶ Probabilistic (機率分析)
 - ❑ Juang et al. (2001), (2002)
 - ❑ Kayen et al. (2013)



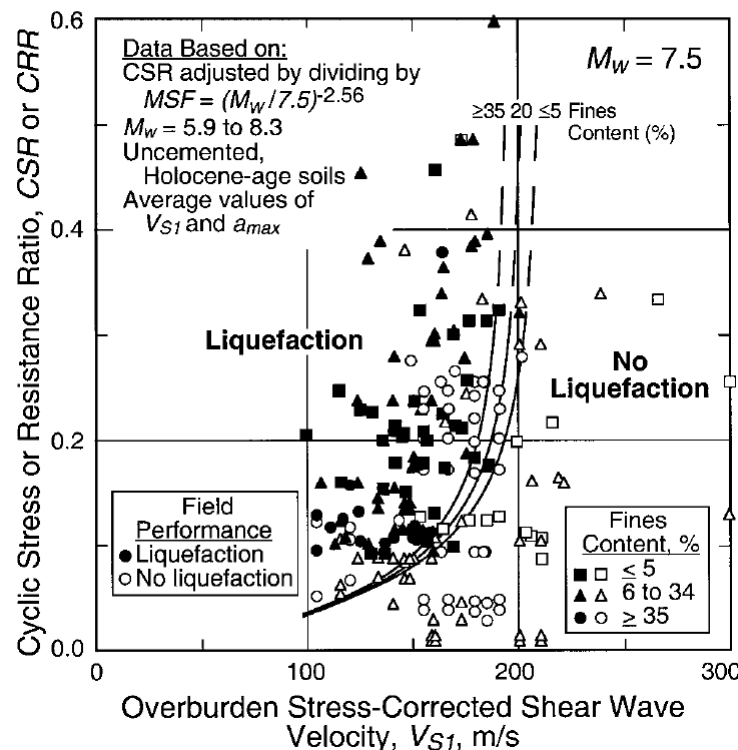


Andrus & Stokoe (2000)

► Loading:

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65 \left(\frac{a_{\max}}{g} \right) \left(\frac{\sigma_v}{\sigma'_v} \right) r_d$$

$$r_d = \frac{(1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.000 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2)}$$



► Resistance:

$$V_{S1} = V_s C_V = V_s \left(\frac{P_a}{\sigma'_v} \right)^{0.25}$$

$$CRR = \left\{ a \left(\frac{V_{S1}}{100} \right)^2 + b \left(\frac{1}{V_{S1}^* - V_{S1}} - \frac{1}{V_{S1}^*} \right) \right\} MSF$$

$$a=0.022, b=2.8$$

$$MSF = \left(\frac{M_w}{7.5} \right)^n \quad n=-2.56$$

$$V_{S1}^* = 215 \text{ m/s, for sands with } FC \leq 5\% \quad (11a)$$

$$V_{S1}^* = 215 - 0.5(FC - 5) \text{ m/s, for sands with } 5\% < FC < 35\% \quad (11b)$$

$$V_{S1}^* = 200 \text{ m/s, for sands and silts with } FC \geq 35\% \quad (11c)$$

$$FS_{LF} = \frac{CRR}{CSR_{EQ}}$$



Note: treat gravelly soils as clean sand



Kayen et al. (2013)

- 422 case histories around the world
- 14 cases from Chi-Chi EQ with high CSR & FC
- Provide both deterministic and probabilistic approaches

► Loading:

$$CSR = \frac{\tau_{avg}}{\sigma'_v} = 0.65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_v}{\sigma'_v} \cdot r_d$$

$$r_d(d, M_w, a_{max}, V_{s,12m}) = \frac{\left(1 + \frac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.0525 \cdot V_{s,12m}^*}{16.258 + 0.201 \cdot e^{0.341 \cdot (-d + 0.0785 \cdot V_{s,12m}^* + 7.586)}}\right)}{\left(1 + \frac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.0525 \cdot V_{s,12m}^*}{16.258 + 0.201 \cdot e^{0.341 \cdot (0.0785 \cdot V_{s,12m}^* + 7.586)}}\right)} \pm \sigma_{end}$$

$$r_d(d, M_w, a_{max}, V_{s,12m})$$

d: 深度; M_w :地震矩規模

$V_{s,12m}$: 40 ft 深度內平均波速

► Resistance:

$$CRR = \exp \left\{ \left[\frac{(0.0073 \cdot V_{s1})^{2.8011} - 2.6168 \cdot \ln(M_w) - 0.0099 \cdot \ln(\sigma'_{vo})}{+0.0028 \cdot FC + 0.4809 \cdot \Phi^{-1}(P_L)} \right] / 1.946 \right\}$$

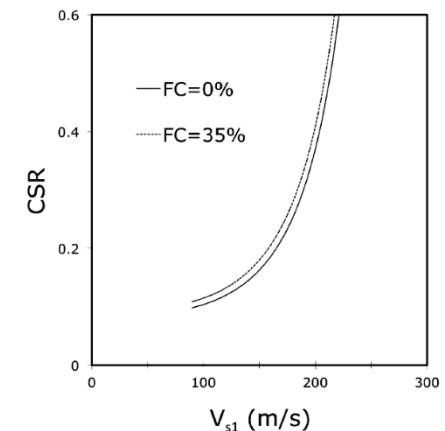
FC: 細粒料含量百分比

P_L : 液化機率 (=0.15)

Φ^{-1} : 累積常態分佈反函數

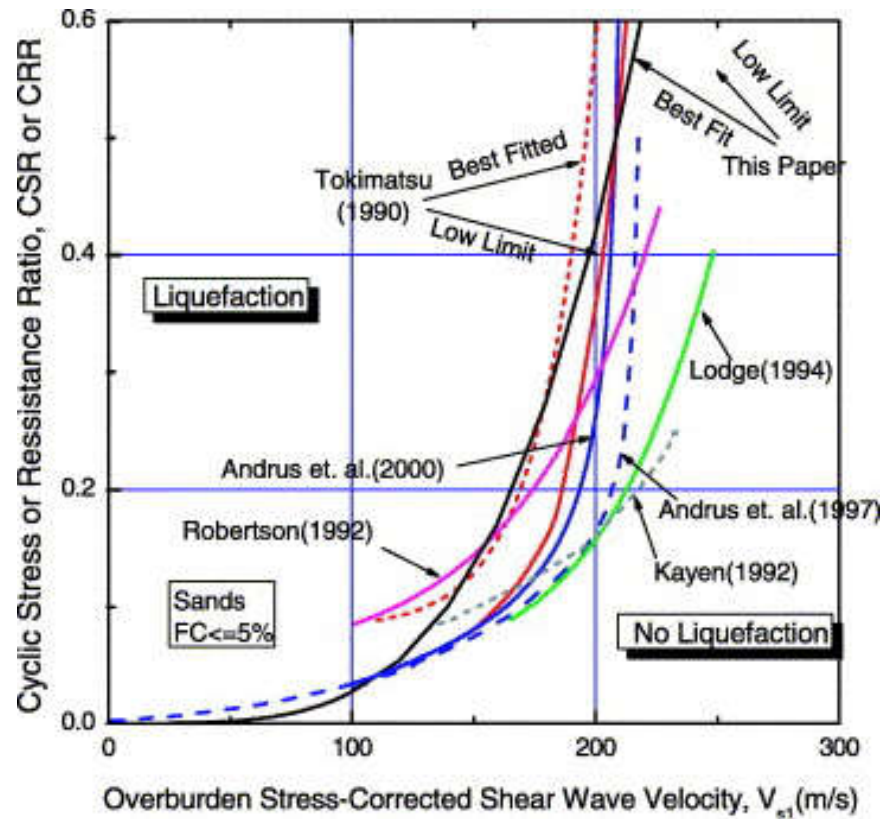
$$\Phi^{-1}(0.15) = -1.03643$$

$$DWF = 15M_w^{-1.342}$$

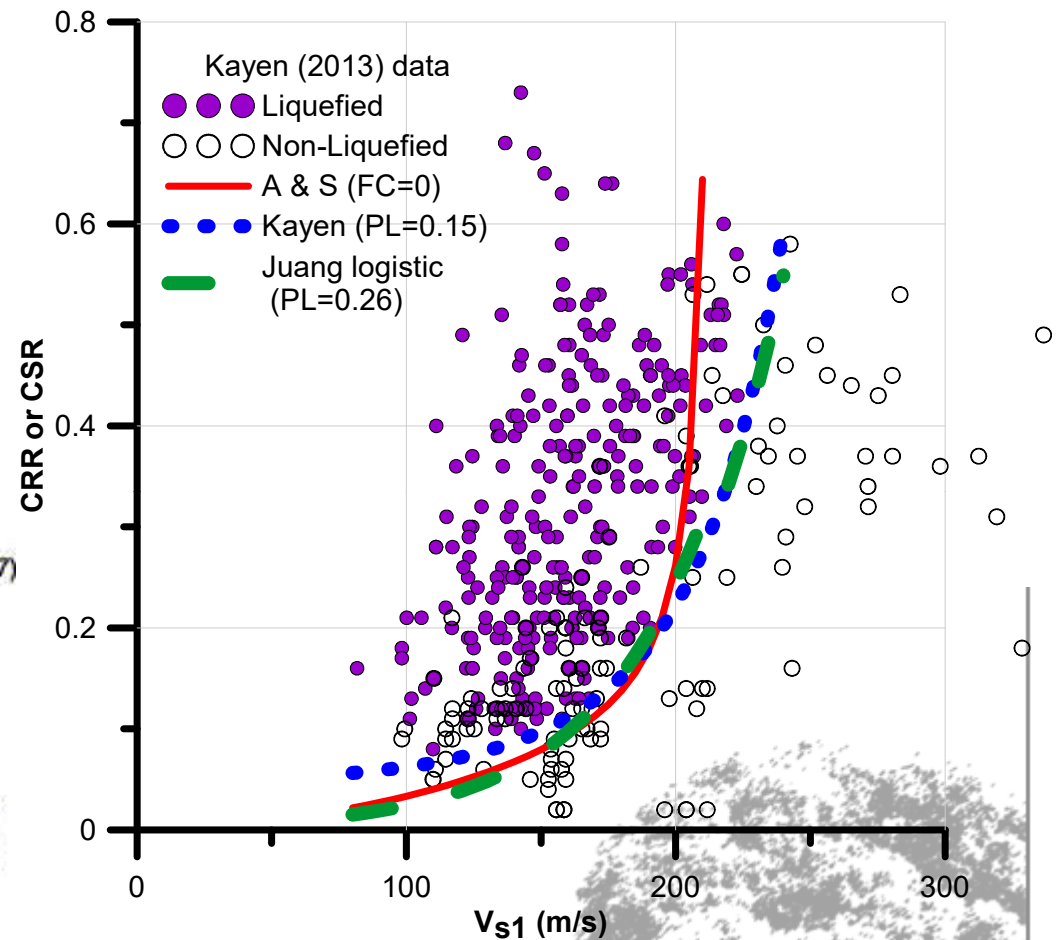


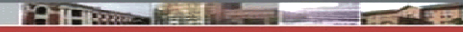


不同Vs-based定值法比較



(Chen et al., 2005)





Juang et al.(2002) Vs-based 機率法分析

$$CSR_{7.5} = 0.65 \left(\frac{\sigma_v}{\sigma'_v} \right) \left(\frac{a_{\max}}{g} \right) (r_d) / MSF \quad MSF = (M_w / 7.5)^{-2.56}$$

Logistic regression:

$$\ln[P_L / (1 - P_L)] = 14.8967 - 0.0611 V_{s1,cs} + 2.6418 \ln(CSR_{7.5})$$

Bayesian mapping:

$$P_L = 1 / [1 + (F_s / A)^B] \quad F_s = \frac{CRR_{AS}}{CRR_{7.5}}, A=0.73, B=3.4$$

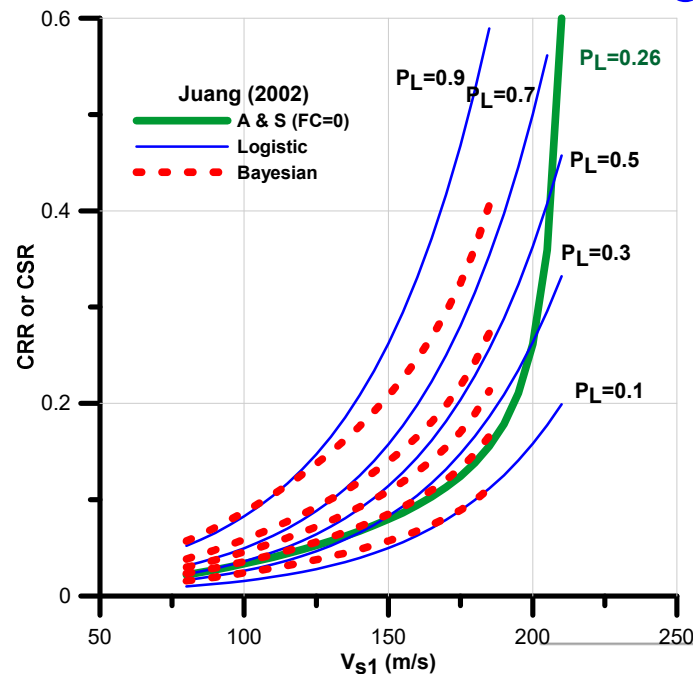


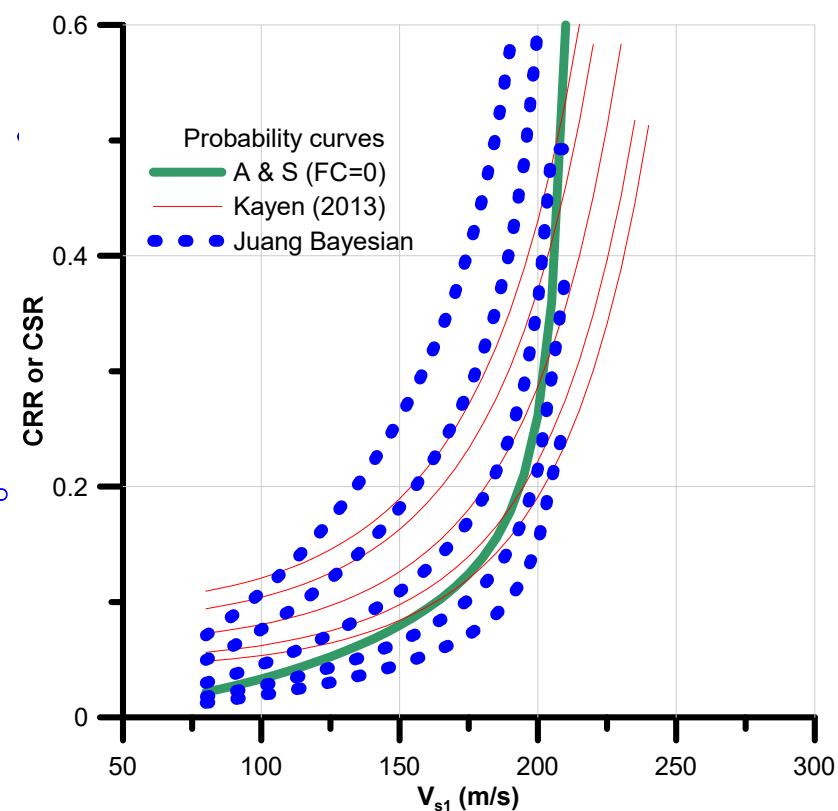
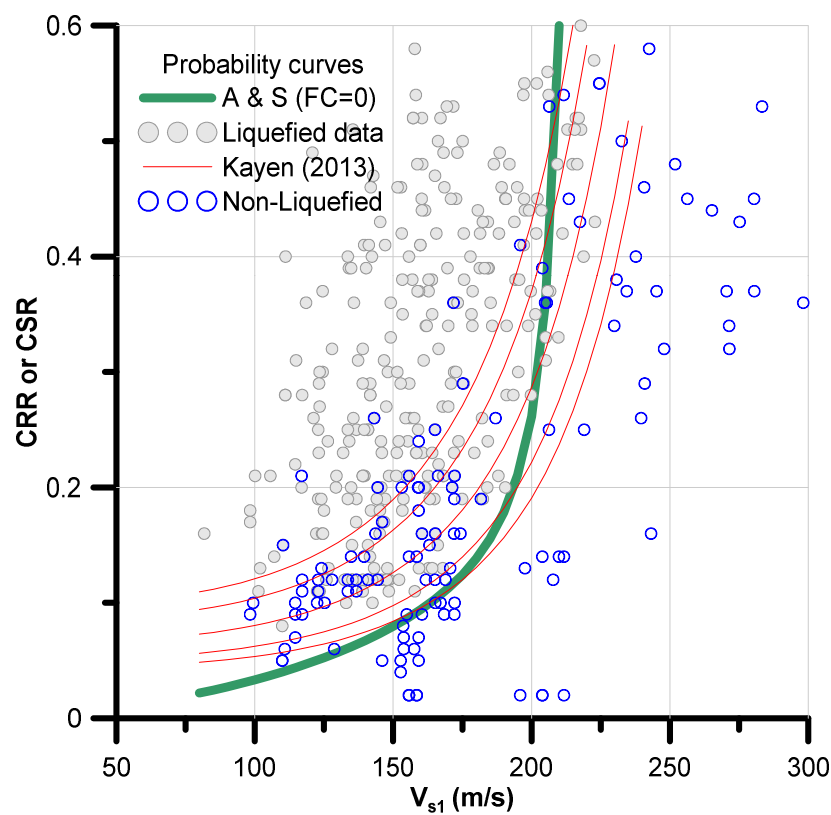
Table 2. Liquefaction Likelihood Classification (Chen and Juang 2000)

Class	Probability of liquefaction (P_L)	Description of likelihood
5	$P_L \geq 0.85$	Almost certain that it will liquefy
4	$0.65 \leq P_L < 0.85$	Very likely to liquefy
3	$0.35 \leq P_L < 0.65$	Liquefaction and no liquefaction are equally likely
2	$0.15 \leq P_L < 0.35$	Unlikely to liquefy
1	$P_L < 0.15$	Almost certain that it will not liquefy



Kayen et al. (2013) Vs-based 機率法分析

$$P_L = \Phi \left\{ \frac{\left[(0.0073 \cdot V_{s1})^{2.8011} - 1.946 \cdot \ln(\text{CSR}) - 2.6168 \cdot \ln(M_w) - 0.0099 \cdot \ln(\sigma'_{v0}) + 0.0028 \cdot (\text{FC}) \right]}{1.4809} \right\}$$



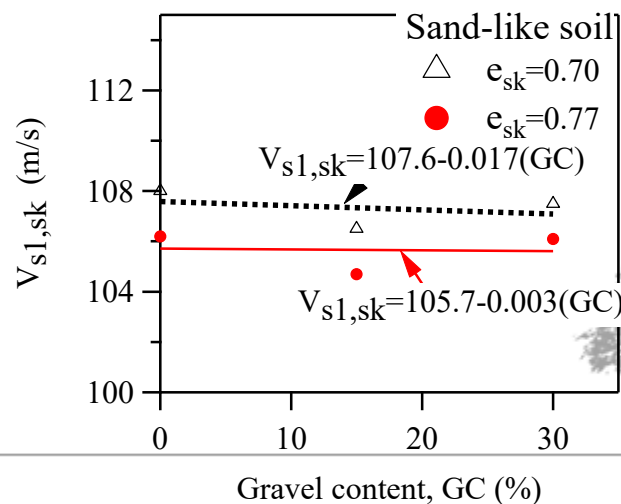
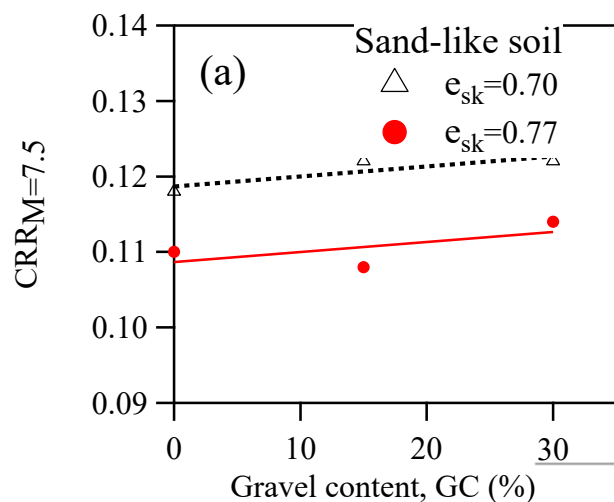
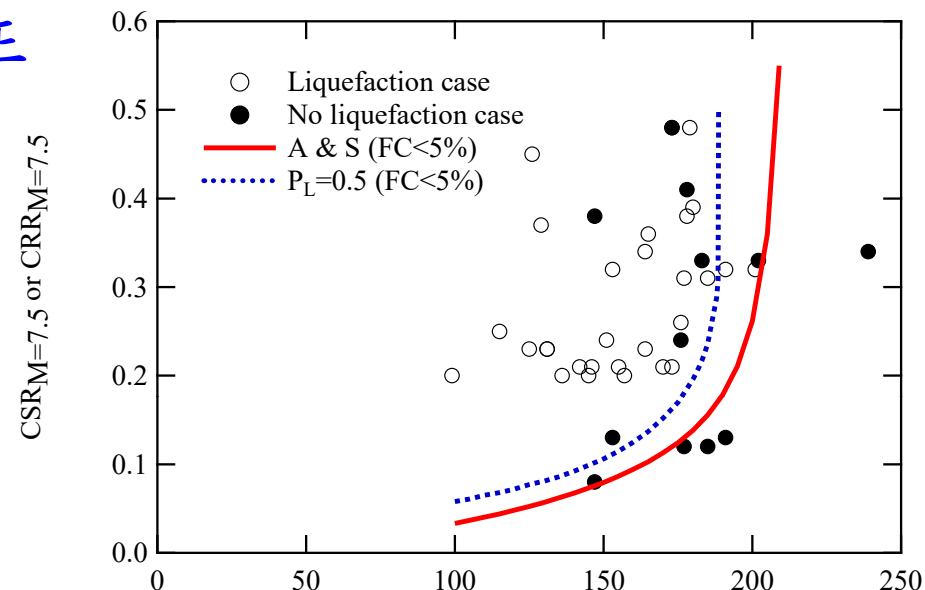
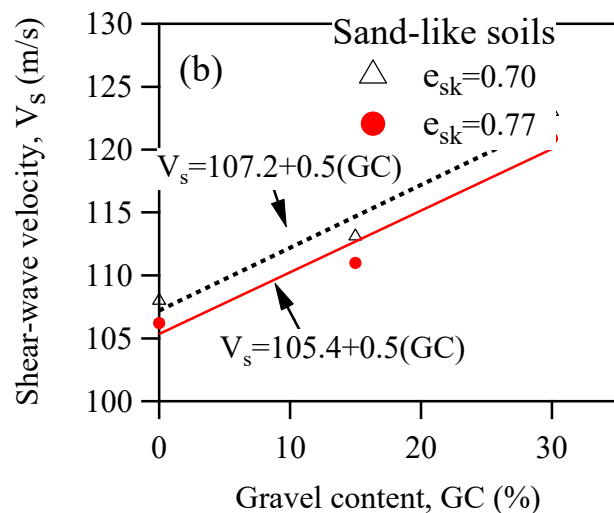
礫石砂土層液化評估 (Chang 2016)



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- 礫石砂土液化發生於分隔礫石顆粒之砂土
- 考慮不同顆粒間粒間狀態 (intergrain state) 概念
- 進行砂土中礫石含量對 V_s 修正



$$\frac{V_{s1,sk}}{V_{s1}} \approx 1 - \frac{b}{(1+e)} \cdot GC$$

$$TGC = \frac{1+e_2}{1+e_1+e_2}$$



礫石砂土層液化評估程序

Step 1:
Screen for $15 \leq GC \leq TGC$ and
 $TGC=70\%$ for general case

Step 2:
Calculate $V_{s1,sk}$ and ΔV_s^* from V_{s1} :
$$\frac{V_{s1,sk}}{V_{s1}} \approx 1 - \frac{b}{(1+e)} \cdot GC$$

with $b=0.65$

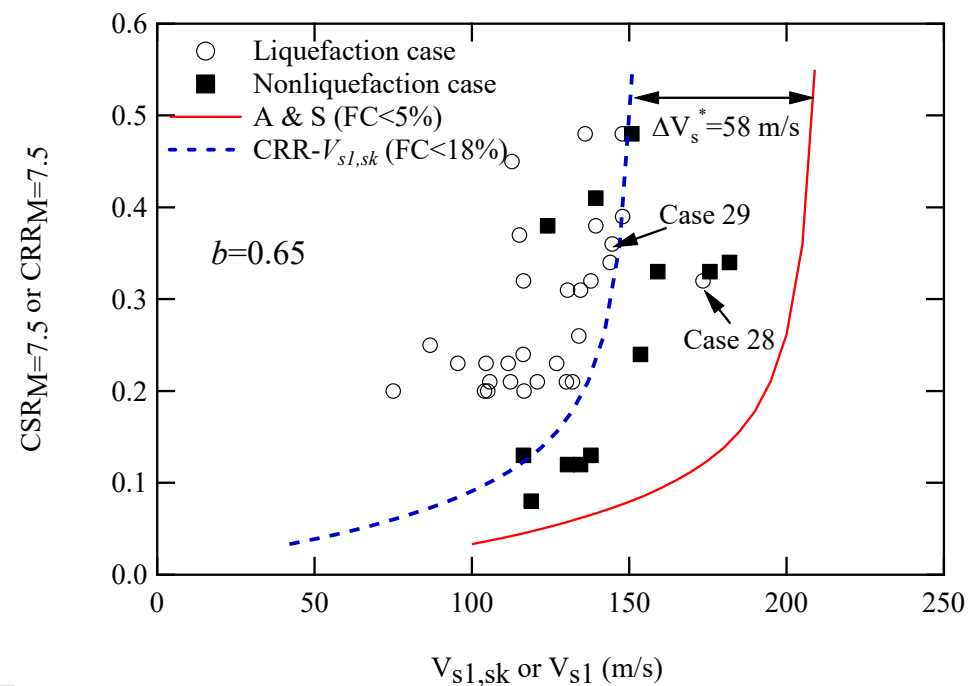
Step 3:
Calculate CRR:
$$CRR = \left\{ 0.022 \left(\frac{(V_{s1,sk} + \Delta V_s^*)}{100} \right)^2 + 2.8 \left(\frac{1}{V_{s1,sk}^* - V_{s1,sk}} - \frac{1}{(V_{s1,sk}^* + \Delta V_s^*)} \right) \right\} MSF$$

 $\Delta V_s^* = 58 \text{ m/s}$ and $V_{s1,sk}^* = 157 \text{ m/s}$ for $b=0.65$

$$TGC = \frac{1 + e_2}{1 + e_1 + e_2}$$

$$V_{s1,sk}^* = V_{s1}^* - \Delta V_s^*$$

$$CRR = \left\{ 0.022 \left(\frac{(V_{s1,sk} + \Delta V_s^*)}{100} \right)^2 + 2.8 \left(\frac{1}{V_{s1,sk}^* - V_{s1,sk}} - \frac{1}{(V_{s1,sk}^* + \Delta V_s^*)} \right) \right\} MSF$$



室內礫石砂土實驗結果比對



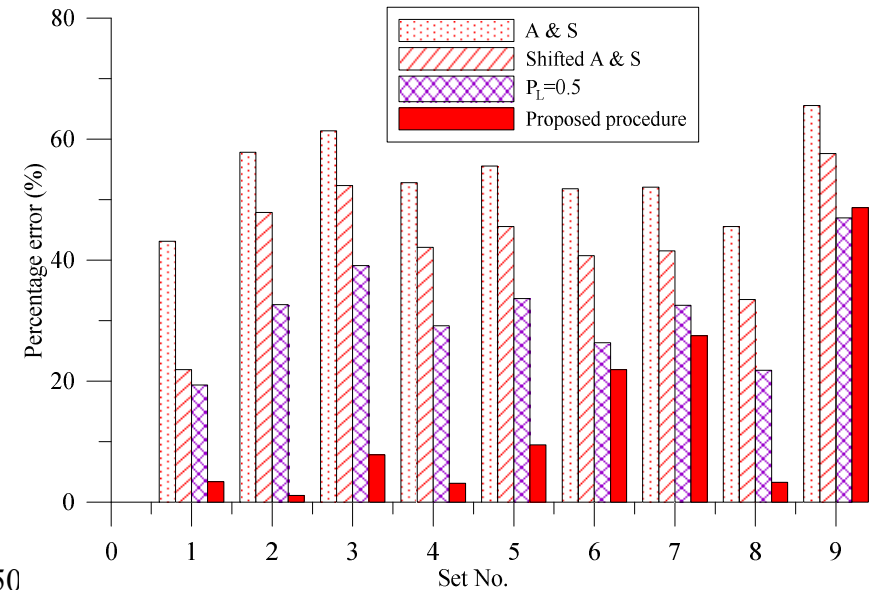
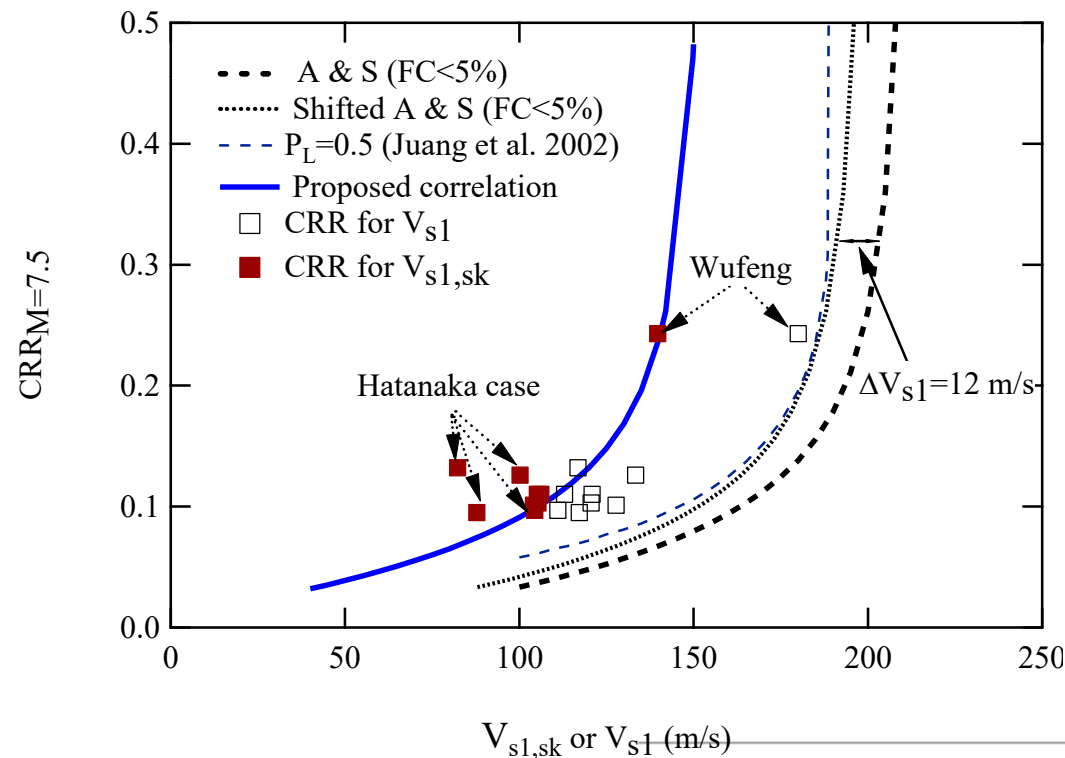
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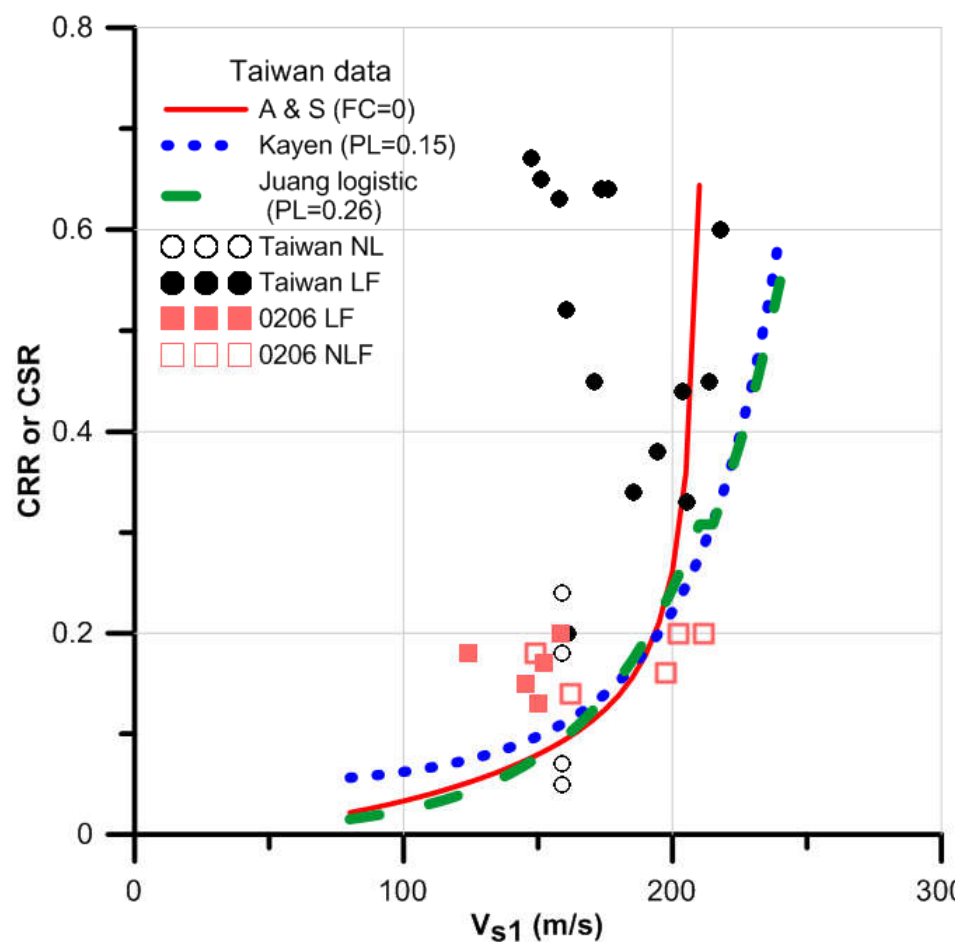
Table 4. Summary of Laboratory Liquefaction Testing Results Used for Verification

Set number	Description	GC (%)	e	FC (%)	V_{s1} (m/s)	$V_{s1,sk}$ (m/s)	Field $CSR_{M=7.5}$	Reference
1	Wufeng, Chi-Chi EQ (1999), remolded sample, CTX	53	0.54	3	180.0	139.7	0.243	Lin et al. (2004)
2	Sample ID: SC85-1~3, remolded sample, K_0 -CDSS	15	0.65	0	111.0	104.4	0.097	Chang et al. (2014)
3	Sample ID: SC85-4~6, remolded sample, K_0 -CDSS	15	0.61	0	113.0	106.2	0.110	Chang et al. (2014)
4	Sample ID: SC70-1~3, remolded sample, K_0 -CDSS	30	0.54	0	120.6	105.3	0.103	Chang et al. (2014)
5	Sample ID: SC70-4~6, remolded sample, K_0 -CDSS	30	0.50	0	120.9	105.2	0.110	Chang et al. (2014)
6	Sample: KPU, fill, frozen sample, CTX	53.3	0.38	7.9	117.2	87.8	0.095	Hatanaka et al. (1997)
7	Sample: KPM, fill, frozen sample, CTX	53.7	0.40	4.1	133.4	100.2	0.126	Hatanaka et al. (1997)
8	Sample: KPL, fill, frozen sample, CTX	41.8	0.46	5.4	127.8	104.1	0.101	Hatanaka et al. (1997)
9	Sample: MO, Holocene, frozen sample, CTX	60	0.32	8.5	116.8	82.3	0.132	Hatanaka et al. (1997)

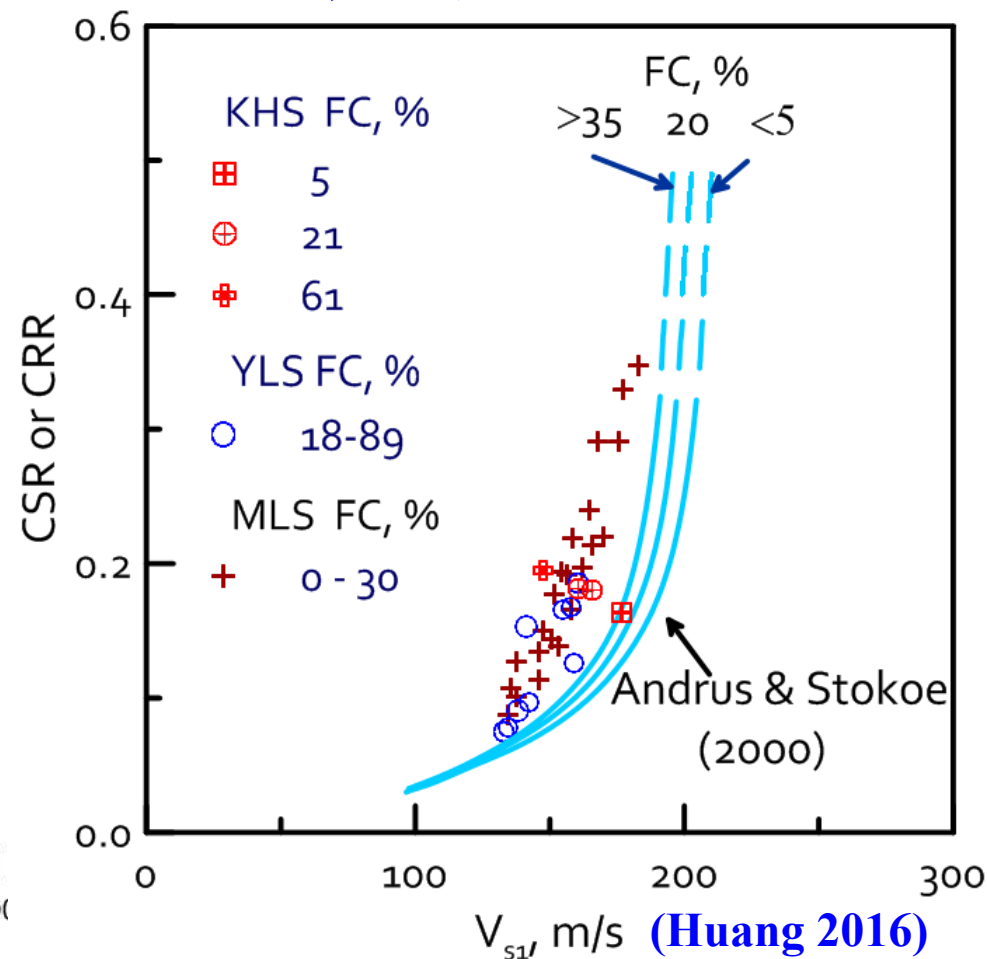
Note: CTX = cyclic triaxial test; K_0 -CDSS = K_0 cyclic direct simple shear test.



台灣現地液化案例



台灣西部粉土CTX 結果





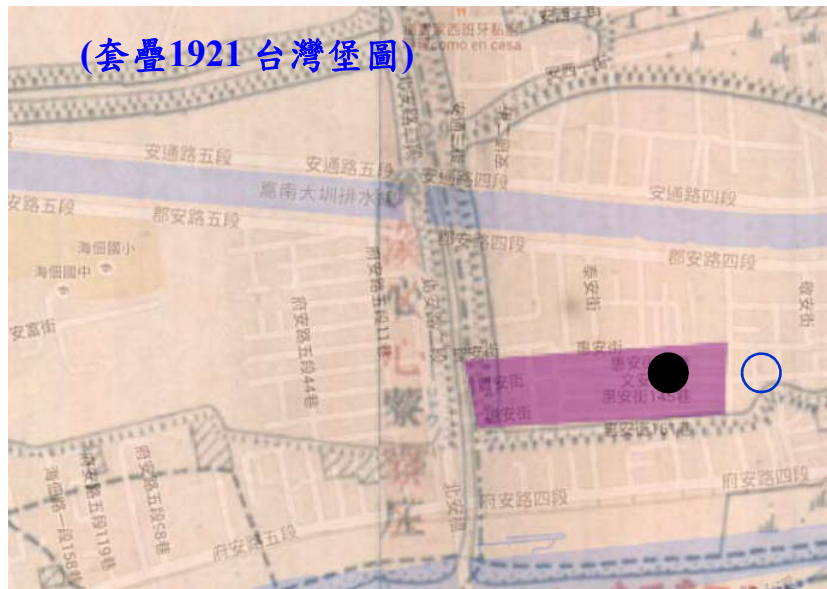
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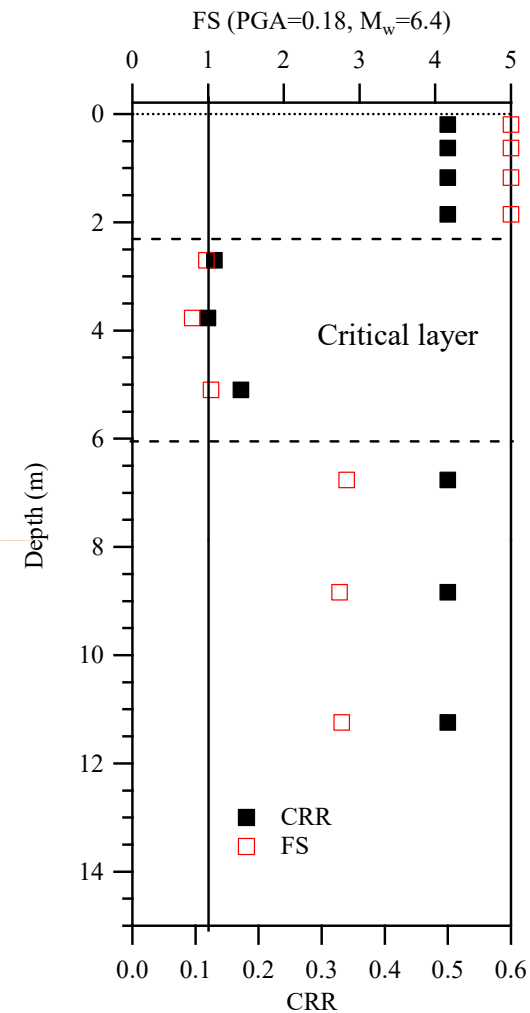
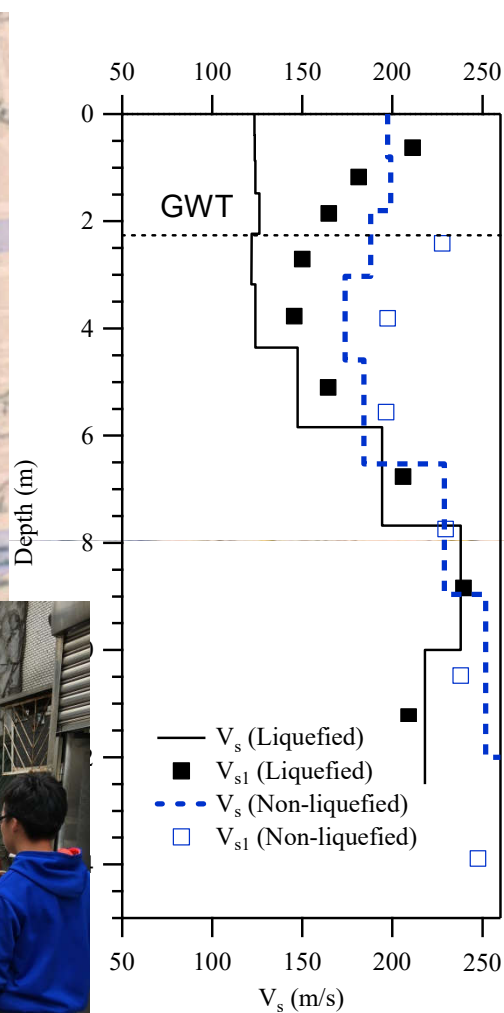


案例1：台南市溪頂里液化調查

(套疊1921 台灣堡圖)

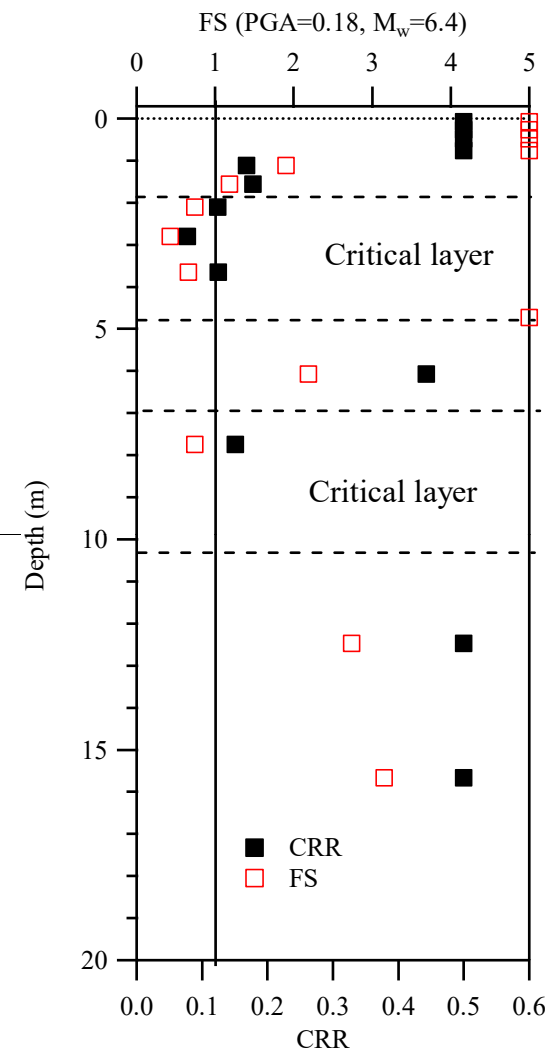
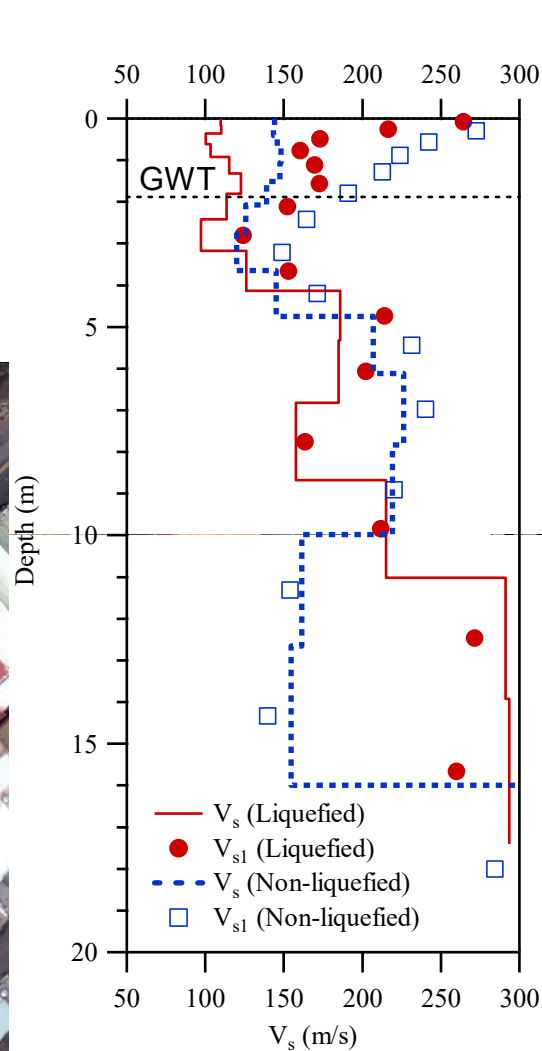
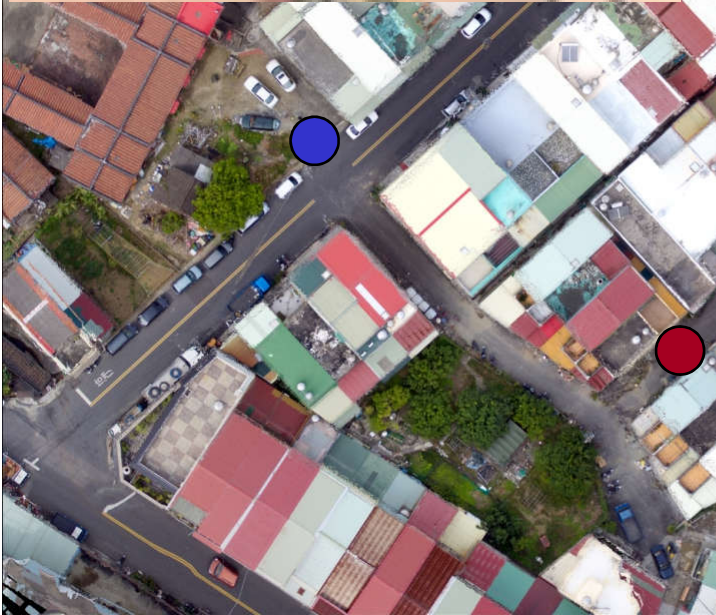
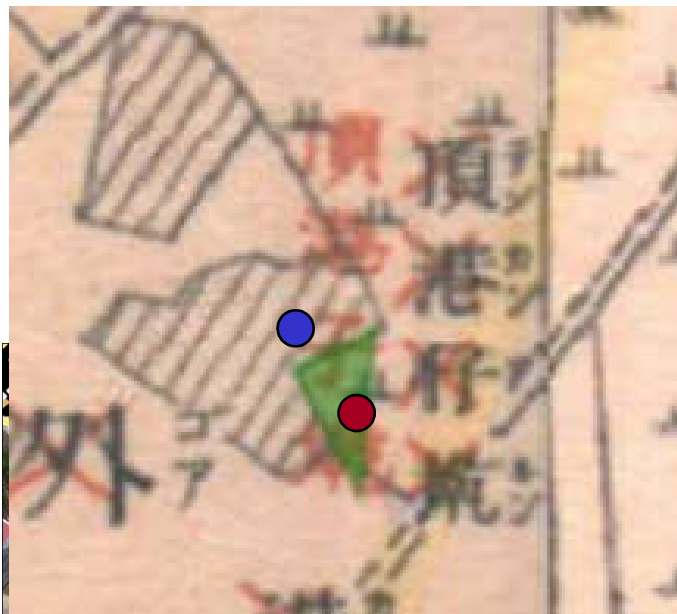


(中研院地科中心)



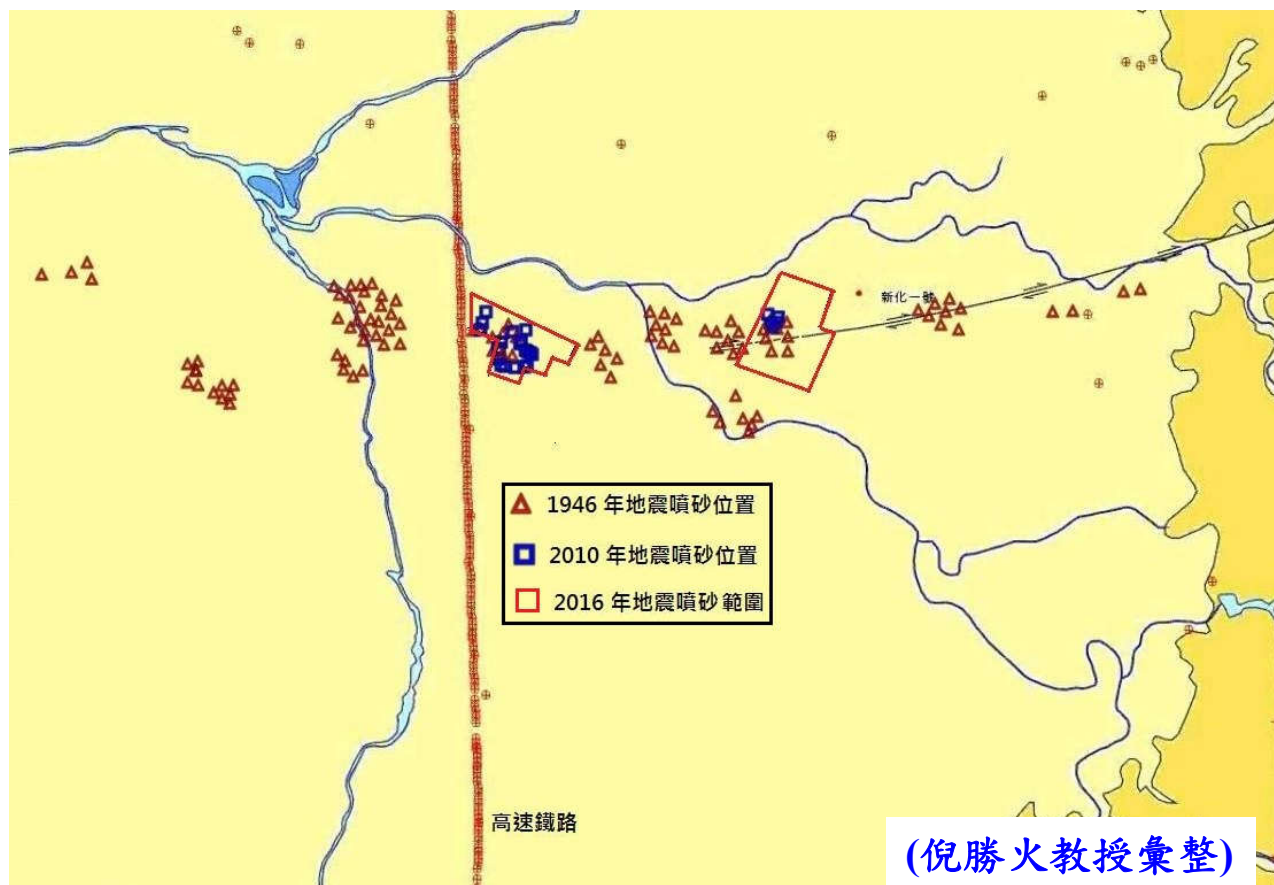


案例2:新市三民街液化分析





案例3::新化區北勢里

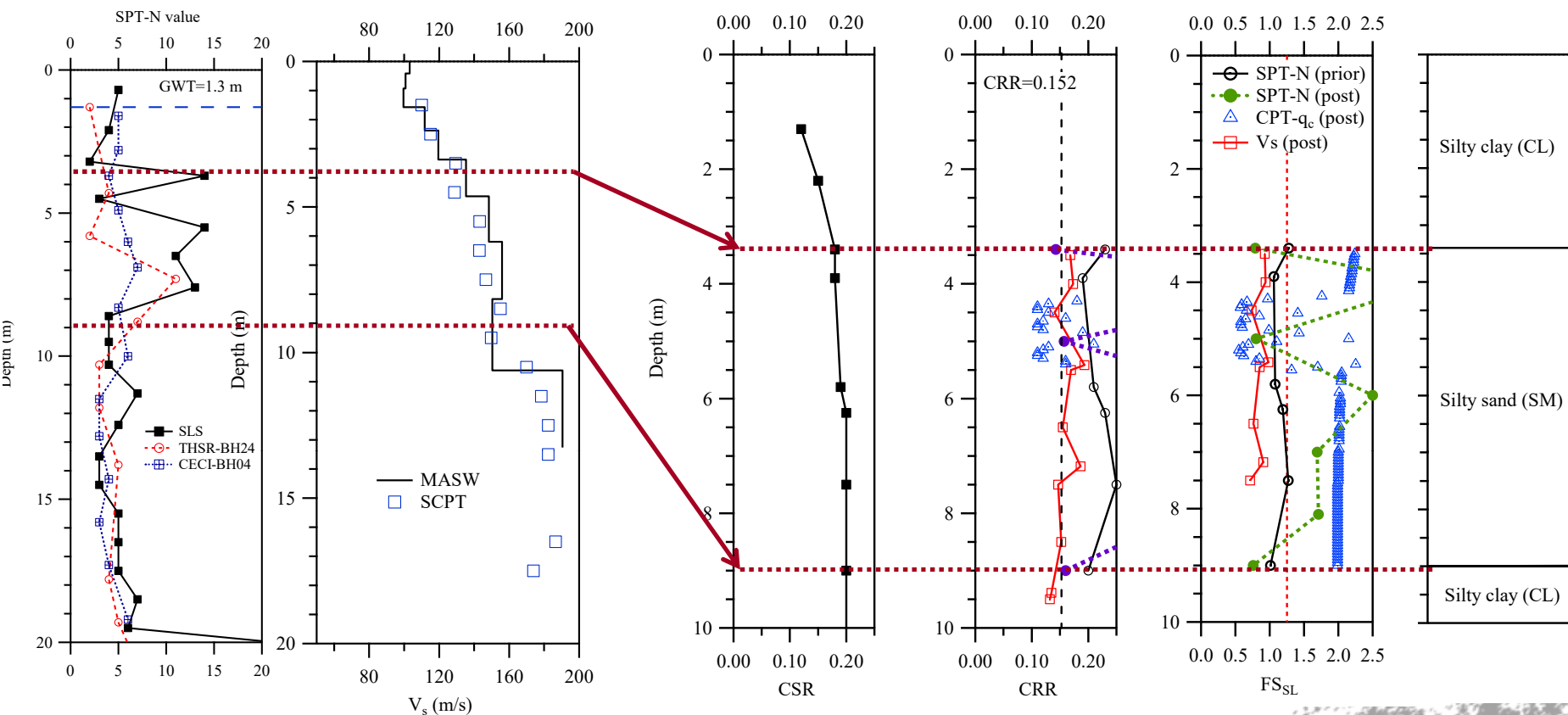


(倪勝火教授彙整)

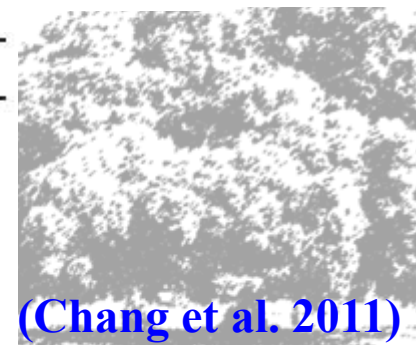


- 多次液化: 1946新化地震, 2010甲仙地震, 2016年0206地震
- 距高鐵高架最近僅 30 m
- 有詳細調查資料

北勢里液化分析成果



Method	$CRR_{7.5}$	$\frac{CRR_{m-slu}}{CRR_{lab}}$	Reference
K_0 -CDSS	0.123	1	Seed (1979)
SPT-N	0.12	0.98	Idriss and Boulanger (2006)
CPT (PR = 20 mm/s)	0.131	1.06	Robertson (2009)
CPT (PR = 1 mm/s)	0.09	0.73	Robertson (2009)
V_s	0.1	0.81	Andrus and Stokoe (2000)
q_c/V_s	0.075	0.61	Roy (2008)



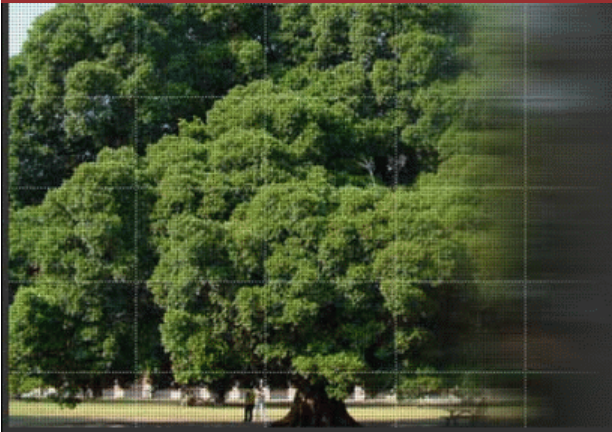
(Chang et al. 2011)

- ▶ 現地剪力波速量測具有非破壞及施測快速之優點，但結果判釋需具專業知識。
- ▶ 以Vs法進行砂土層液化評估時，結果常較SPT-N及CPT-qc保守，且細粒料影響不顯著。
- ▶ 礫石砂土層液化評估，建議進行礫石含量波速修正，以免過於保守。
- ▶ 對於鄰近邊界之液化場址，建議進行多種液化評估分析。





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Thanks !