CPT液化評估法

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2016土壤液化評估方法研討會(2016/08/29)

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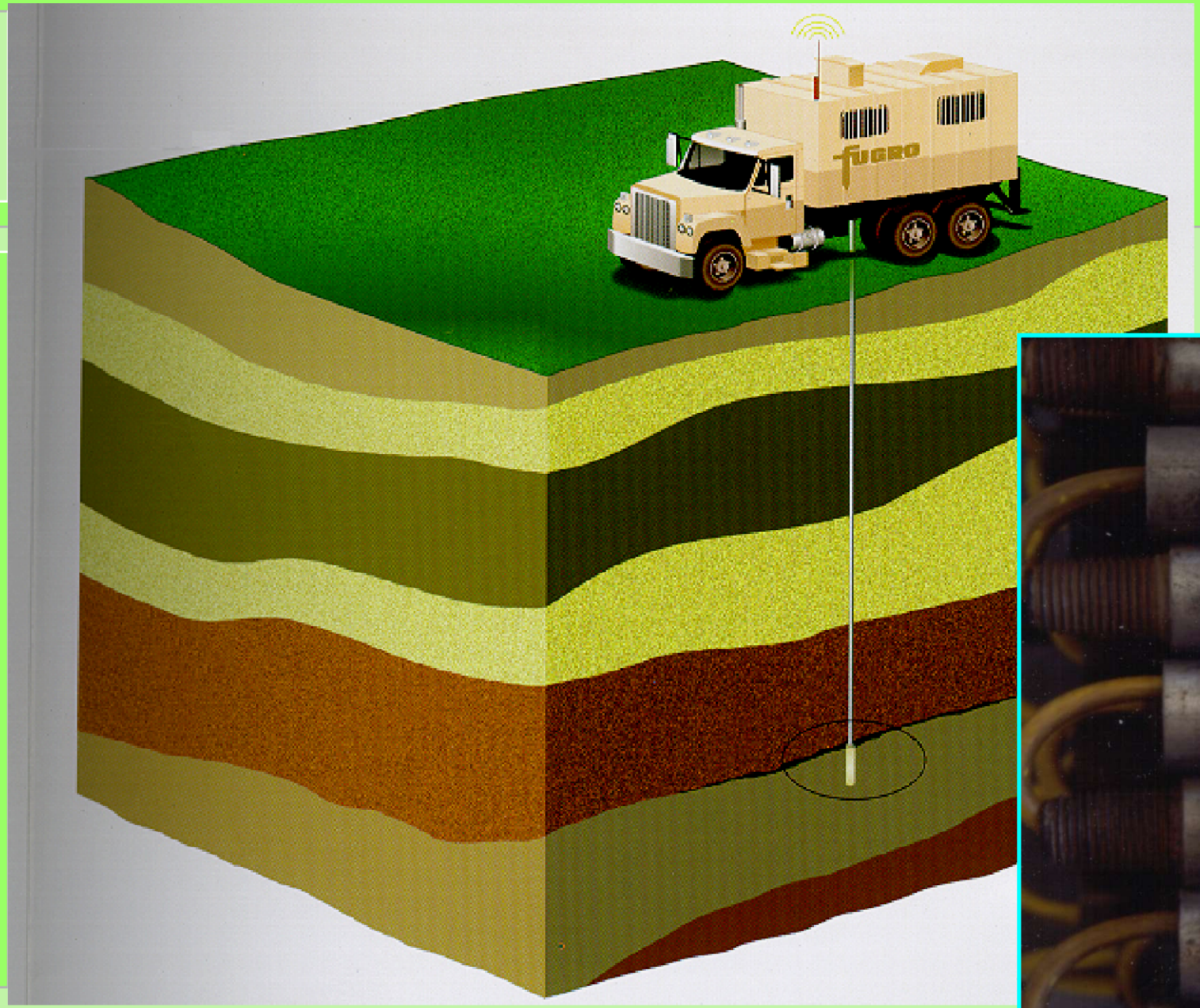
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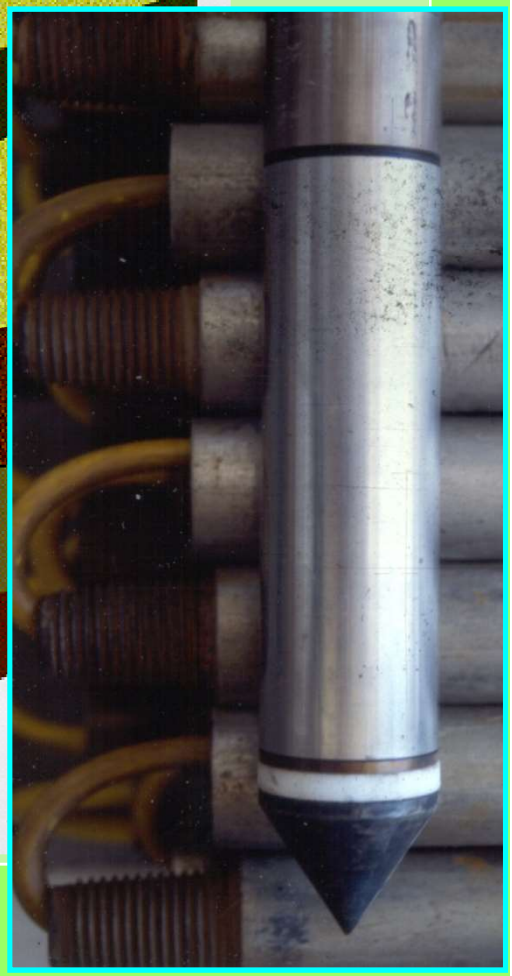


CPT truck and boat

圓錐貫入試驗Cone Penetration Test (CPT)

CPT is a relatively rapid and reliable in-situ test that can provide a (near) continuous soil profile.

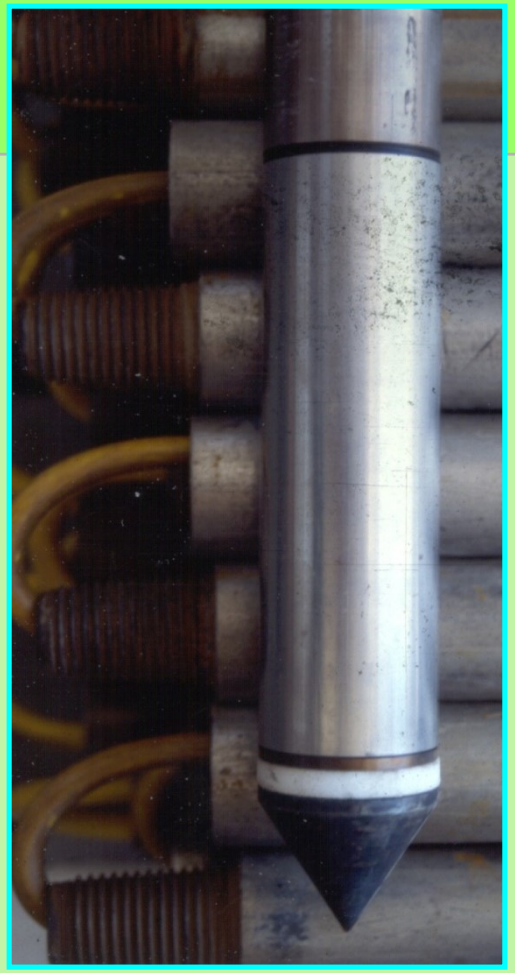
Originally Developed in **Netherlands** 1930s

Further developments in 1950s

Static Penetration Test; Quasi-Static Penetration Test; Dutch Sounding Test

Types of CPT cones ：**機械錐(Mechanical cone)**

- **電子錐(Electric cone)-1948**
- **水壓錐(Piezocone)-1974**
- **震測錐(Seismic cone)-1986**
- **可視錐(Vision cone, VisCPT)-1997**



Cone : 2 cm^2, 10 cm^2, 15 cm^2, 40 cm^2

CPT equipment and procedure

- **Cone** :apex angle=**60**^{o} ,
  base area=**10**cm^{2} ,
  friction sleeve area = **150**cm^{2}.
- Penetration rate is about **20 ±5 mm/sec**, readings are taken at every **50mm (10mm-50mm)**.
- Baseline readings: Zero load readings should be recorded at the start and end of each CPT
- **ASTM D5778 -12 Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils**

Checks and Recalibrations for the CPT

Maintenance	*Start of Project*	*Start of Test*	*End of Test*	*End of Day*	*Once a Month*	*Every 3 months**
Wear	*x*	*x*			*x*	
O-ring seals	*x*			*x*		
Push-rods		*x*			*x*	
Pore pressure-filter	*x*	*x*				
Calibration						*x**
Computer					*x*	
Cone					*x*	
Zero-load		*x*	*x*			
Cables	*x*				*x*	

Robertson and Cabal (2015)

CPT sounding

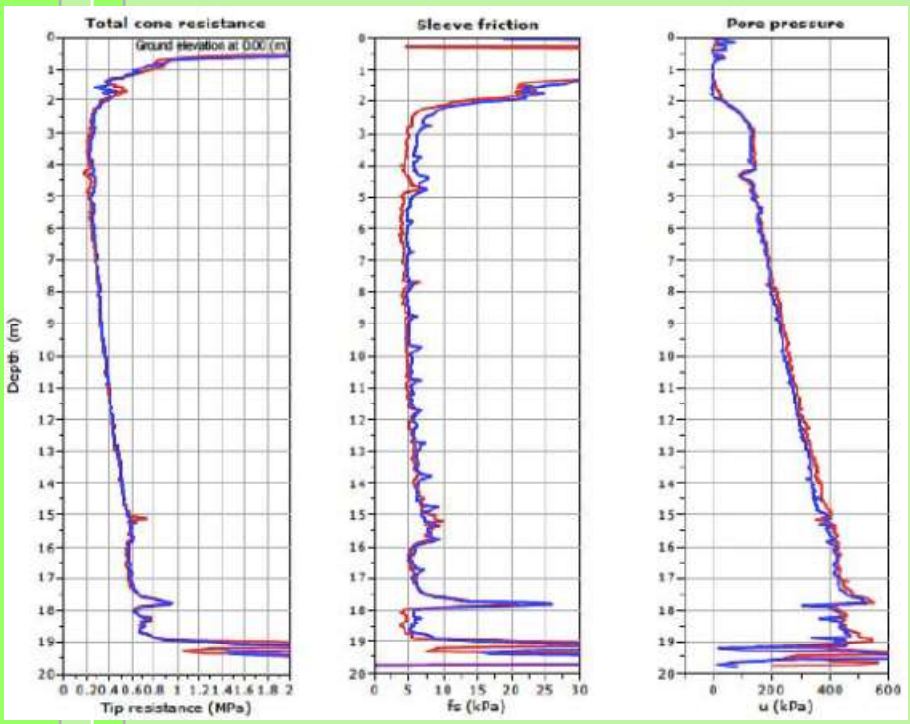
Raw data：Cone resistance (q_c), Local friction (f_s), Porewater pressure (P_w)

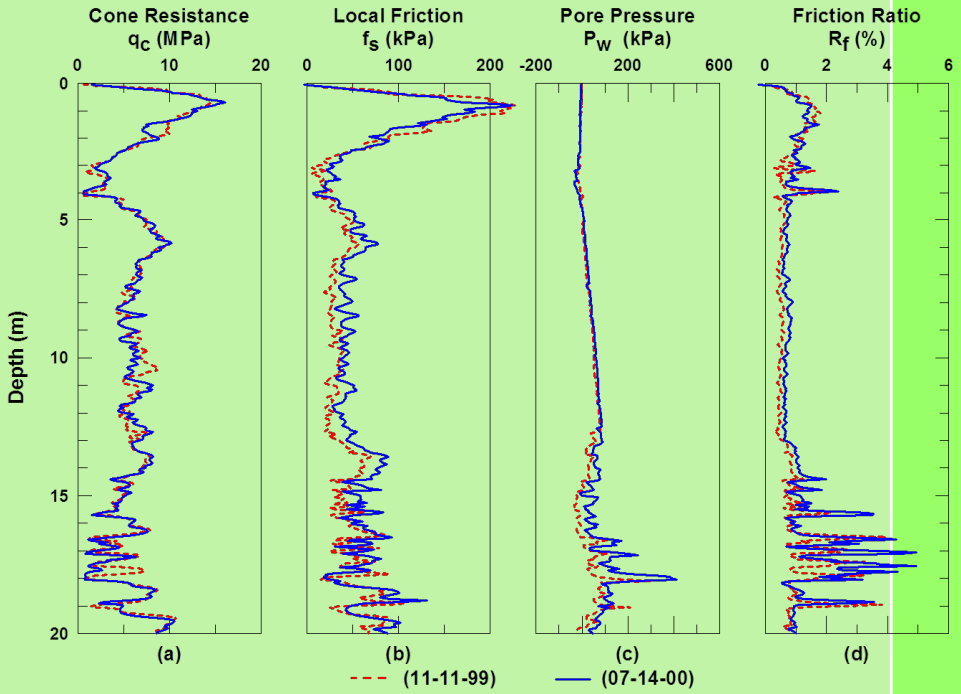
Depth (m)	q_c (MPa)	fs (kPa)	Pw (kPa)	Inc (deg)	Soil Type	SPT- N
⋮	⋮	⋮	⋮	⋮	⋮	⋮
13.8	1.449	29.87	166.64	2.54	Clayey silt	7
13.85	1.351	28.58	278.23	2.54	Clayey silt	7
13.9	1.416	20.81	349.63	2.55	Silty sand	6
13.95	1.66	26.67	343.59	2.55	Silty sand	7
14	2.035	23.38	359.02	2.55	Silty sand	8
14.05	4.336	38.68	125.12	2.55	Sand with some Silt	15
14.1	5.149	48.65	82.83	2.55	Sand with some Silt	17
14.15	5.568	59.2	86.41	2.55	Sand with some Silt	19
14.2	5.634	57.58	92.16	2.55	Sand with some Silt	19
⋮	⋮	⋮	⋮	⋮	⋮	⋮

CPT **ADVANTAGES**

- **Fast and continuous profiling**
  - Reliable and fast (~180 m/day)
  - Continuous profile (reading per 2cm or 5cm)
- **Repeatable data**
- **Strong theoretical basis for interpretation**
- **More than one measurement (q_c, f_s, u)**
- **Additional sensors (e.g. seismic Vs)**

Accuracy and repeatability





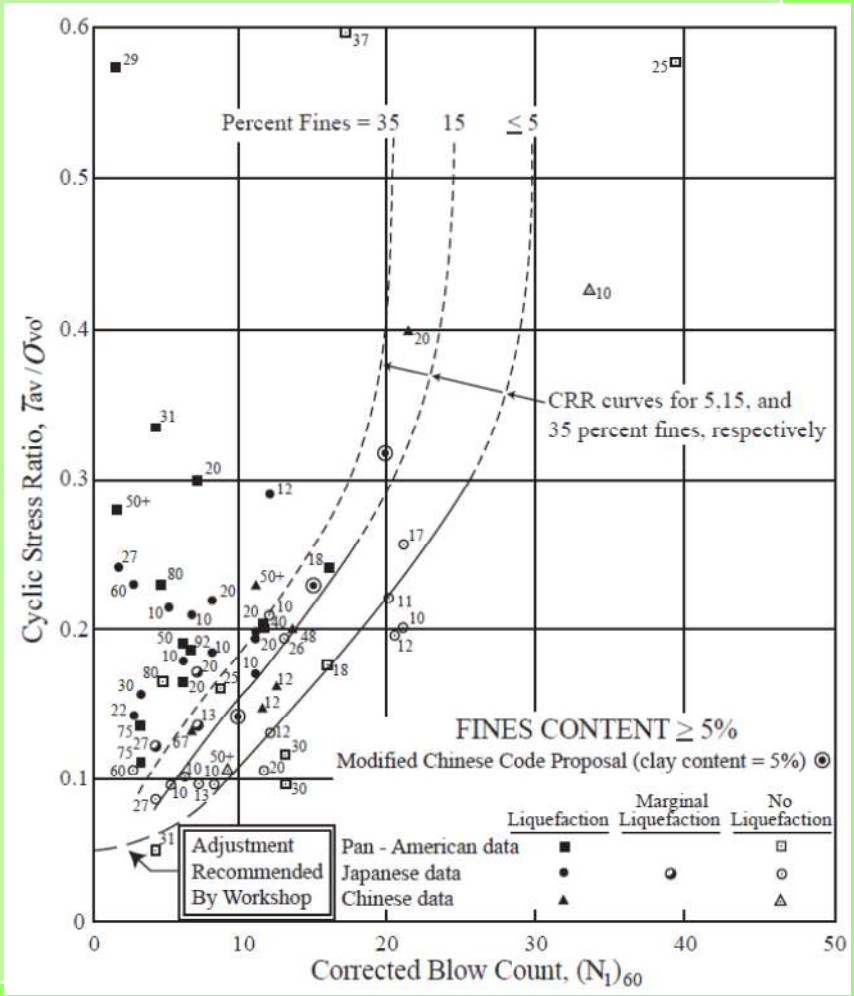
Cabal and Robertson (2014)

CPT液化評估方法(簡易法)

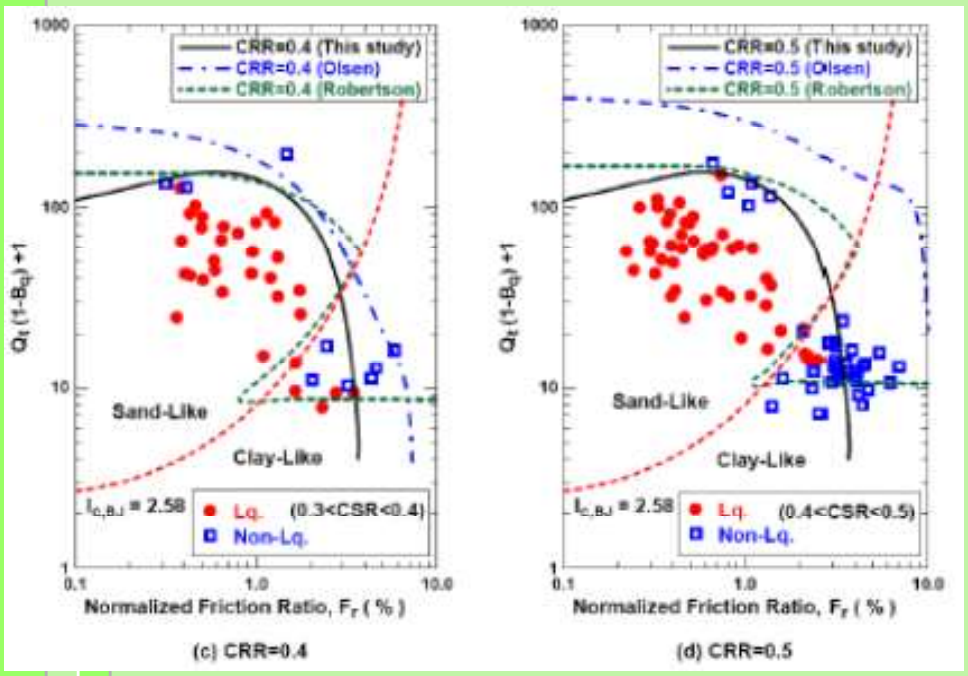
- ✓ **Seed method (1971-1997)**
- ✓ **Seed et al, (1983):SPT-N ⟶ CPT-q_c**
- ✓ **Shibata and Teparaksa (1988)**
- ✓ **Stark and Olson (1995)**
- ✓ **Olsen (1997)**
- ✓ **Moss et al. (2006)**
- ✓ **Robertson method (1985-2009)**
- ✓ **Juang et al. method (1999-2016)**
- ✓ **Boulanger and Idriss (2004-2016)**

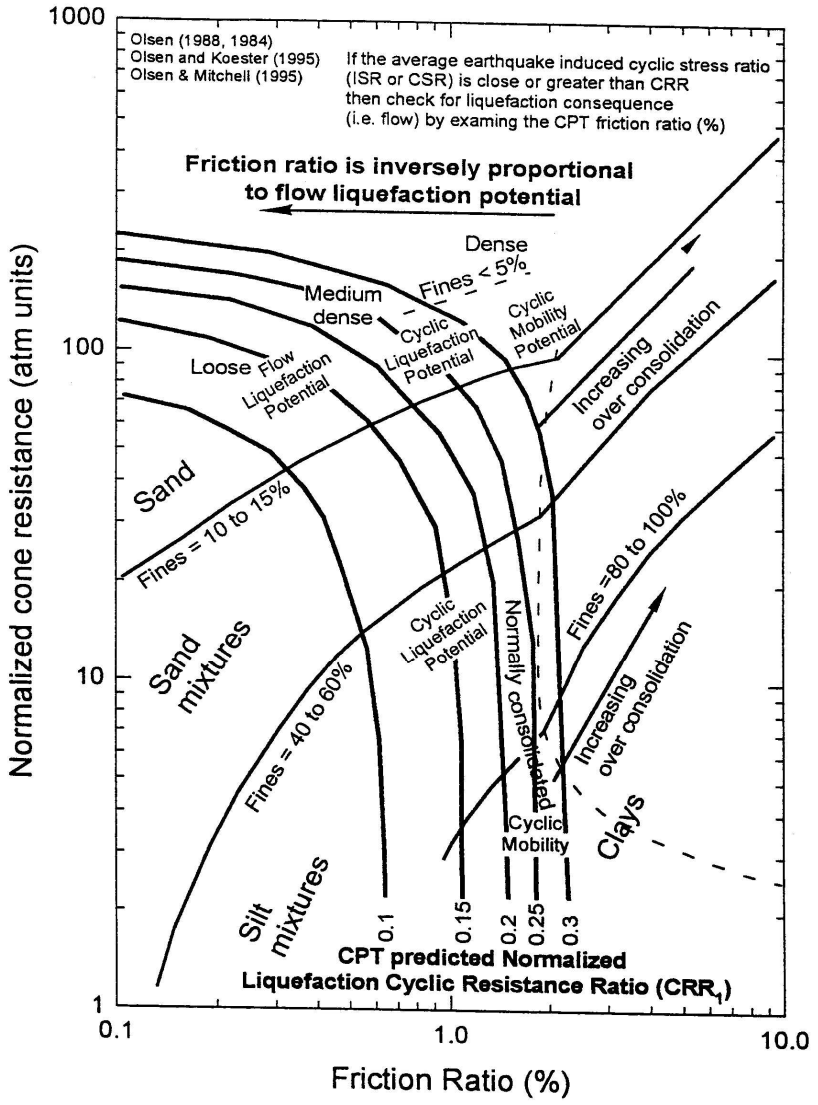
Seed method

$$CSR = \left(\frac{\tau_{av}}{\sigma_{vo}^{'}} \right) = 0.65 \left(\frac{a_{\max}}{g} \right) \left(\frac{\sigma_{vo}}{\sigma_{vo}^{'}} \right) r_d$$



Olsen method (1997)

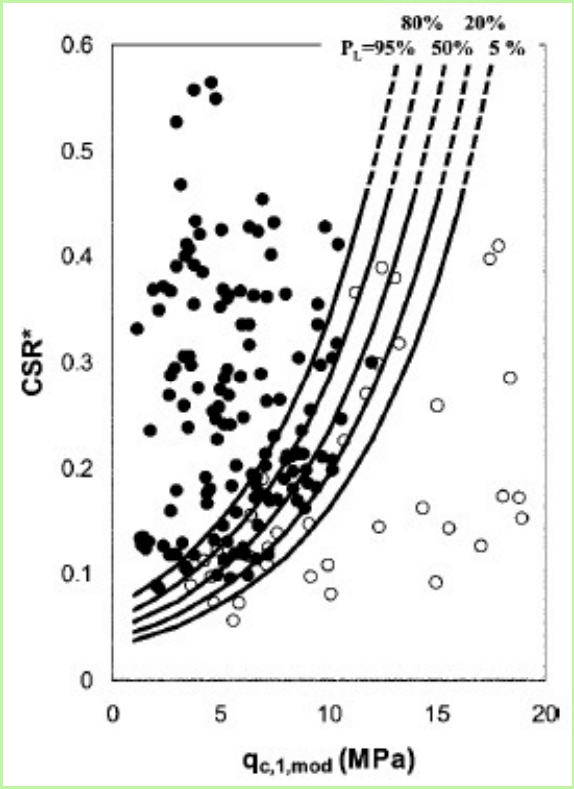




Ku and Juang (2012)

$$CRR = (0.00128q_{c1}) - 0.025 + (0.17R_f) - (0.028R_f^2) + (0.0016R_f^3)$$

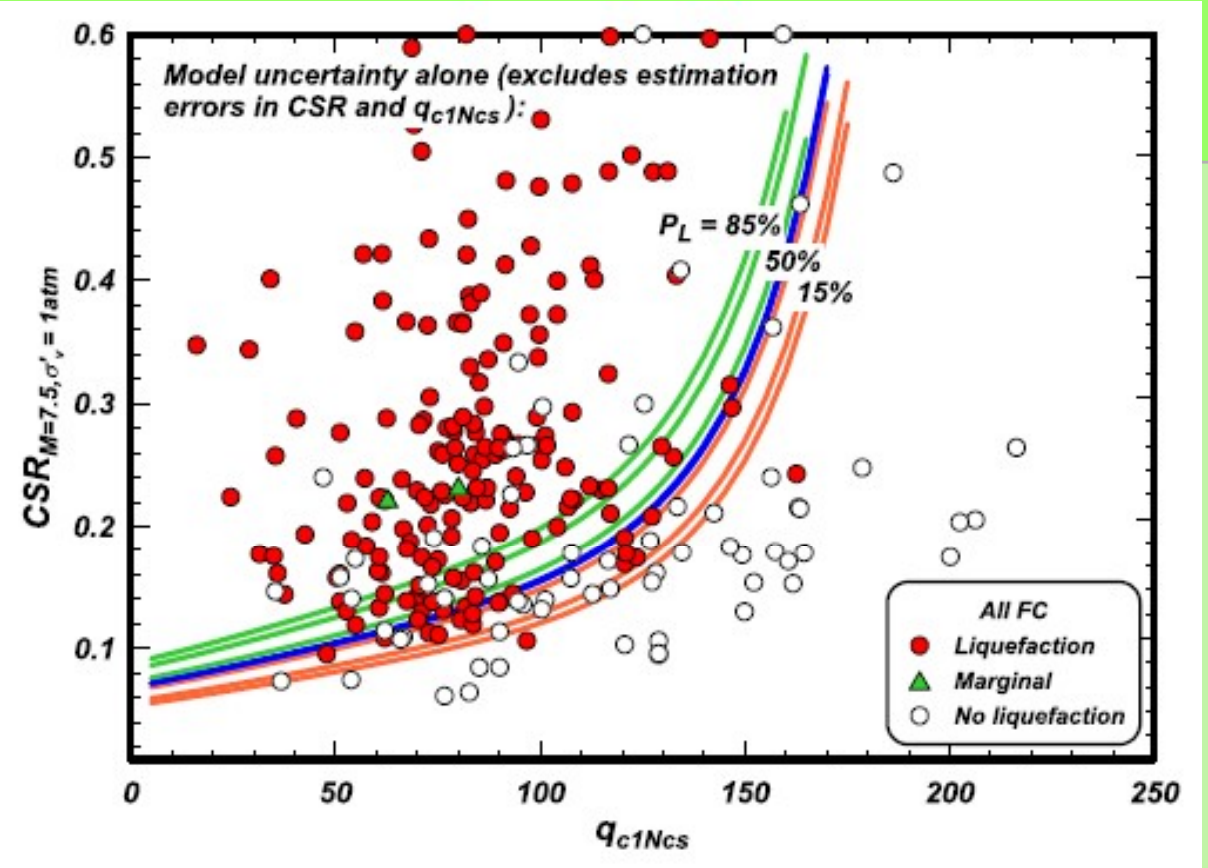
Moss et al. (JGGE, 2006)



$$P_L = \Phi\left(-\frac{q_{c1}^{1.045} + q_{c1}(0.110 \cdot R_f) + (0.001 \cdot R_f) + c(1 + 0.850 \cdot R_f - 7.177\ln(CSR) - 0.848\ln(M_w) - 0.002\ln(\sigma'_v) - 20.923}{1.632}\right)$$

$$CRR = \exp\left(\frac{q_{c1}^{1.045} + q_{c1}(0.11 \cdot R_f) + (0.001 \cdot R_f) + c(1 + 0.85 \cdot R_f - 0.848\ln(M_w) - 0.002\ln(\sigma'_{vo}) - 20.923 + 1.632\Phi^{-1}(P_L)}{7.177}\right)$$

Boulanger and Idriss(JGGE, 2016)



$$CRR = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.6 + \sigma_{\ln(R)} \cdot \Phi^{-1}(P_L)\right)$$

$$P_L(q_{c1Ncs}, \mathrm{CSR}_{M=7.5,\sigma'_v=1\ \mathrm{atm}}) = \Phi\left[-\frac{\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1{,}000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.60 - \ln(\mathrm{CSR}_{M=7.5,\sigma'_v=1\ \mathrm{atm}})}{\sigma_{\ln(R)}}\right]$$

CRR of Clay-Like fine-grained soils

塑性指數大於等於7以上視為類粘性土壤

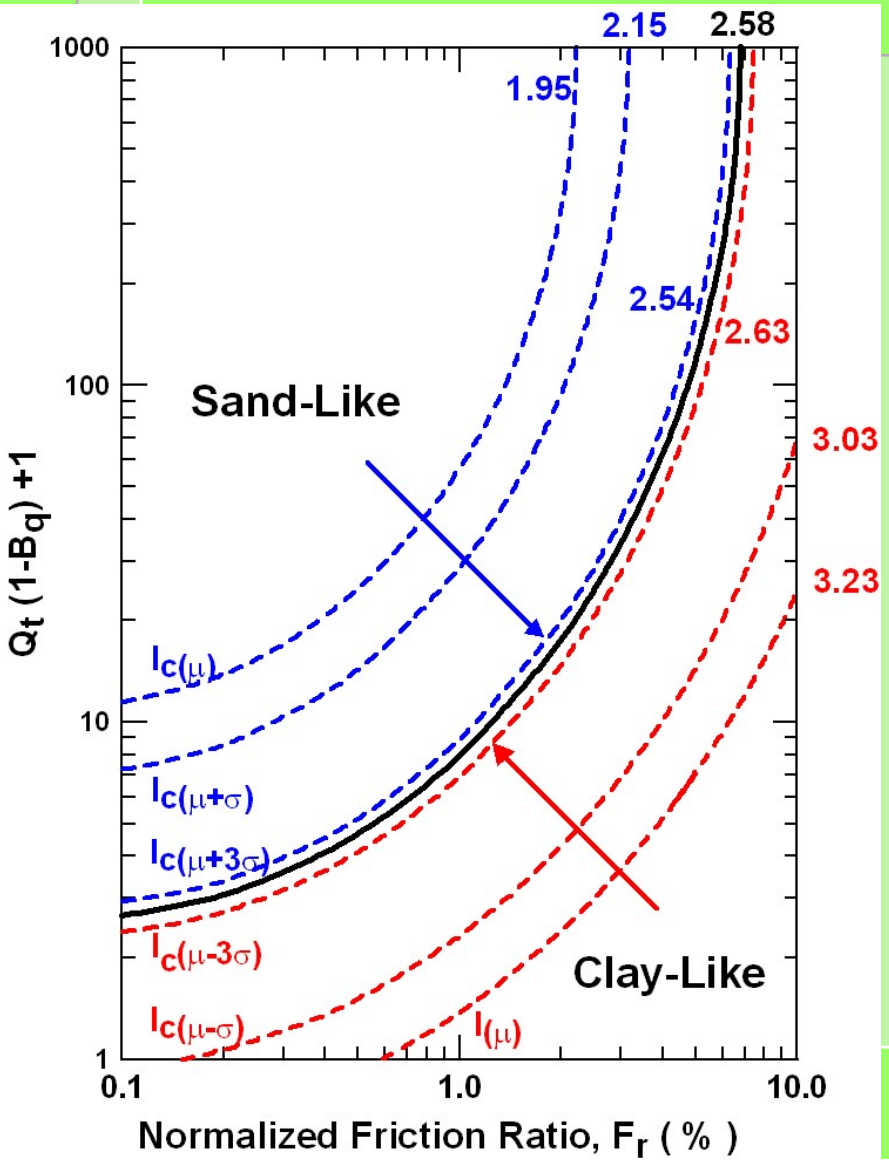
土讓行為分類指數(Ic)2.6以上視為類粘性土壤

Boulanger and Idriss (2007)

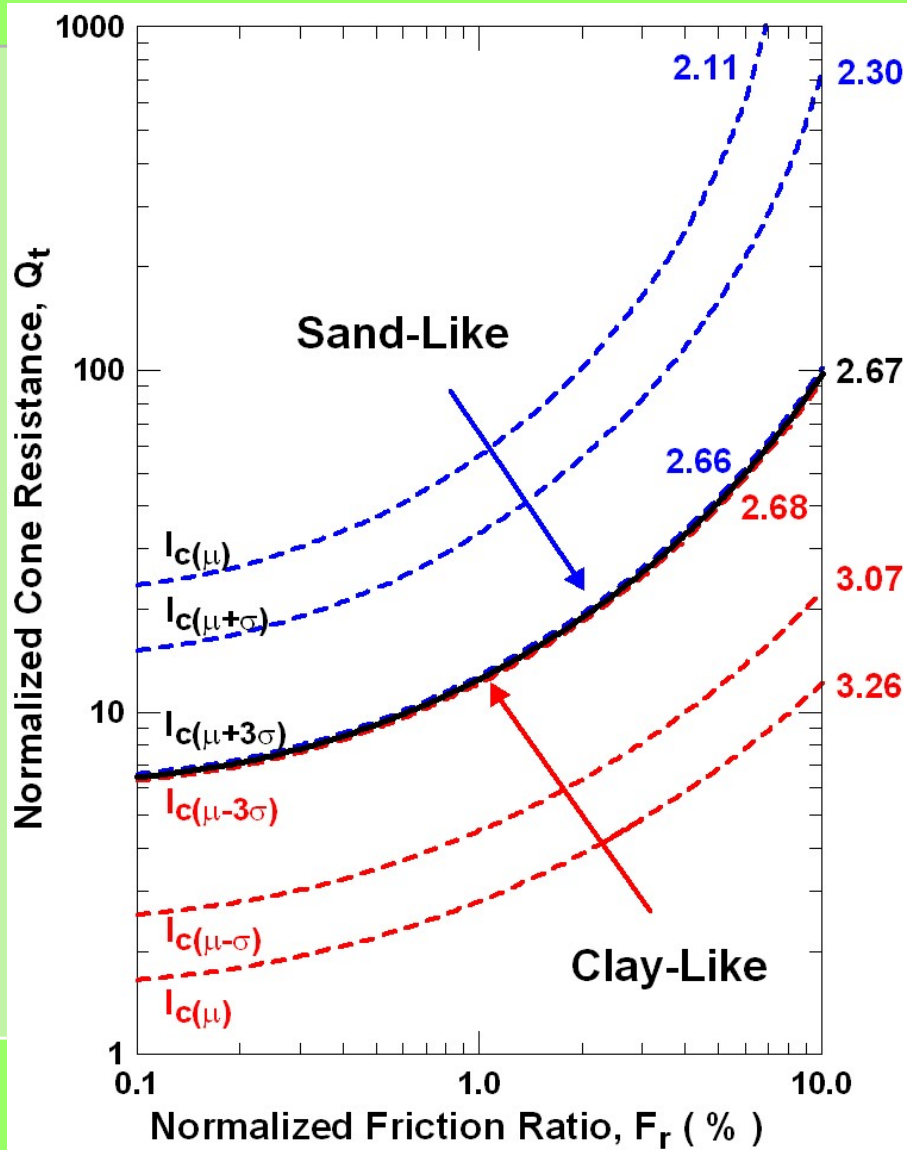
1. directly using cyclic **laboratory testing**;
2. empirically based on **undrained shear strength** profile;
3. empirically based on consolidation stress history i.e., **OCR** profile.

Sand-Like and Clay-Like soils (Ku et al. 2010)

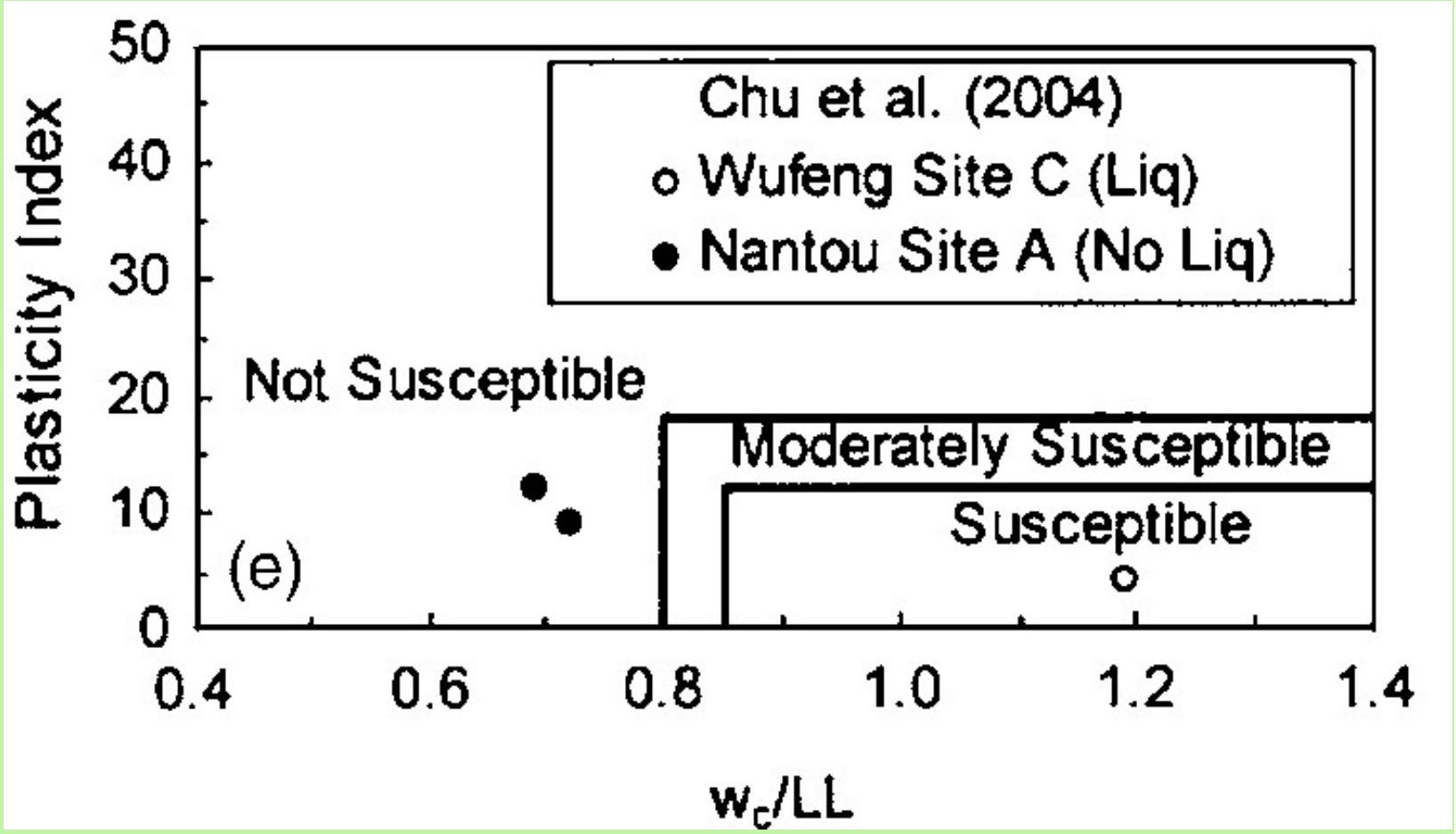
Been and Jefferies



Robertson and Wride



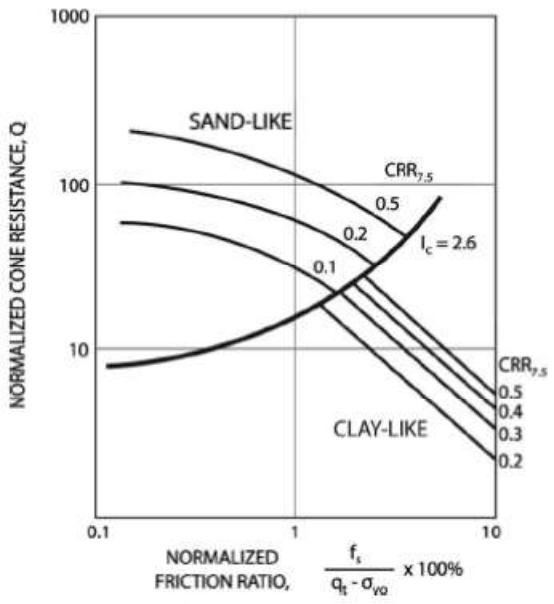
Liquefaction susceptibility criteria (Bray and Sancio, 2006)

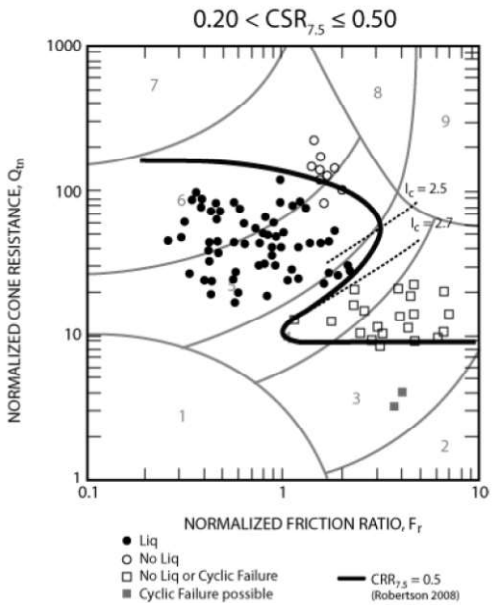


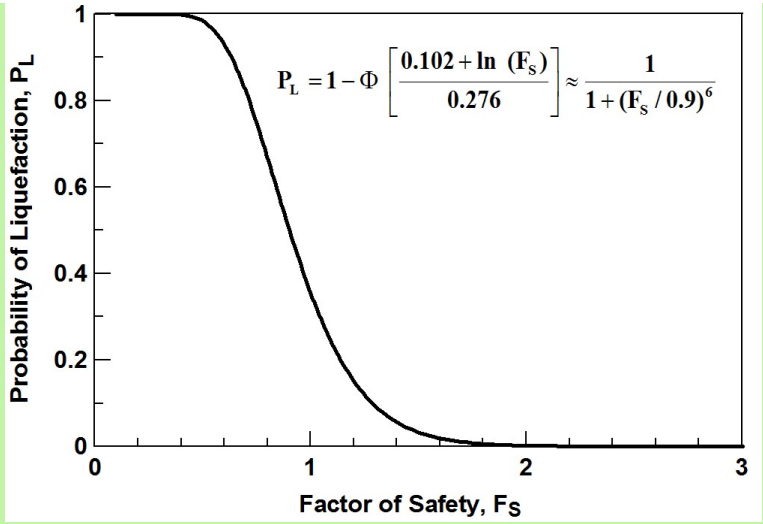
Cyclic Liquefaction and Softening Susceptibility of Soils – A Unified CPT-based Approach

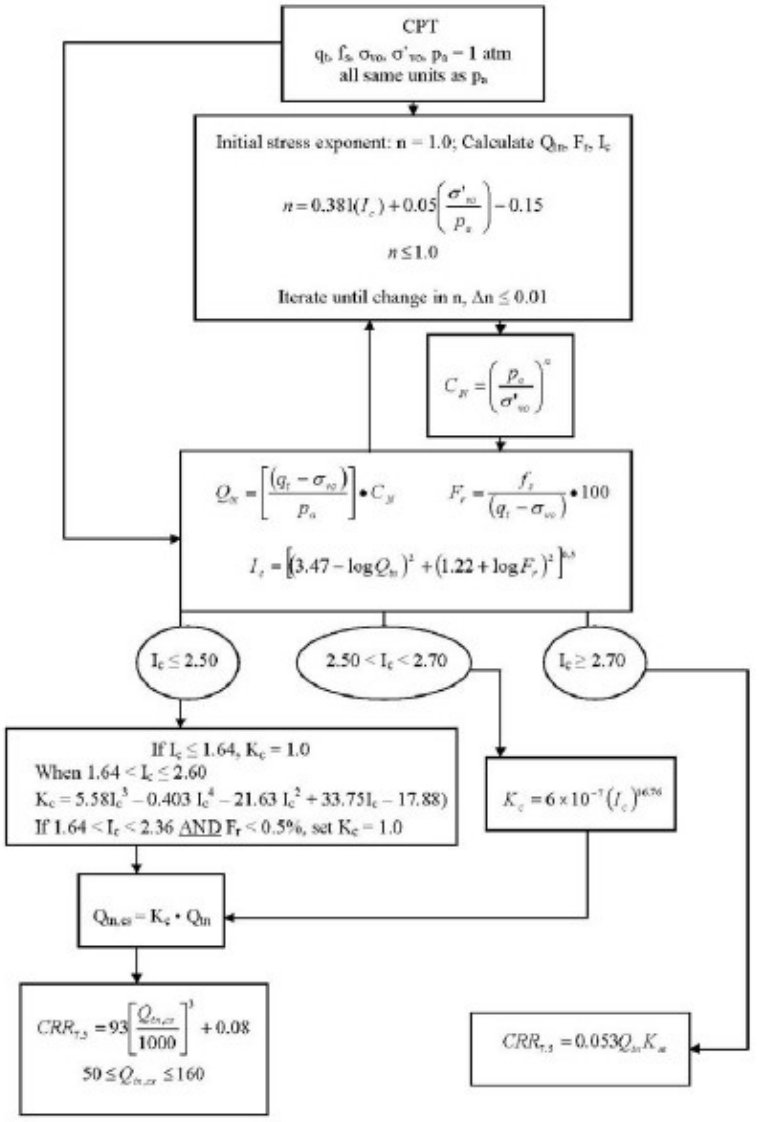
- Different approaches (cyclic triaxial test or cyclic simple shear test) have been suggested for assessing liquefaction or cyclic softening resistance of clay-like soils.
- The approach might not be the ideal approach for initial screening of possible hazards of cyclic liquefaction and cyclic softening.

Robertson (2009a, 2009b)





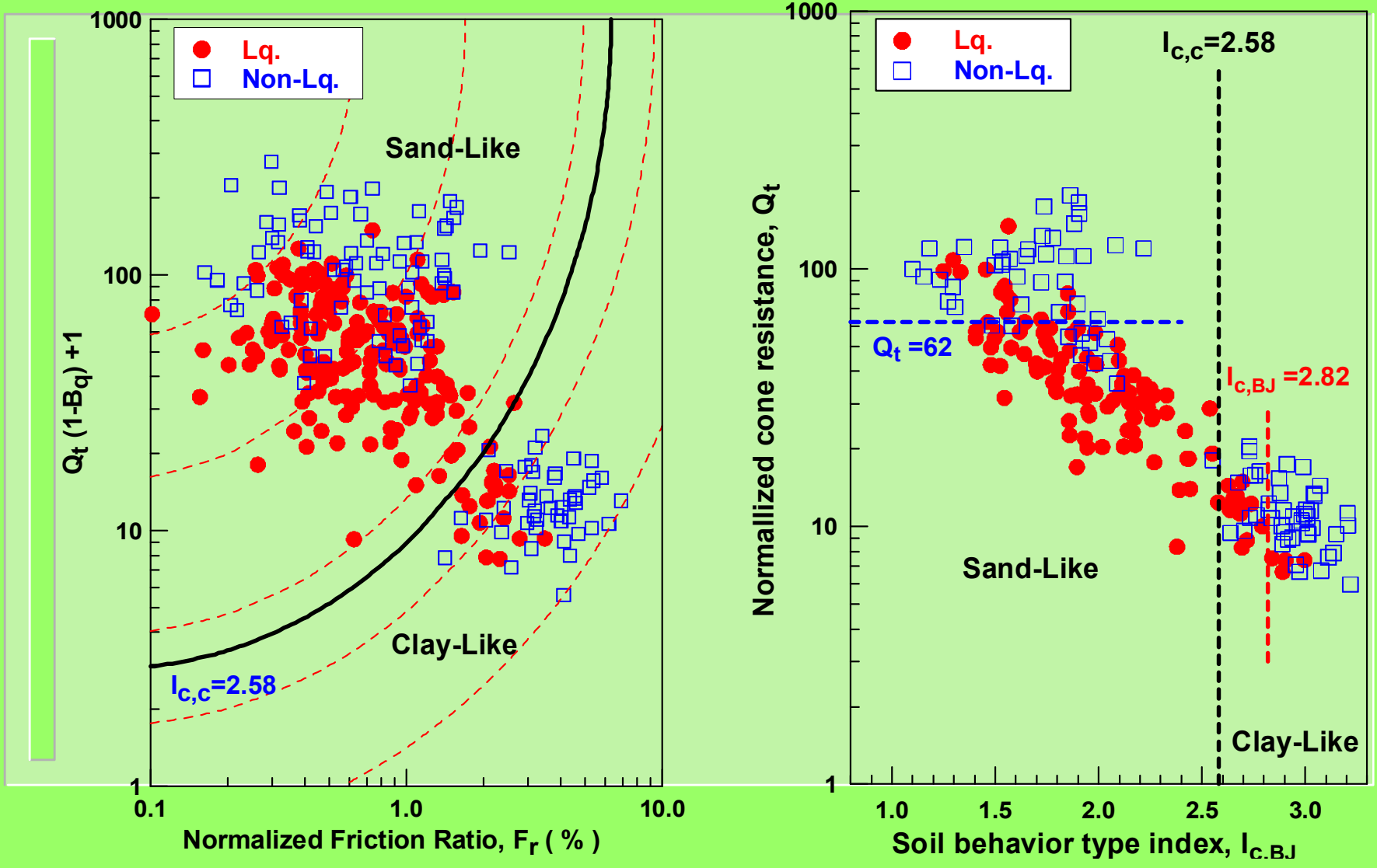




$$CRR = 0.833 \cdot \left(\frac{q_{c1N,cs}}{1000}\right) + 0.05 \qquad q_{c1N,cs} < 50$$

$$CRR = 93 \cdot \left(\frac{q_{c1N,cs}}{1000}\right)^3 + 0.08 \qquad 50 \le q_{c1N,cs} < 160$$

Distribution of liquefaction/no liquefaction



Juang et al. (2008) $CRR = 0.05 + \exp[A + B \times (q_{t1N}/100)^C]$

$$A = I_c \cdot (q_{t1N}/100) - 10.455$$

$$B = 0.669 \cdot I_c^3 - 5.55 \cdot I_c + 12.993$$

$$C = 0.284 - 0.0214 \cdot I_c^2$$

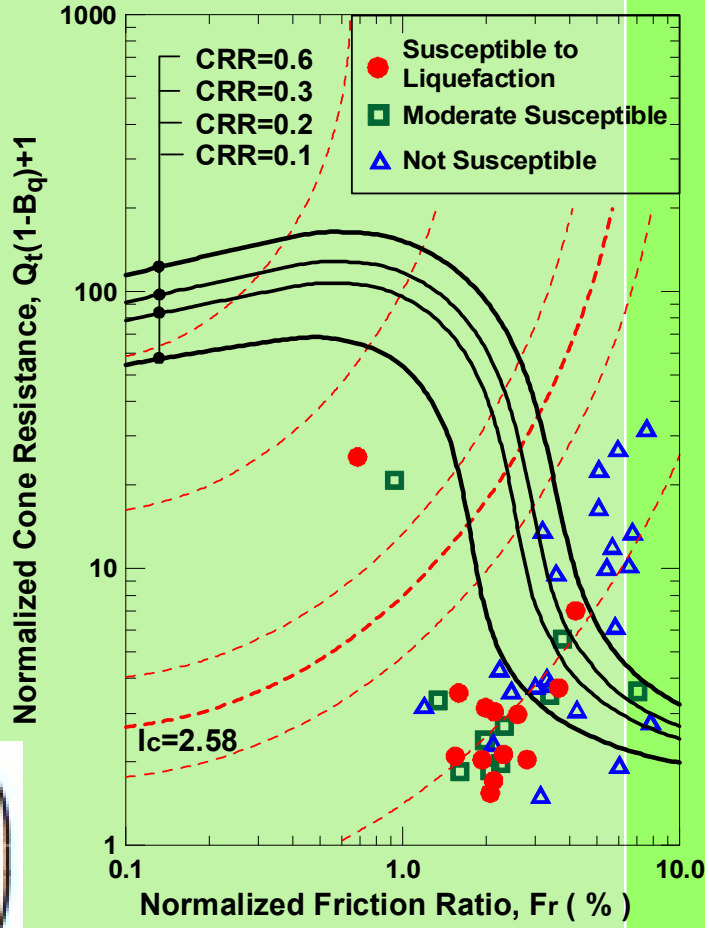
Ku and Juang (2012)

$$A = I_c \cdot (q_{t1N}/100) - 14.7$$

$$B = 0.909 \cdot I_c^3 - 7.47 \cdot I_c + 19.28$$

$$C = 0.059 + 0.015 \cdot I_c^2$$

$$P_L = \exp\left(-\exp\left[\frac{\{[\mathrm{CRR}(q^*_{t1N})/\mathrm{CSR}] - 0{\cdot}9214\} \times (3{\cdot}1379 - 0{\cdot}006197 q^*_{t1N})}{0{\cdot}005939 + 0{\cdot}009893 q^*_{t1N}}\right]\right)$$



Juang et al. (2012)

液化分析模式應用成效檢核

混淆矩陣(Confusion Matrix)(Oommen et al., 2010)

		Observed	
		Yes	No
Predicted	Yes	TP	FP
	No	FN	TN

整體準確性(Overall accuracy, OA)、
查準率(Precision, p)、查全率(Recall, r) 及F-score

整體準確性(OA) $$OA = \frac{TP + TN}{TP + TN + FP + FN} = \frac{T}{T + F}$$

混淆矩陣(Confusion Matrix)

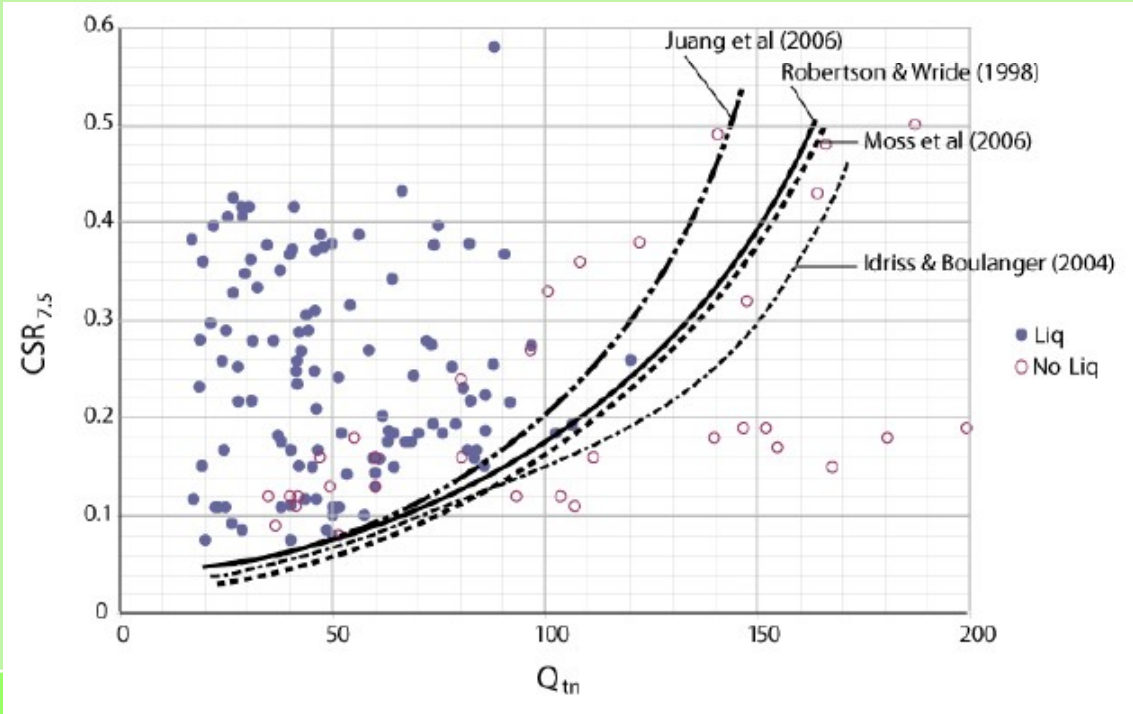
整體準確性(Overall accuracy)

$$\mathbf{OA} = \frac{\mathbf{TP}+\mathbf{TN}}{\mathbf{TP}+\mathbf{TN}+\mathbf{FP}+\mathbf{FN}} = \frac{\mathbf{T}}{\mathbf{T}+\mathbf{F}}$$

查準率(Precision) $p = \frac{TP}{TP+FP}$

查全率(Recall) $r = \frac{TP}{TP+FN}$

$$\mathbf{F}_{\beta} = \frac{(1+\beta^2)\mathbf{pr}}{\mathbf{r}+\mathbf{p}\beta^2}$$



Juang et al. case histories (FS=1.0)

Moss		Observed	
		Yes	No
Predicted	Yes	**190**	**0**
	No	**69**	**54**
Robertson		Observed	
		Yes	No
Predicted	Yes	**161**	**29**
	No	**28**	**97**
Boulanger and Idriss		Observed	
		Yes	No
Predicted	Yes	**186**	**4**
	No	**77**	**46**
Ku and Juang		Observed	
		Yes	No
Predicted	Yes	**184**	**6**
	No	**46**	**77**

定率式CPT液化評估法之應用成效
FS=1.0

Approach	OA	Liquefaction		
		Precision	Recall	F-score
Moss	0.780	0.734	1.000	0.846
Robertson	0.824	0.861	0.847	0.854
Ku and Juang	0.834	0.800	0.968	0.876
Boulanger and Idriss	0.741	0.707	0.979	0.821

Approach	Avg. F-score	Non-Liquefaction		
		Precision	Recall	F-score
Moss	0.728	1.000	0.439	0.610
Robertson	0.817	0.770	0.789	0.779
Ku and Juang	0.812	0.928	0.626	0.748
Boulanger and Idriss	0.676	0.920	0.374	0.532

Juang et al. case histories (P_L=0.5)

Moss		Observed	
		Yes	No
Predicted	Yes	**186**	**4**
	No	**64**	**59**
Robertson		Observed	
		Yes	No
Predicted	Yes	**158**	**32**
	No	**17**	**106**
Boulanger and Idriss		Observed	
		Yes	No
Predicted	Yes	**156**	**34**
	No	**66**	**57**
Ku and Juang		Observed	
		Yes	No
Predicted	Yes	**177**	**13**
	No	**30**	**93**

機率式CPT液化評估法之應用成效
P_L=0.5

Approach	OA	Liquefaction		
		Precision	Recall	F-score
Moss	0.783	0.744	0.979	0.845
Robertson	0.843	0.903	0.832	0.866
Ku and Juang	0.863	0.855	0.932	0.892
Boulanger and Idriss	0.681	0.703	0.821	0.757

Approach	Avg. F-score	Non-Liquefaction		
		Precision	Recall	F-score
Moss	0.740	0.937	0.480	0.634
Robertson	0.839	0.768	0.862	0.812
Ku and Juang	0.852	0.877	0.756	0.812
Boulanger and Idriss	0.645	0.626	0.463	0.533

結論與建議

- ✓ 電子式圓錐貫入試驗(CPT)快速、準確、可靠，可以取得近似連續之地層剖面試驗資料，非常適合應用於土壤地層之調查。
- ✓ **Robertson、Ku and Juang的CPT液化評估法應用成效略優於其他方法，可以考慮作為液化潛能分析之主要評估方式。**
- ✓ 地盤液化災害潛能評估時，在選定液化分評估方法後，建議採用對應之災害潛能分級準則。

Thanks for your attention

問題討論

- CPT相關資料(檔案型式)之應用
- CPT-based 液化分析方法之適用性
- 液化潛能與災害之相關性