Evaluation of SPT Based Approach for Liquefaction Analysis

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- Introduction
- Selected state of art methods
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SPT-N based Approach

Seed et al. (1984)

- Resistance:

$$CRR_{7.5} = f(FC, (N_1)_{60})$$

$$(N_1)_{60} = C_N \cdot N_{60} \quad , C_N = \sqrt{\frac{P_a}{\sigma_v'}} \quad (P_a = 100\text{kPa})$$

- Loading:

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

- FS=CRR/CSR

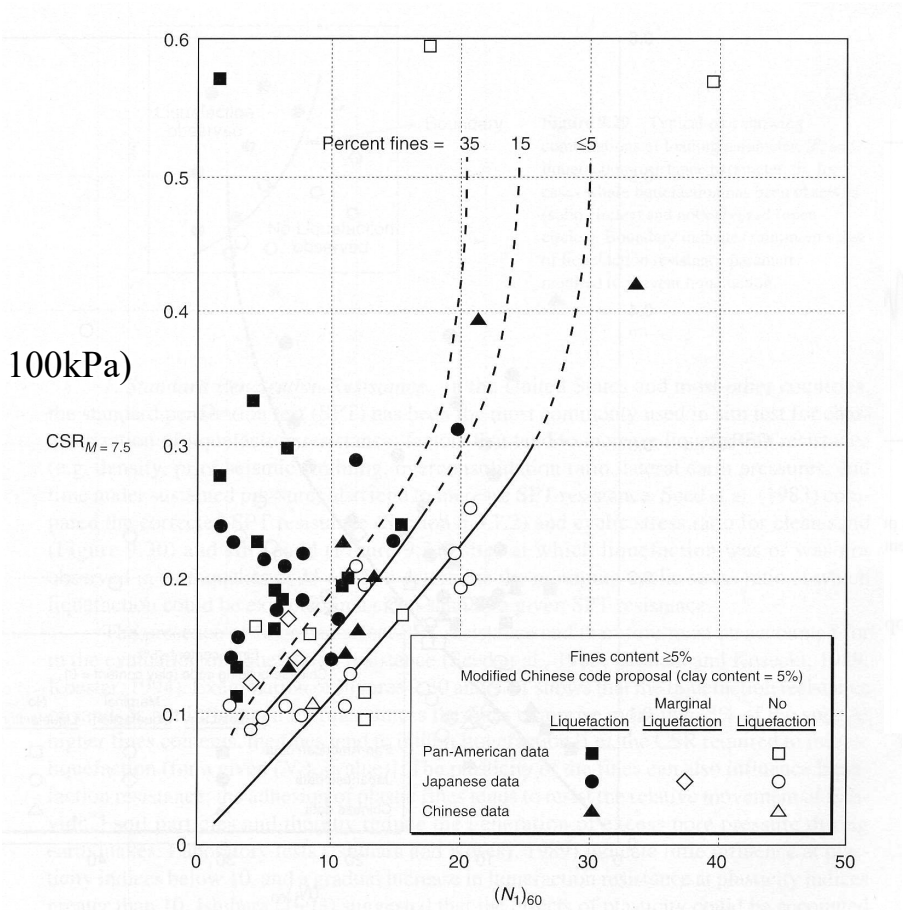
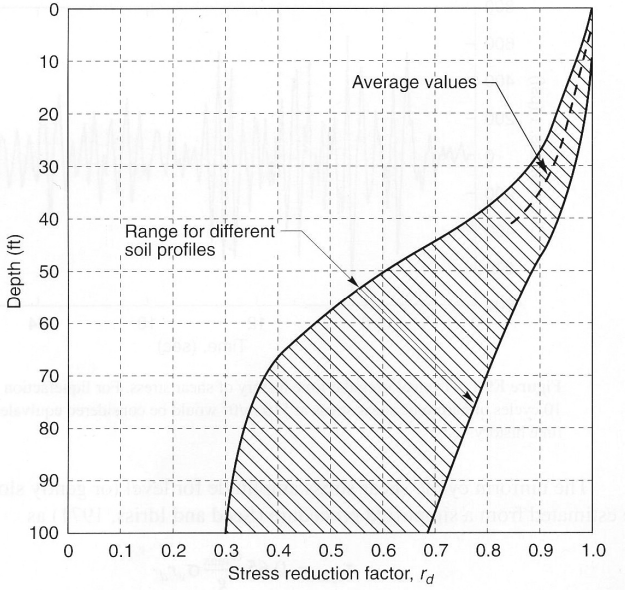


Figure 9.31 Relationship between cyclic stress ratios causing liquefaction and $(N_1)_{60}$ values for silty sands in $M = 7.5$ earthquakes. (After Seed et al. (1975). Influence of SPT procedures in soil liquefaction resistance evaluations, *Journal of Geotechnical Engineering*, Vol. 111, No. 12. Reprinted by permission of ASCE.)



Early Development and Comparison

Seed et al, 1984

1996 NCEER and 1998 NCEER-NSF workshop

Tokimatsu and Yoshimi, 1983

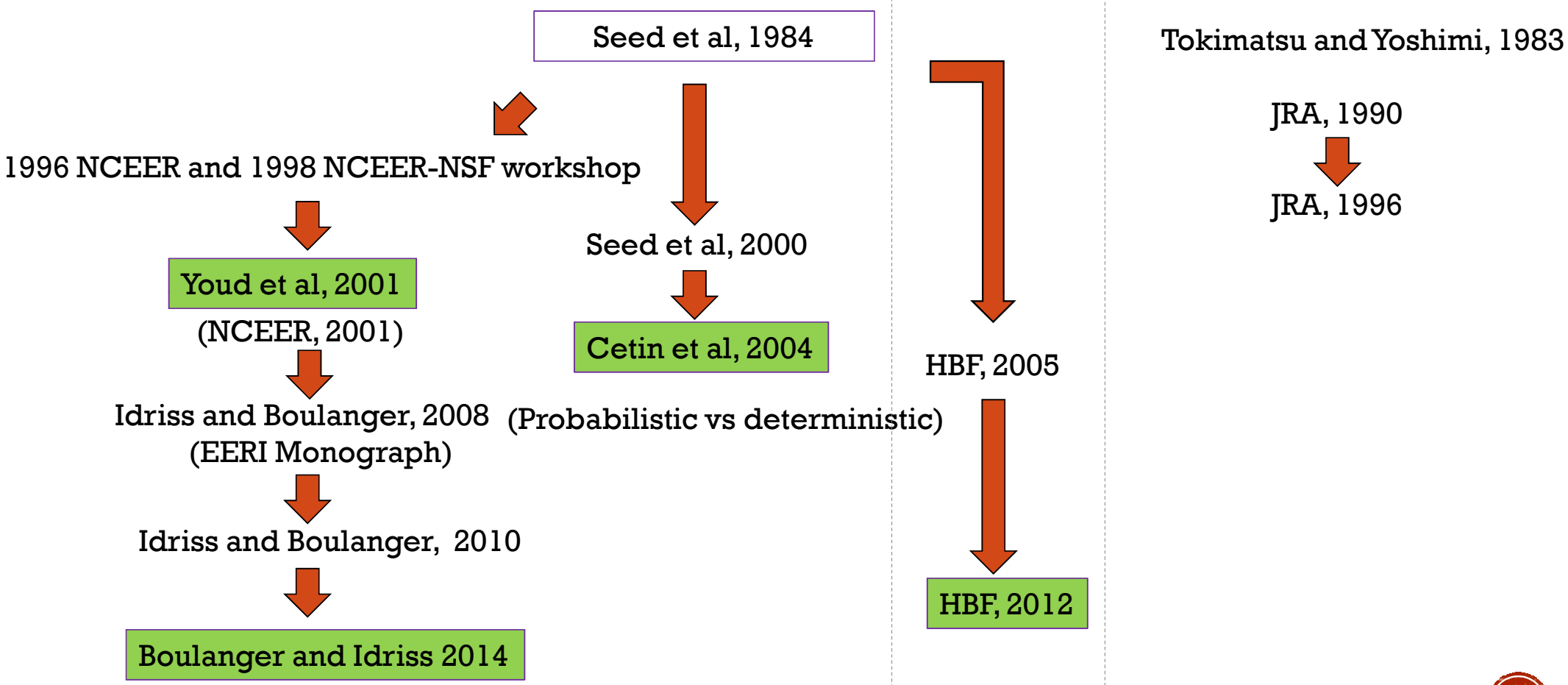
HBF, 2005

JRA, 1978 → JRA, 1990 → JRA, 1996

Success rate		Seed	NCEER	T-Y	JRA'96	JRA'90	HBF
Liquefied	$FC \leqq 10$	96%(143/149)	97%(145/149)	99%(147/149)	99%(147/149)	87%(130/149)	95%(142/149)
	$10 < FC \leqq 30$	88%(136/155)	92%(142/155)	90%(140/155)	97%(150/155)	81%(126/155)	98%(152/155)
	$FC > 30$	91%(63/69)	97%(67/69)	94%(65/69)	97%(67/69)	81%(56/69)	99%(68/69)
Non-liquefied	$FC \leqq 10$	59%(62/105)	57%(60/105)	50%(53/105)	43%(45/105)	61%(64/105)	64%(67/105)
	$10 < FC \leqq 30$	88%(130/147)	86%(126/147)	77%(113/147)	67%(99/147)	79%(116/147)	80%(117/147)
	$FC > 30$	91%(40/44)	82%(36/44)	75%(33/44)	75%(33/44)	64%(28/44)	75%(33/44)
Liquefied		92%(342/373)	95%(354/373)	94%(352/373)	98%(364/373)	84%(312/373)	97%(362/373)
Non-liquefied		78%(232/296)	75%(222/296)	67%(199/296)	60%(177/296)	70%(208/296)	73%(217/296)
Total		86%(574/669)	86%(576/669)	82%(551/669)	81%(541/669)	78%(520/669)	87%(579/669)

Hwang et al, 2005

Selected State of Art Approaches



SPT-N based Approach – Youd et al. (2001)

細粒料含量 FC

地震規模 M_w

地表最大加速度 a_{max}

有效覆土應力 σ'_{vo}

SPT-N值 N_m

應力折減因子

$$r_d = \frac{(1.0 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.0 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^{2})}$$

SPT-N值有效覆土應力修正

$$C_N = \frac{2.2}{1.2 + \sigma'_{v0}/p_a} \quad (P_a = 100\text{kPa}),\ C_N \le 1.7$$

$$(N_1)_{60} = C_N \cdot N_{60}$$

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d$$

SPT-N值細粒料含量修正

$$(N_1)_{60CS} = \alpha + \beta (N_1)_{60}$$

α		β	
$\alpha = 0$	for FC ≤ 5%	$\beta = 0$	for FC ≤ 5%
$\alpha = \exp[1.76 - (190/FC^2)]$	for 5%<FC<35%	$\beta = [0.99 + (FC^{1.5}/1000)]$	for 5%<FC<35%
$\alpha = 5.0$	for FC ≥ 35%	$\beta = 1.2$	for FC ≥ 35%

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60CS}} + \frac{(N_1)_{60CS}}{135} + \frac{50}{[10 \cdot (N_1)_{60CS} + 45]^2} - \frac{1}{200}$$

規模修正因子 (Idriss)

$$MSF = 10^{2.24} / M_w^{2.56}$$

覆土壓力修正

$$K_\sigma = (\sigma'_{v0}/P_a)^{(f-1)}$$

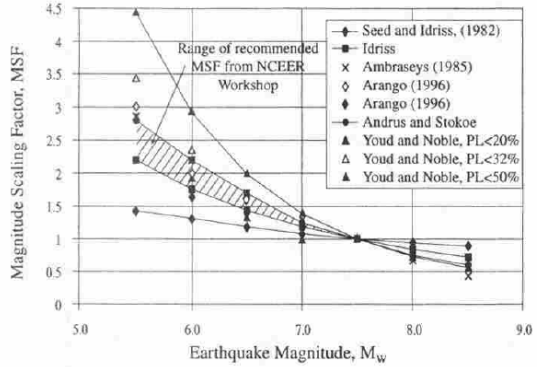
$D_r = 40\% \sim 60\%$, f=0.7~0.8

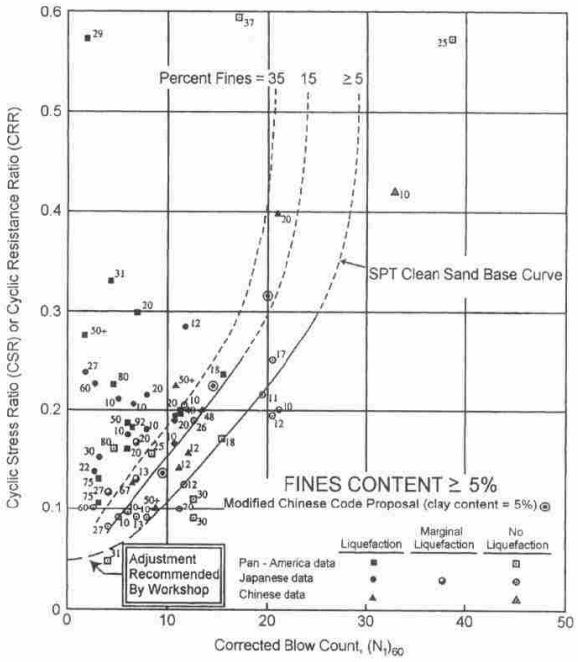
$D_r = 60\% \sim 80\%$, f=0.6~0.7

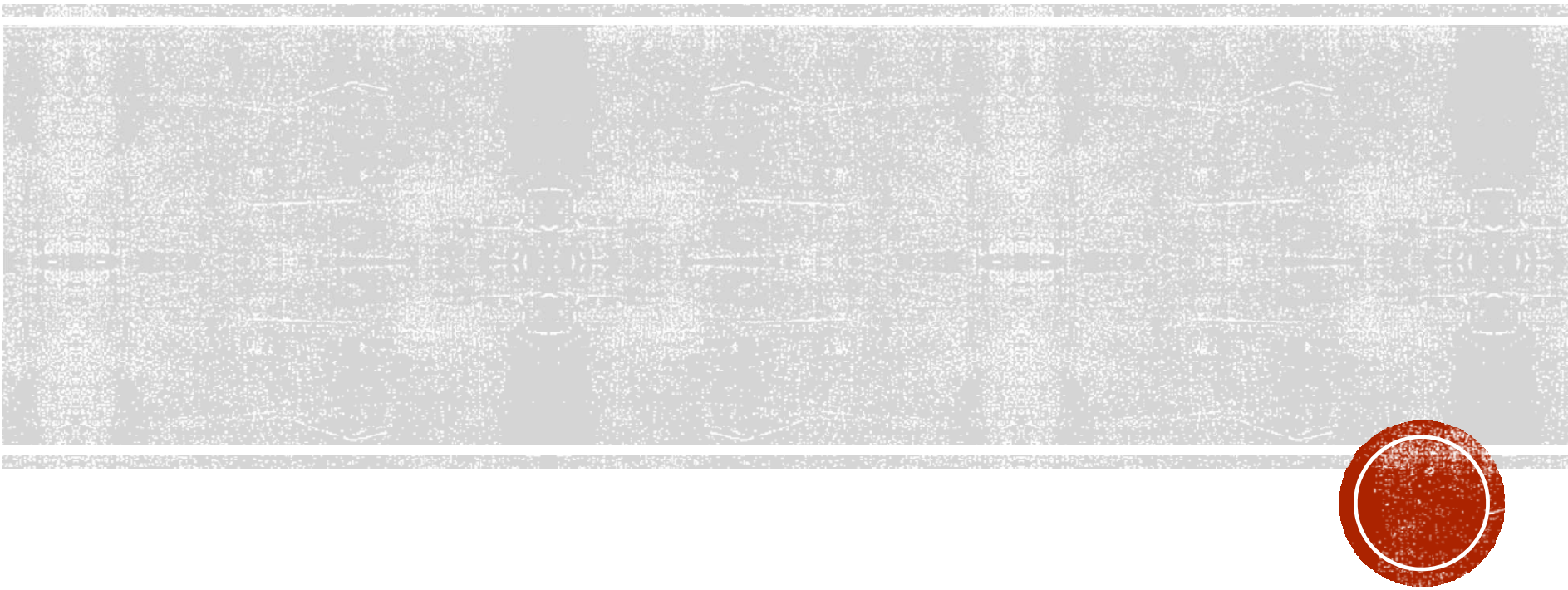
反覆抗液化強度比

$$CRR = CRR_{7.5} \cdot MSF \cdot K_\sigma$$

$$FS = \frac{CRR}{CSR}$$







SPT-N based Approach – HBF(2012)

細粒料含量 FC

地震規模 M_w

地表最大加速度 a_{max}

有效覆土應力 σ'_{v0}

SPT-N值 N_m

應力折減因子

$r_d = 1 - 0.01z$ for $z(m) \le 10$

$r_d = 1.2 - 0.03z$ for $10 \le z(m) \le 20$

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d$$

SPT-N值有效覆土應力修正

$$C_N = \frac{1}{\sqrt{\sigma'_{v0}}} \quad (\sigma'_{v0} : kg/cm^2)$$

$$(N_1)_{60} = C_N \times N \times \frac{E_m}{E_{60}}$$

SPT-N值細粒料含量修正

$$(N_1)_{60,CS} = K_s \times (N_1)_{60}$$

$K_s = 1.0$ for $FC(\%) \le 10$

$K_s = 1 + 0.07 \times \sqrt{FC - 10}$ for $FC(\%) > 10$

$$CRR_{7.5} = A + \frac{B \times (N_1)_{60,CS}}{1 - (N_1)_{60,CS}/C}$$

$A = CRR_{min} = 0.08$

$B =$ increasing slope of $(N_1)_{60,CS} = 0.0035$

$C =$ upper bound of $(N_1)_{60,CS} = 39$

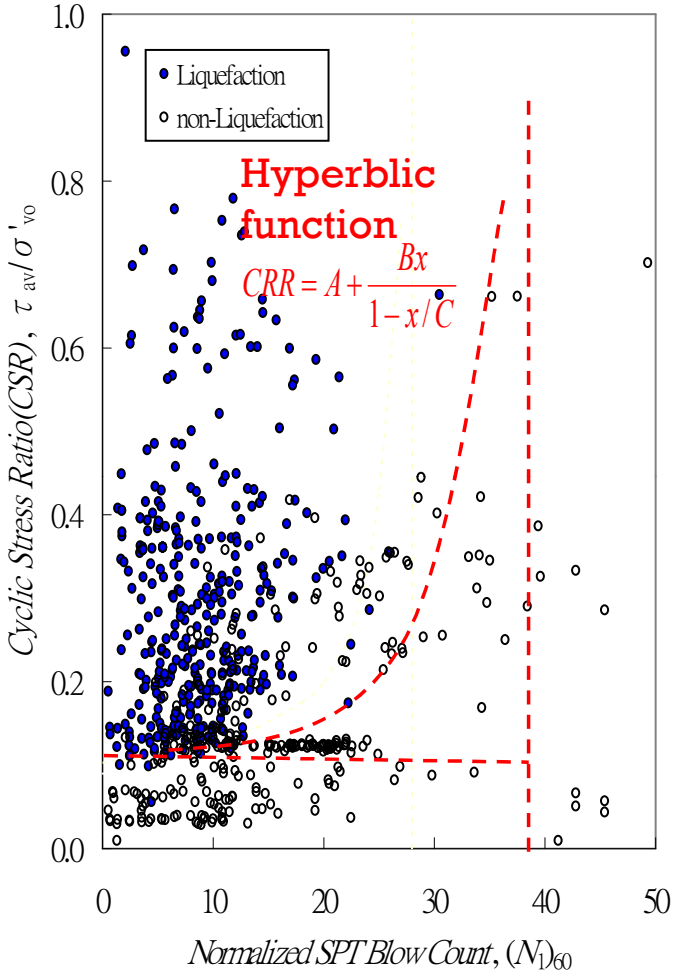
規模修正因子

$MSF = (M_w / 7.5)^{-3.3}$

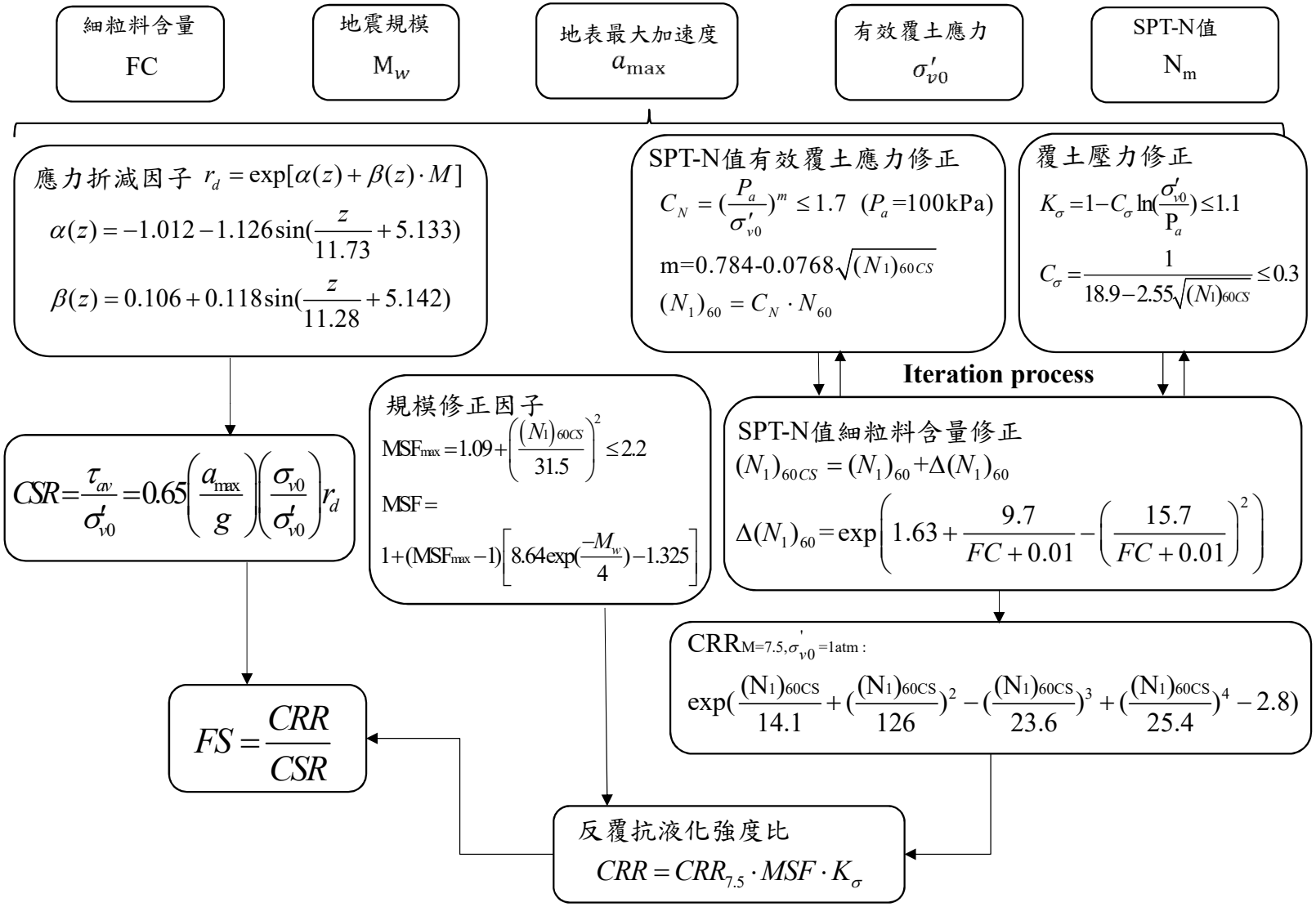
反覆抗液化強度比

$CRR = CRR_{7.5} \cdot MSF$

$$FS = \frac{CRR}{CSR}$$

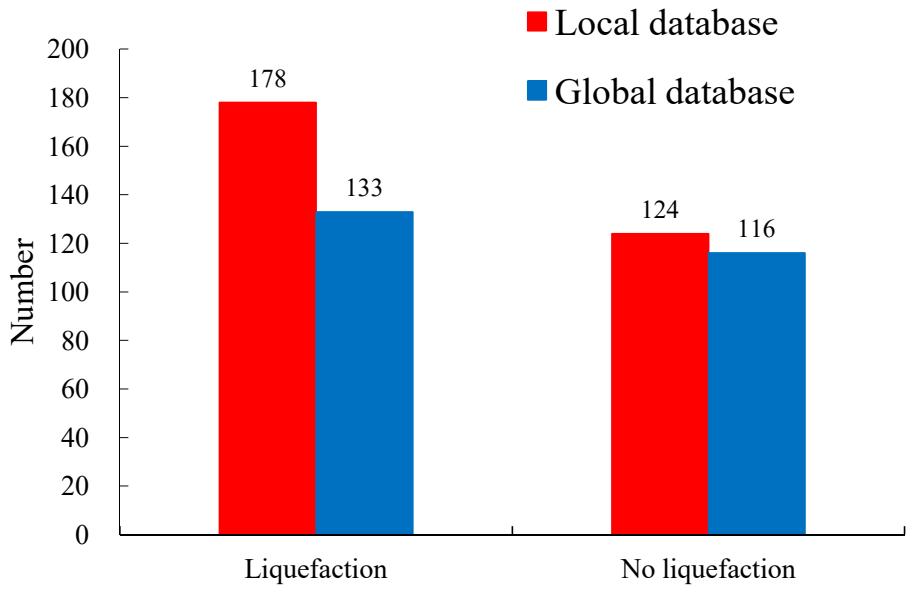


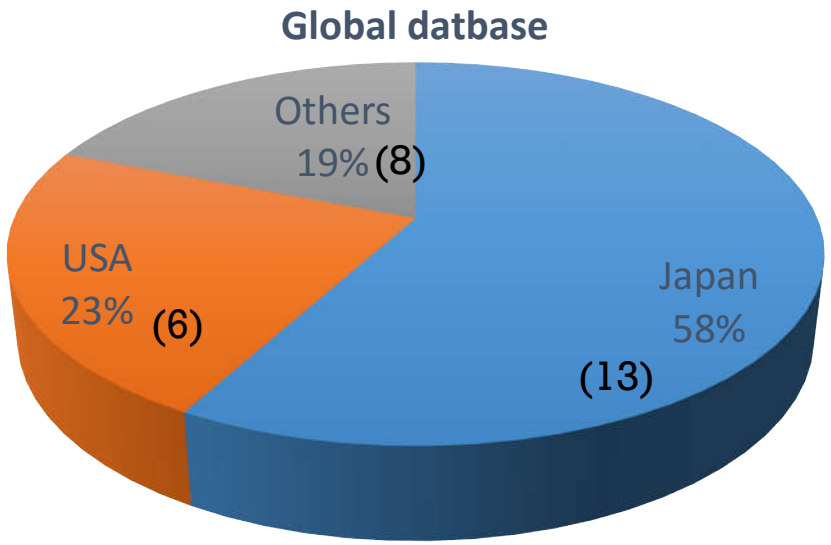
SPT-N based Approach – B & I (2014)



Database

- Local database-921 Chi-Chi EQ
  - Yang (2001) Ph. D. thesis (supervised by Prof. Hwang)
- Global database
  - Idriss and Boulanger (2010) and Boulanger and Idriss (2014)



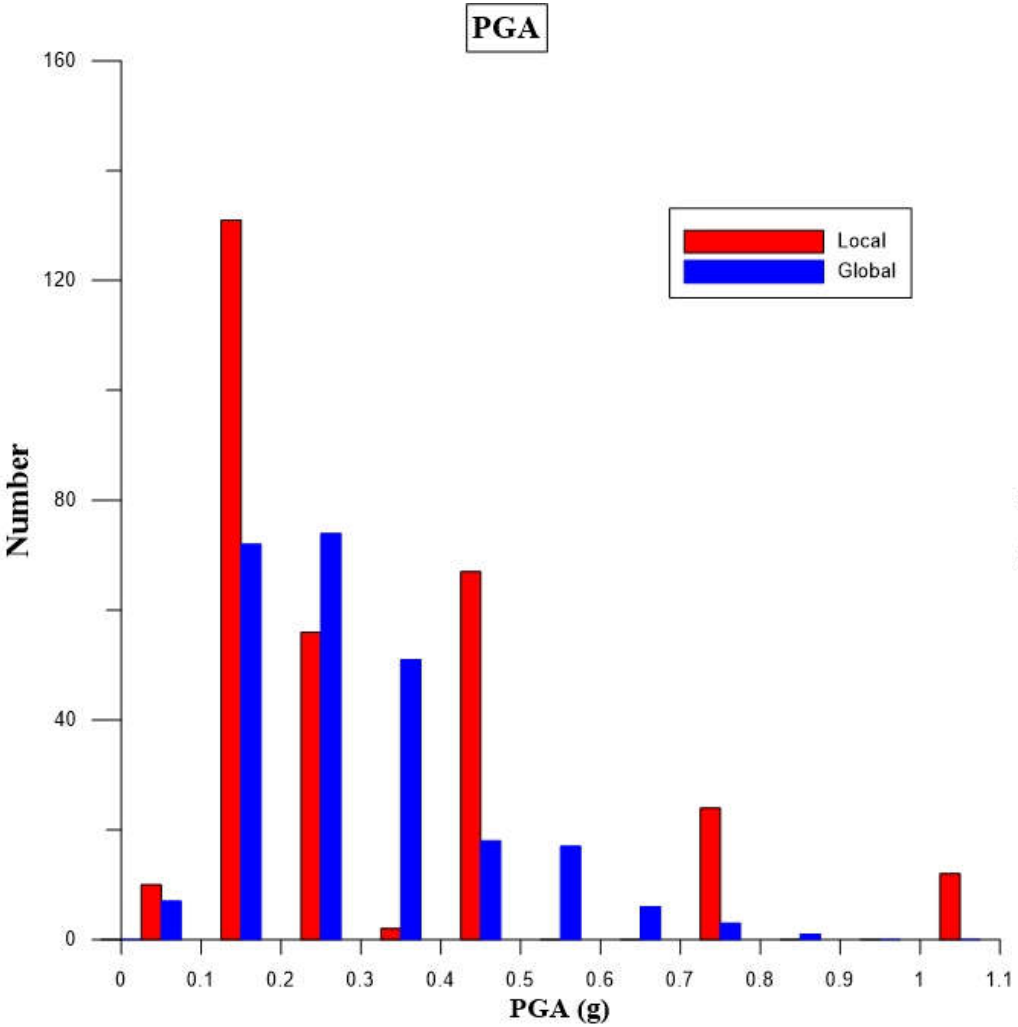


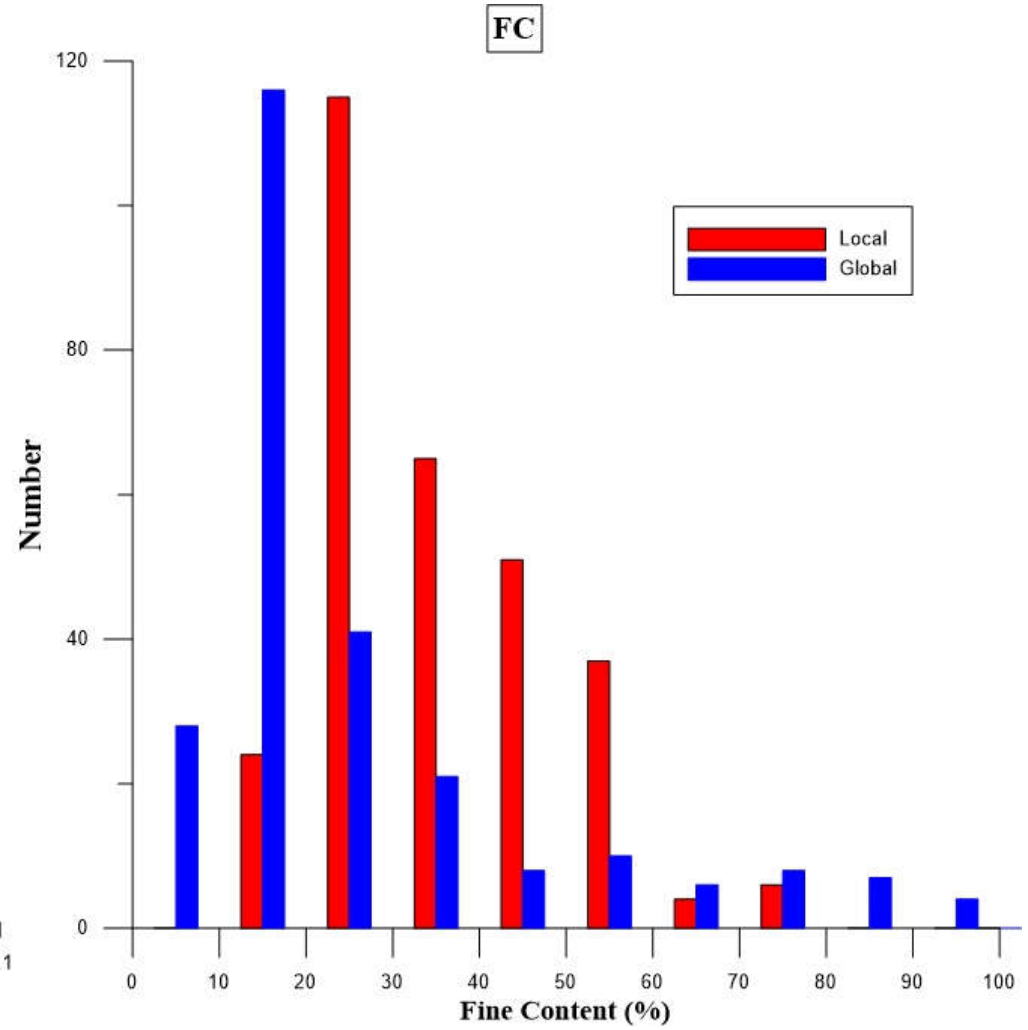
Information in Database

Earthquake & site	M	a_{max} (g)	Liq ?	Avg depth (m)	Depth GWT (m)	σ_v (kPa)	σ'_v (kPa)	Avg N_m	$(N_1)_{60}$
1994 M=8.1 Tohnankai earthquake - Dec 7									
Komei	8.1	0.200	Yes	5.2	2.1	98	68	5.9	8.2
Ienaga	8.1	0.200	Yes	4.3	2.4	80	61	2.3	3.4
Meiko	8.1	0.200	Yes	3.7	2.1	69	39	1.0	1.7
1948 M=7.3 Fukui earthquake - June 28									
Shonenji Temple	7.0	0.400	Yes	4.0	1.2	75	48	8.0	11.8
Takaya45	7.0	0.350	Yes	7.5	3.7	141	104	17.3	21.1

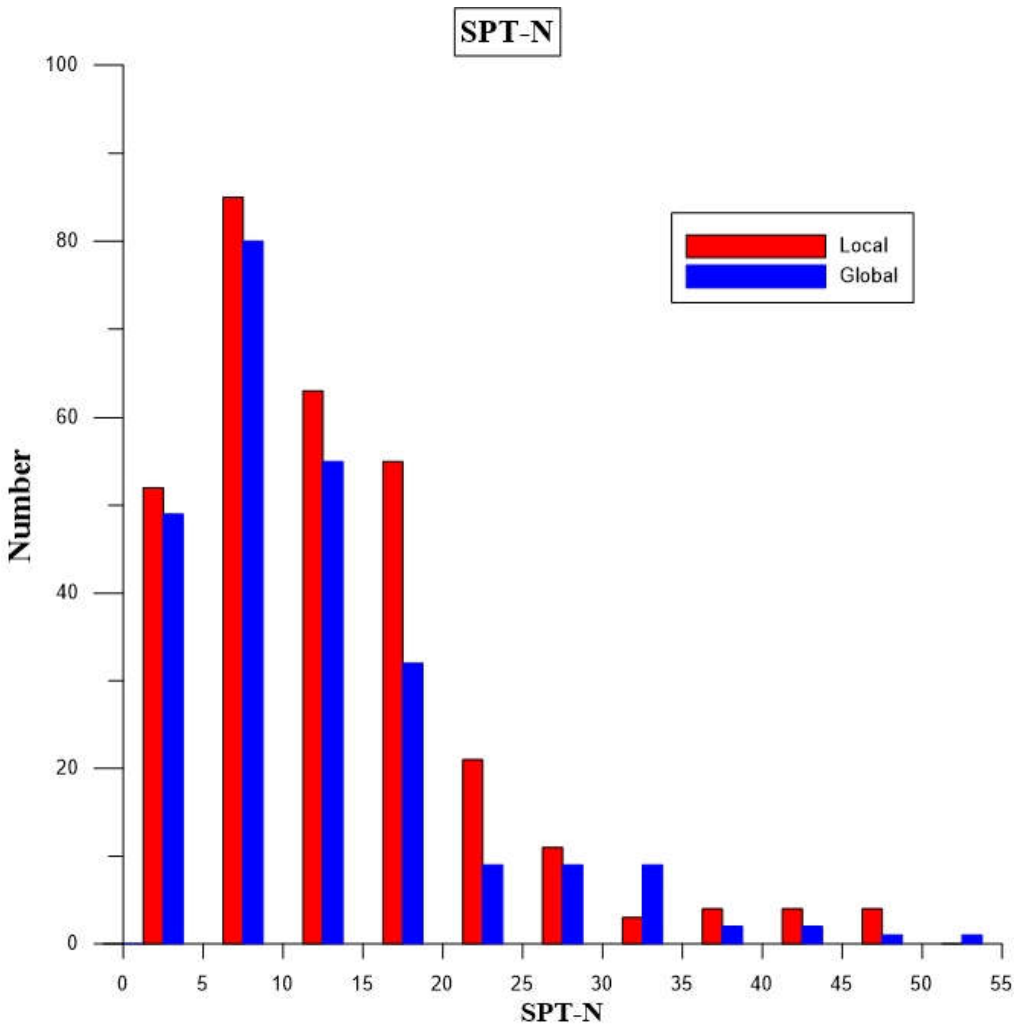
C_B	C_E	C_N	C_R	C_S	FC (%)	$(N_1)_{60cs}$	r_d	K_σ	MSF	CSR	CSR for M=7.5, σ'_v =1	Primary source of data
1	1.17	1.25	0.95	1	10	9.3	0.98	1.04	0.85	0.182	0.207	Kishida(1969), Seed et al. (1984), Cetin et al(2000)
1	1.17	1.32	0.95	1	30	8.7	0.99	1.07	0.85	0.144	0.159	Kishida(1969), Seed et al. (1984), Cetin et al(2000)
1	1.17	1.70	0.85	1	27	6.9	0.99	1.08	0.85	0.225	0.245	Kishida(1969), Seed et al. (1984), Cetin et al(2000)
1	1.17	1.48	0.85	1	0	11.8	0.96	1.07	1.14	0.390	0.318	Kishida(1969), Seed et al. (1984), Cetin et al(2000)
1	1.30	0.99	0.95	1	4	21.1	0.90	0.99	1.14	0.283	0.251	Kishida(1969), Seed et al. (1984), Cetin et al(2000)

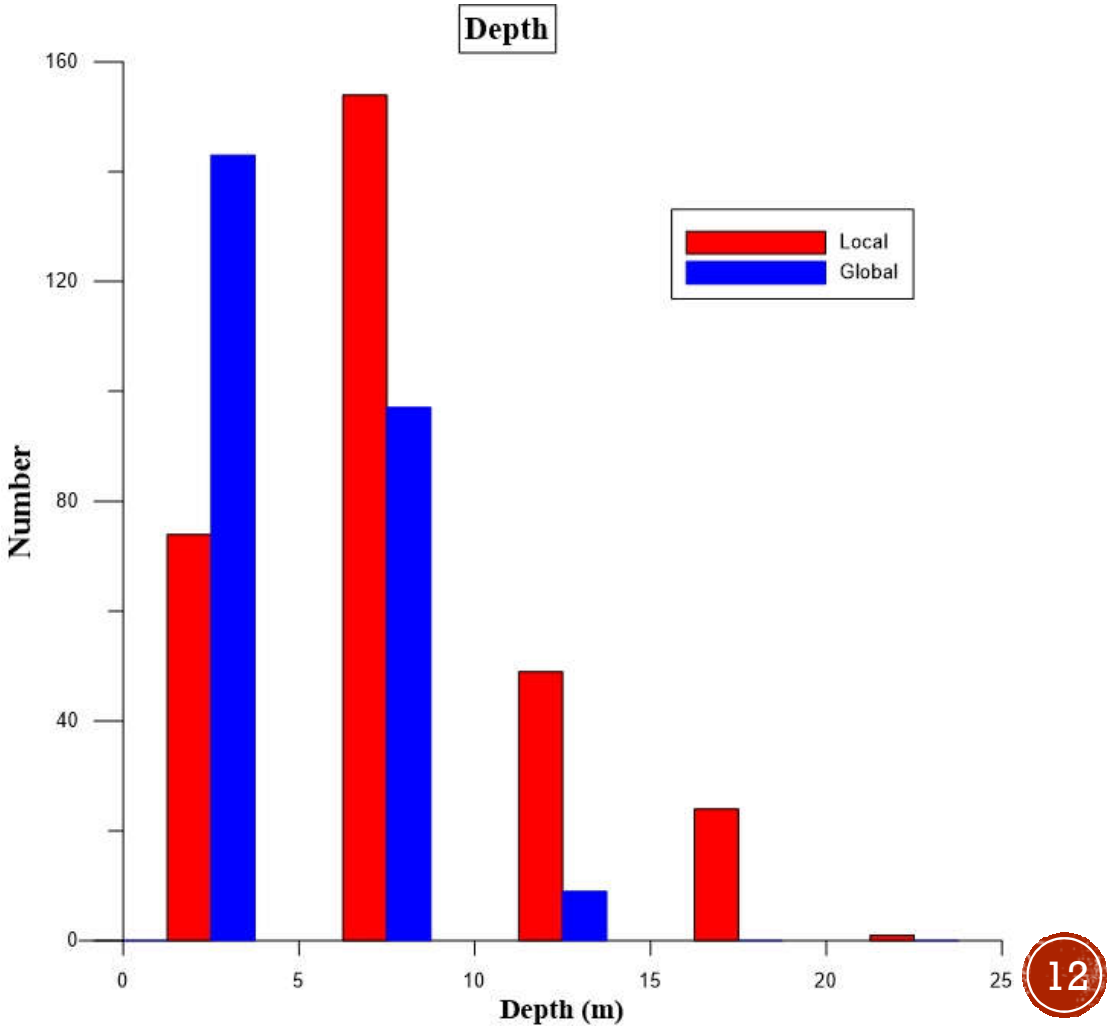
Comparison of Database (1/3)



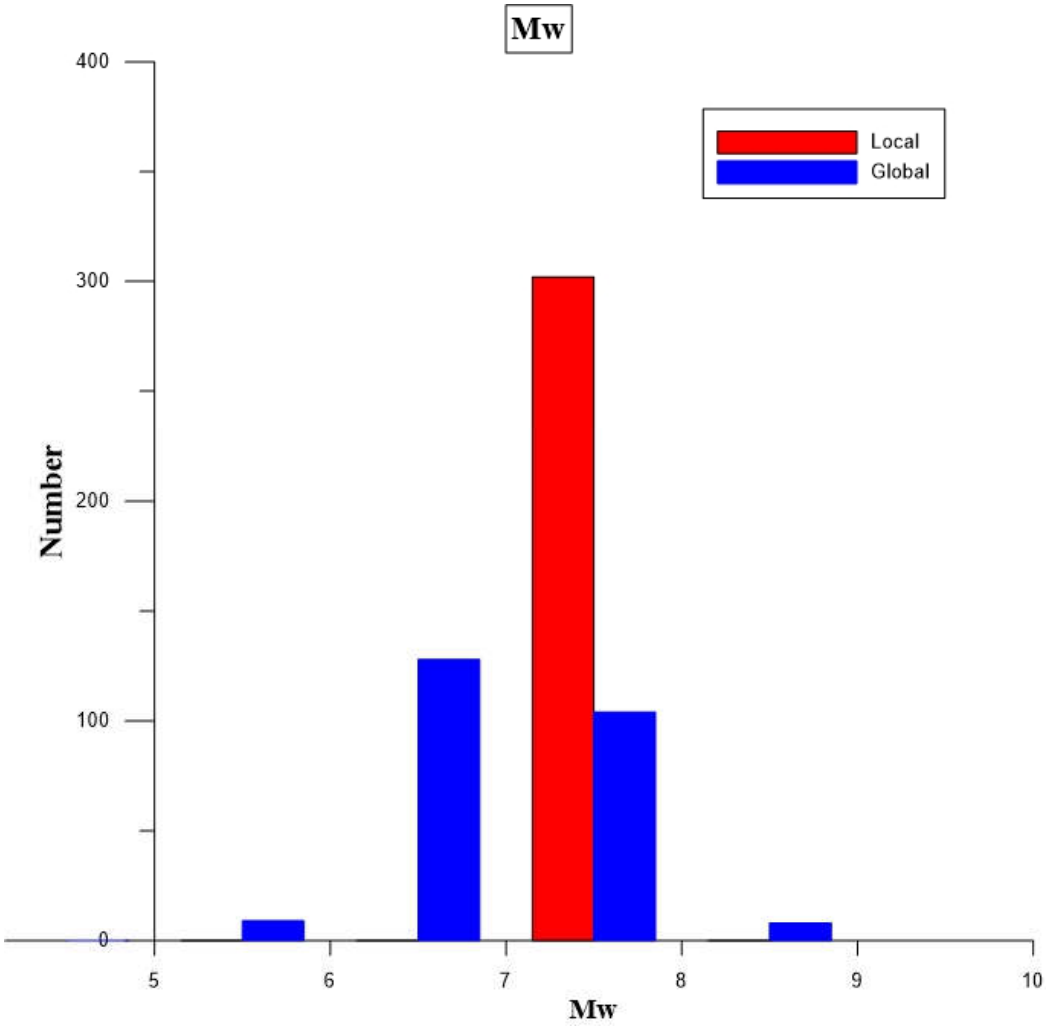


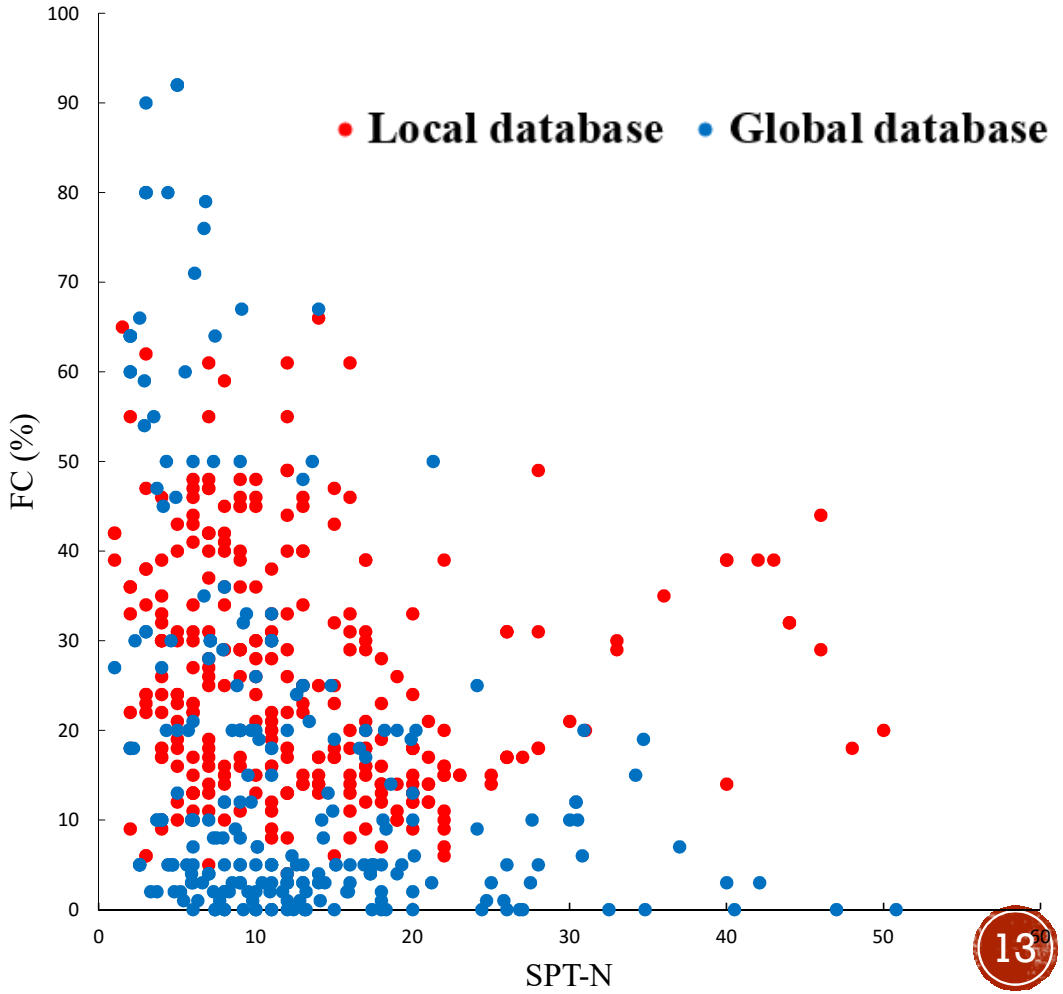
Comparison of Database (2/3)





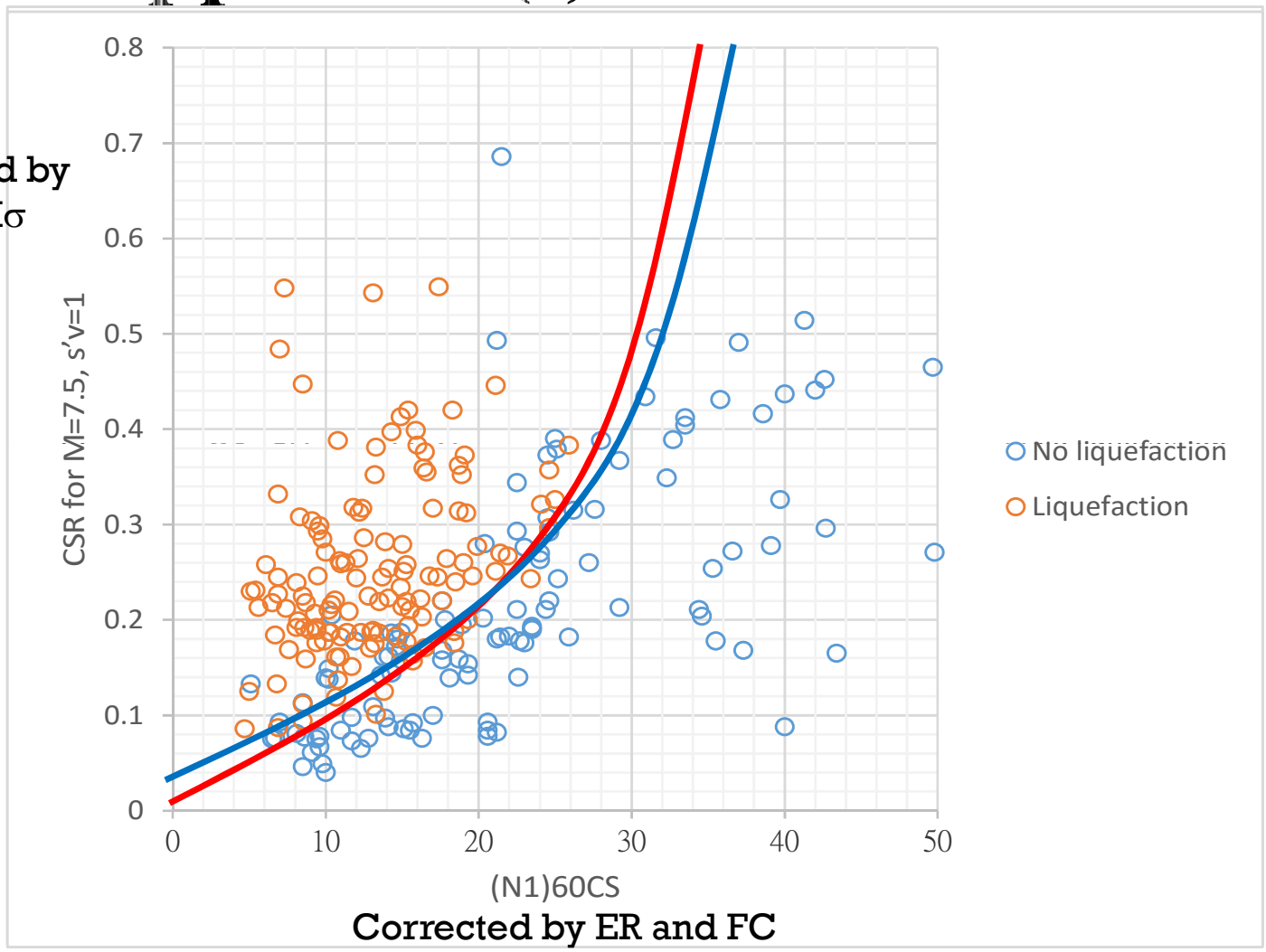
Comparison of Database (3/3)





Evaluation Approach (I)

Corrected by MSF, Kσ



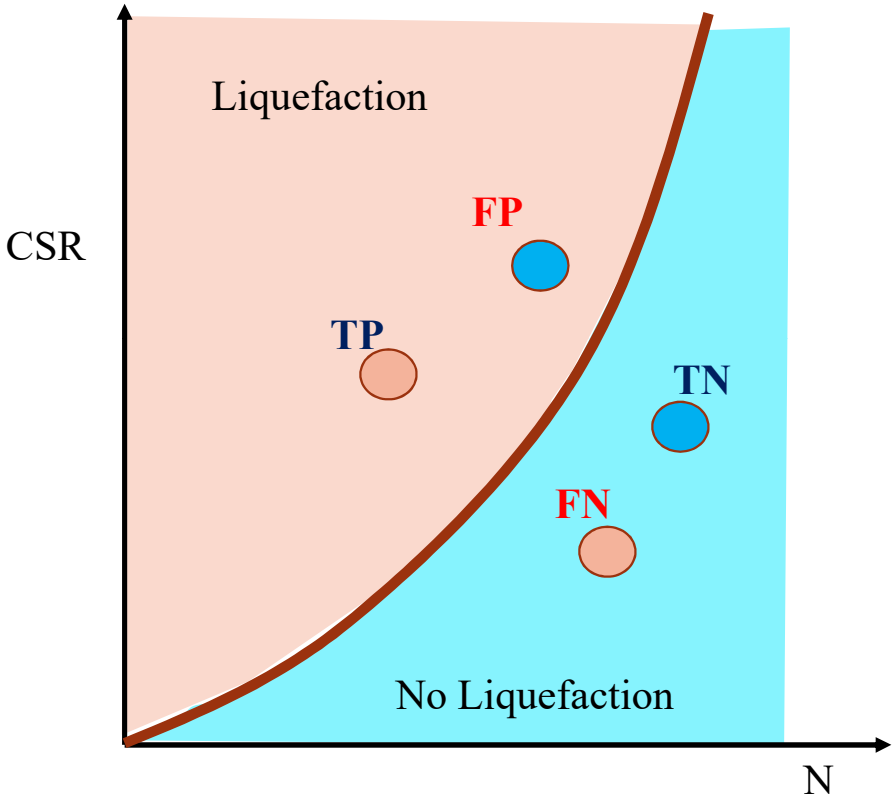
Corrected by ER and FC

Evaluation Approach (II)

- Overall performance
  1. Accuracy of prediction (liquefaction vs no liquefaction)
  2. 至少安全係數誤差指標 Fm (Hwang et al., 2005)
  3. Residual analysis

Accuracy of Prediction

		Observed	
		Yes	No
Predicted	Yes	TP	FP
	No	FN	TN



整體準確性(Overall accuracy, OA)

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

至少安全係數誤差指標 Fm

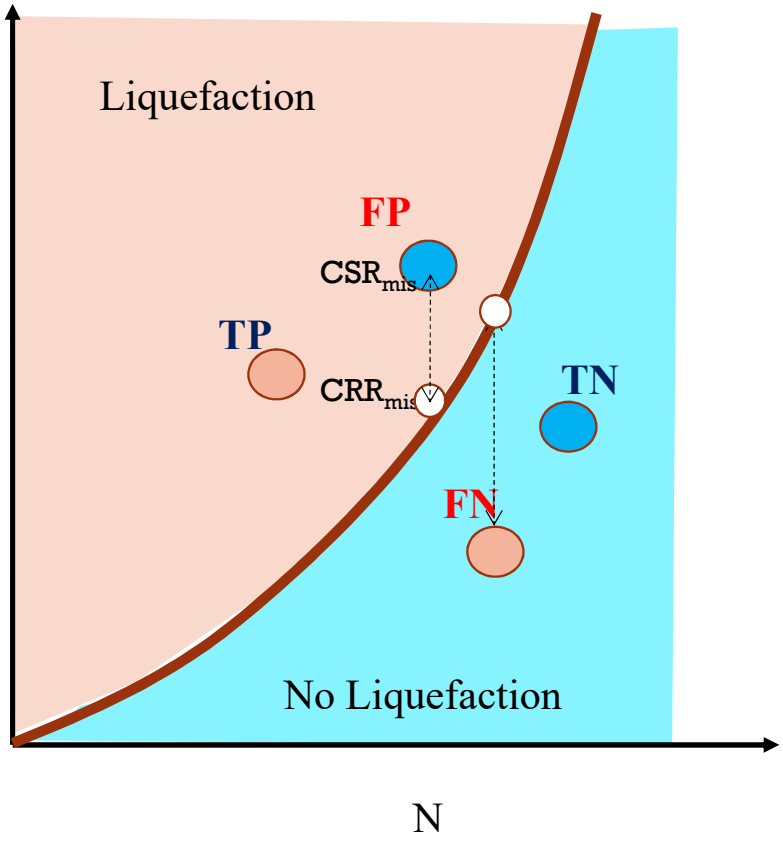
$$F_m = \sqrt{\frac{\sum_{i=1}^{n_{mis}} [(F_{L\,mis})_i - 1.0]^2}{n_{mis} - 1}} = \sqrt{\frac{\sum_{i=1}^{n_{mis}} [\frac{(CRR_{mis})_i}{(CSR_{mis})_i} - 1.0]^2}{n_{mis} - 1}}$$

其中：F_{Lmis} ：誤判案例之預估安全係數值

n_{mis} ：誤判案例之個數

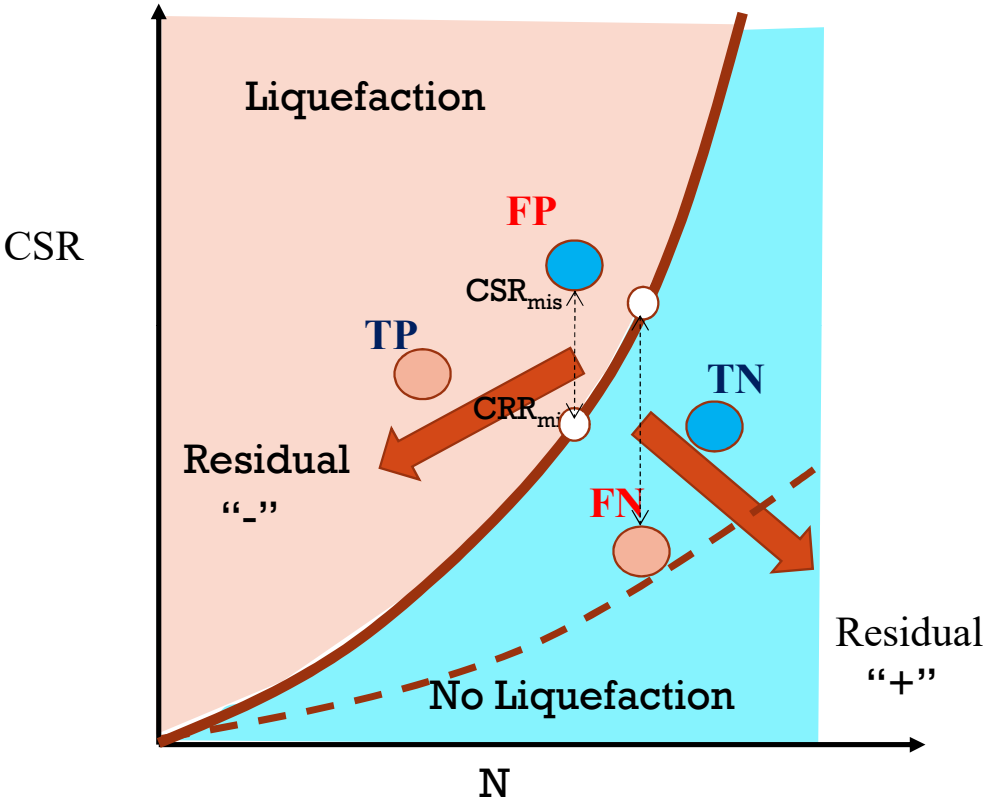
CRR_{mis} ：誤判案例之預估 CRR

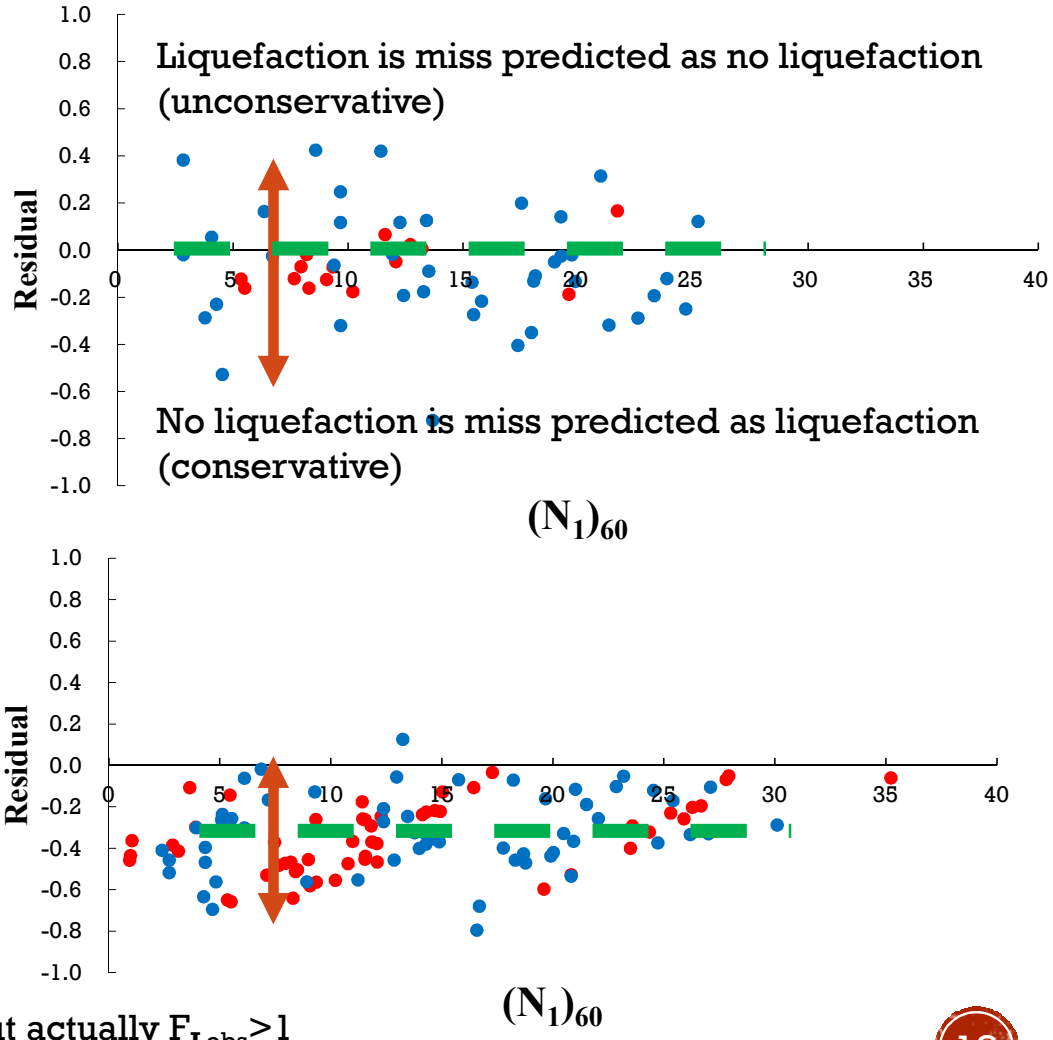
CSR_{mis} ：誤判案例之 CSR **(Hwang et al., 2005)**



Residual Analysis

$$Residual = F_{Lmis} - 1 = (CRR_{mis} - CSR_{mis})/CSR_{mis}$$





Take FP (miss prediction) for example: miss predicted $F_{Lpred} < 1$ but actually $F_{Lobs} > 1$
Therefore, residual is negative

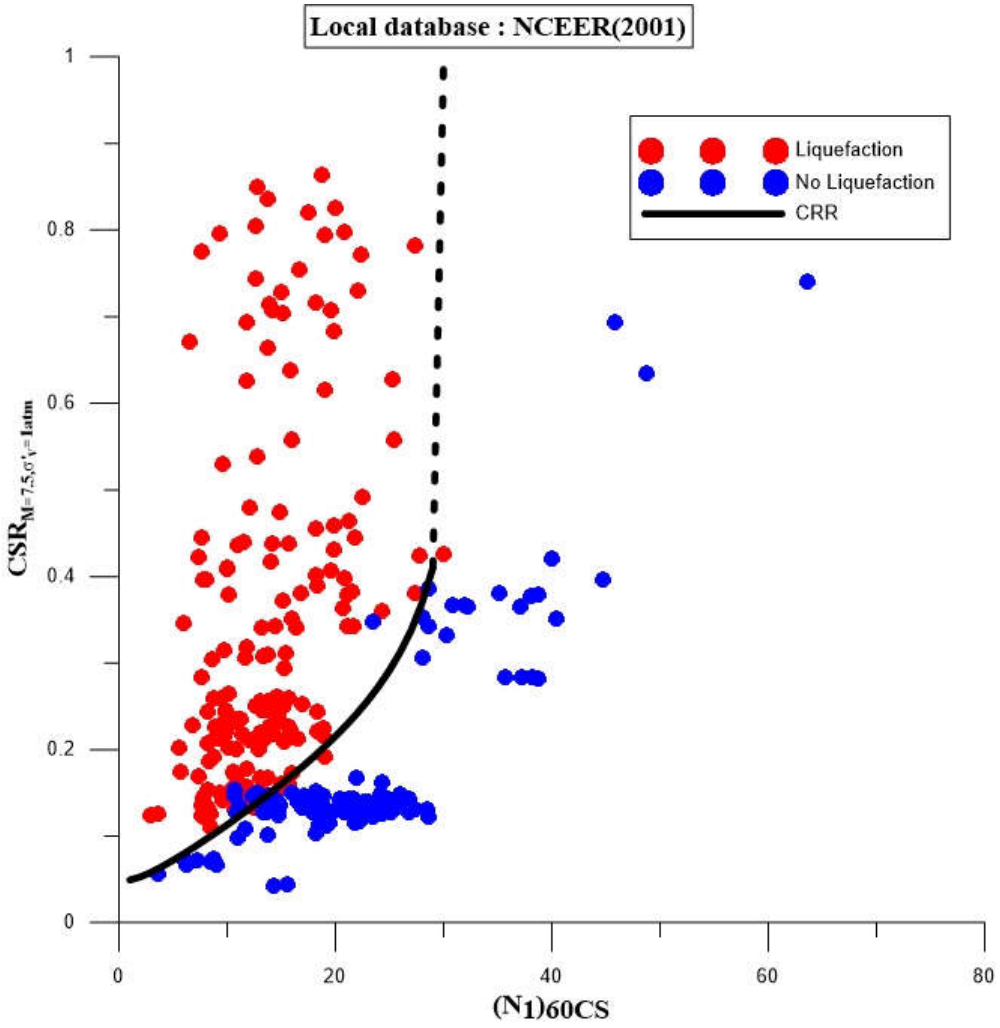
Evaluation Result of Local Database

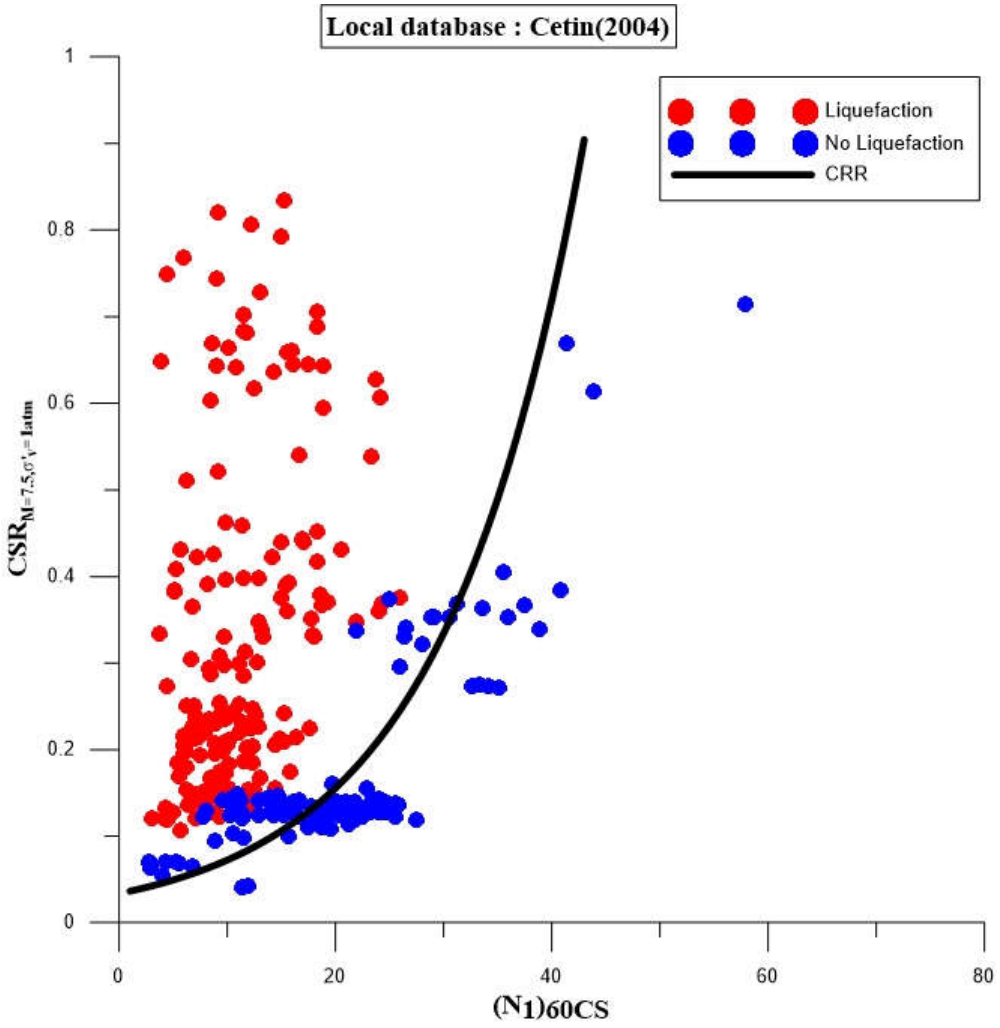
Local database			Liquefied Cases :178				No Liquefied Cases :124	
	NCEER(2001)		Cetin(2004)		HBF (2012)		Boulanger and Idriss (2014)	
	正判案例	誤判案例	正判案例	誤判案例	正判案例	誤判案例	正判案例	誤判案例
液化案例	172	6	178		0	173	5	168
非液化案例	117	7	70		54	113	11	115

	NCEER(2001)		Cetin(2004)		HBF (2012)		Boulanger and Idriss (2014)	
	正判率	誤判率	正判率	誤判率	正判率	誤判率	正判率	誤判率
液化案例	96.63%	3.37%	100.00%	0.00%	97.19%	2.81%	94.38%	5.62%
非液化案例	94.35%	5.65%	56.45%	43.55%	91.13%	8.87%	92.74%	7.26%
OA	95.70%		82.12%		94.70%		93.71%	

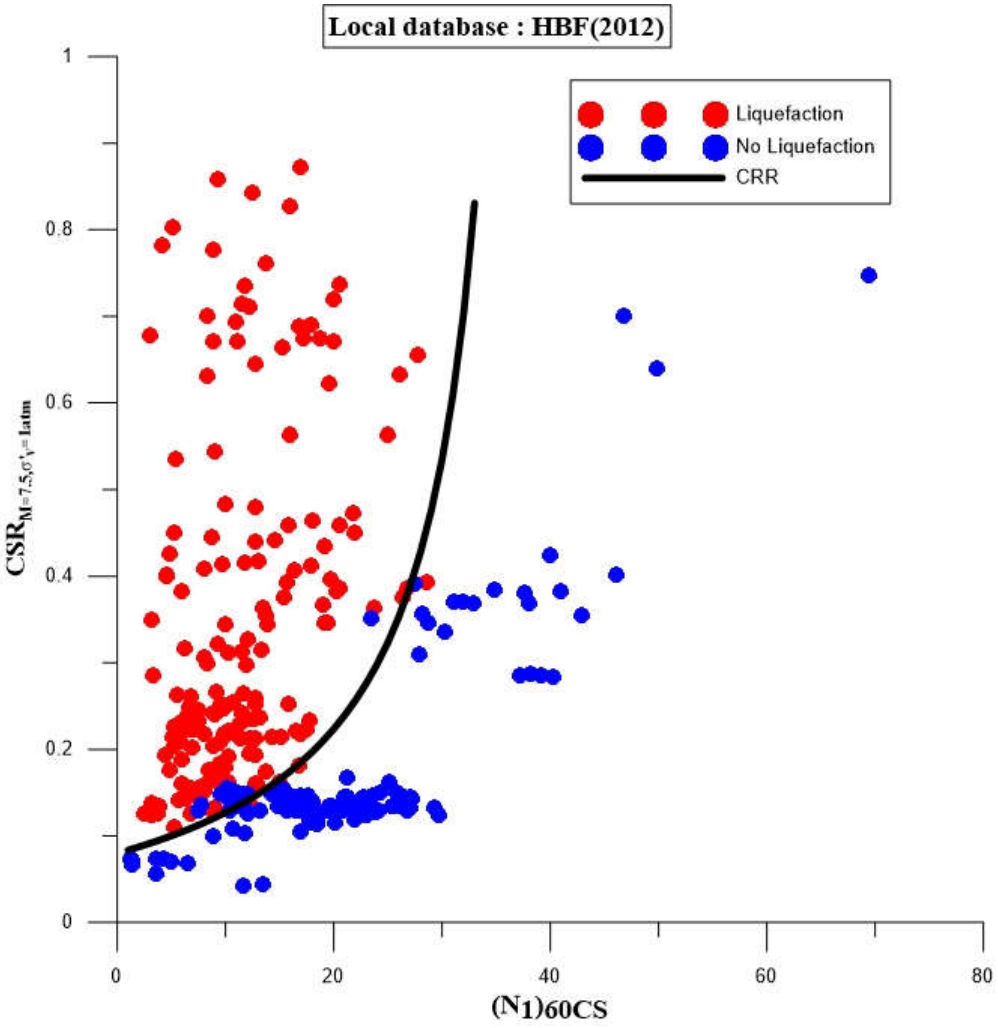
Fm	NCEER(2001)	Cetin(2004)	HBF (2012)	Boulanger and Idriss (2014)
液化案例	0.45	0.00	0.09	0.10
非液化案例	0.17	0.39	0.13	0.16
Total	0.31	0.39	0.12	0.13

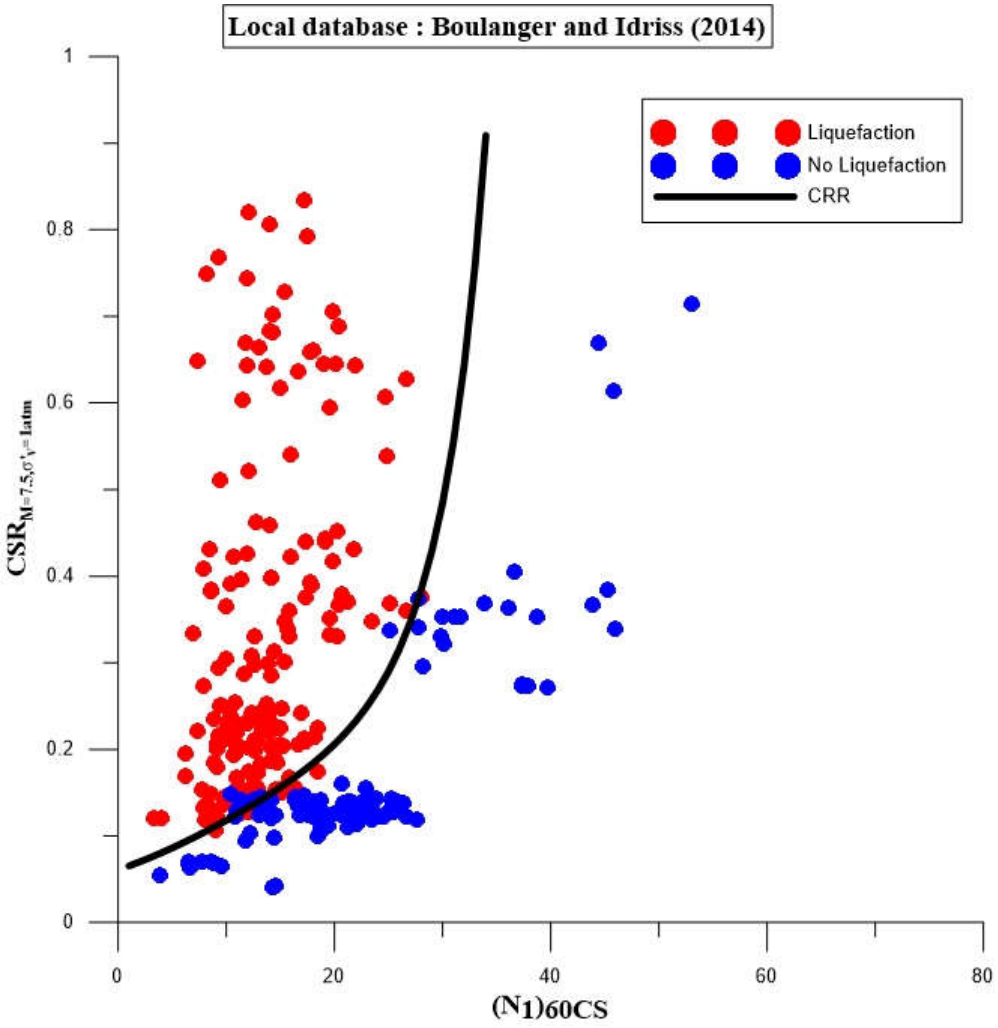
Comparisons of $CSR_{M,\sigma'v}$ v.s $(N_1)_{60CS}$ for Local Database(1/2)



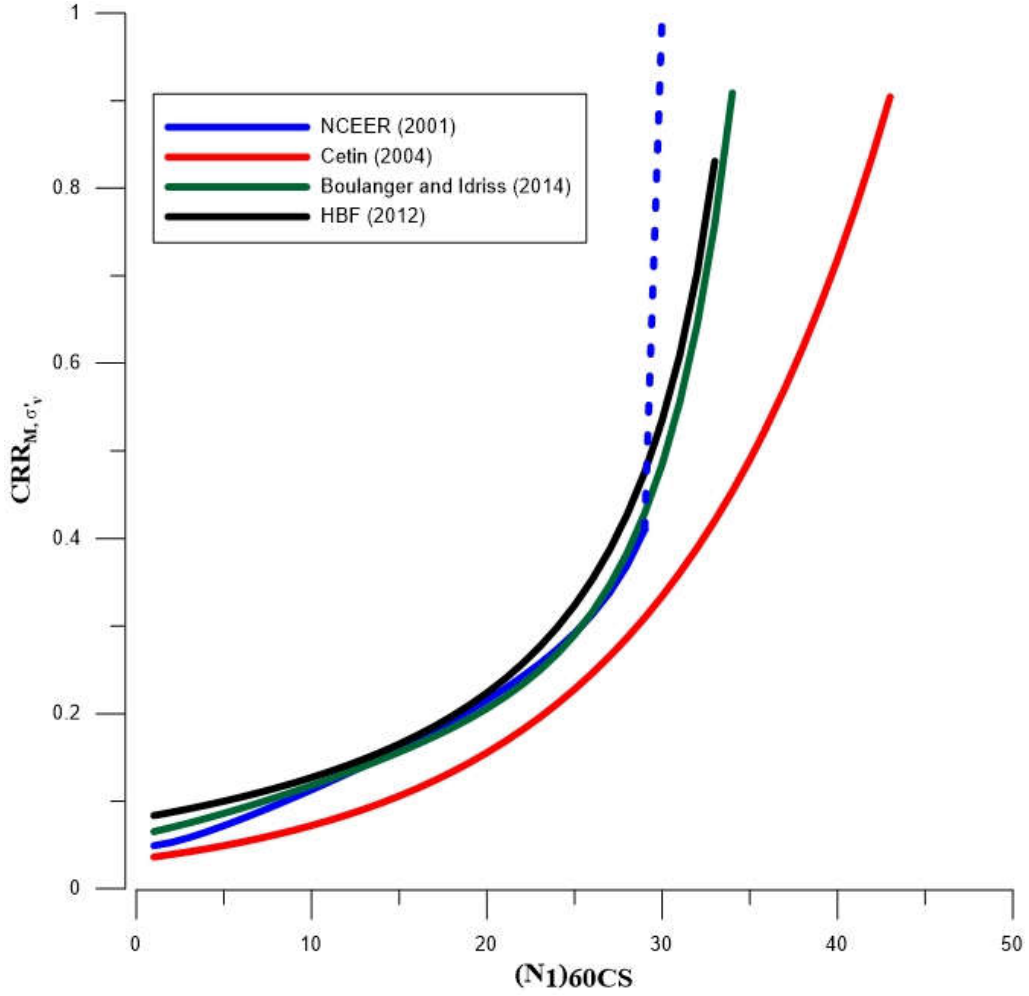


Comparisons of $CSR_{M,\sigma'v}$ v.s $(N_1)_{60CS}$ for Local Database (2/2)





Comparisons of CRR in Different Methods



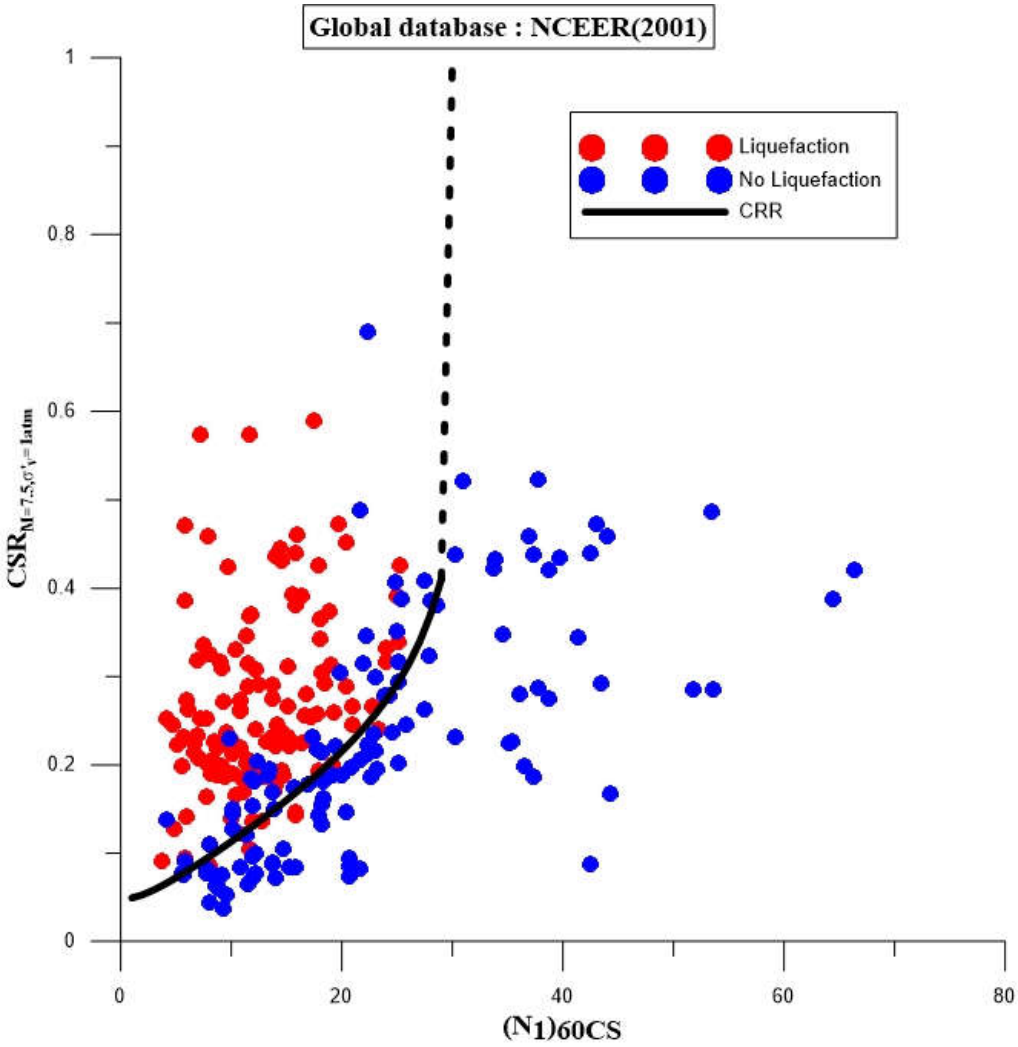
Evaluation Result of Global Database

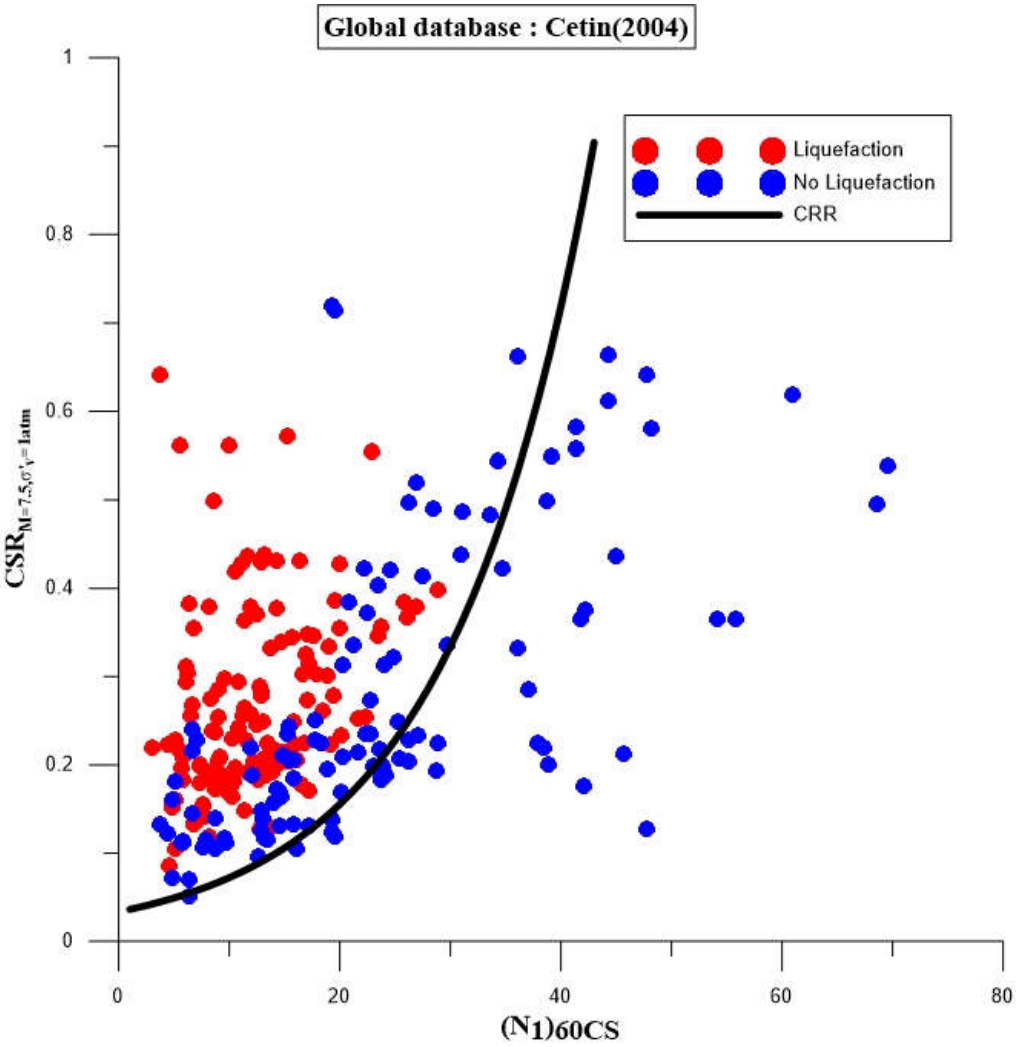
Global database			Liquefied Cases :133				No Liquefied Cases :116	
	NCEER(2001)		Cetin(2004)		HBF (2012)		Boulanger and Idriss (2014)	
	正判案例	誤判案例	正判案例	誤判案例	正判案例	誤判案例	正判案例	誤判案例
液化案例	125	8	132	1	120	13	127	6
非液化案例	81	35	60	56	87	29	85	31

	NCEER(2001)		Cetin(2004)		HBF (2012)		Boulanger and Idriss (2014)	
	正判率	誤判率	正判率	誤判率	正判率	誤判率	正判率	誤判率
液化案例	93.98%	6.02%	99.25%	0.75%	90.23%	9.77%	95.49%	4.51%
非液化案例	69.83%	30.17%	51.72%	48.28%	75.00%	25.00%	73.28%	26.72%
OA	82.73%		77.11%		83.13%		85.14%	

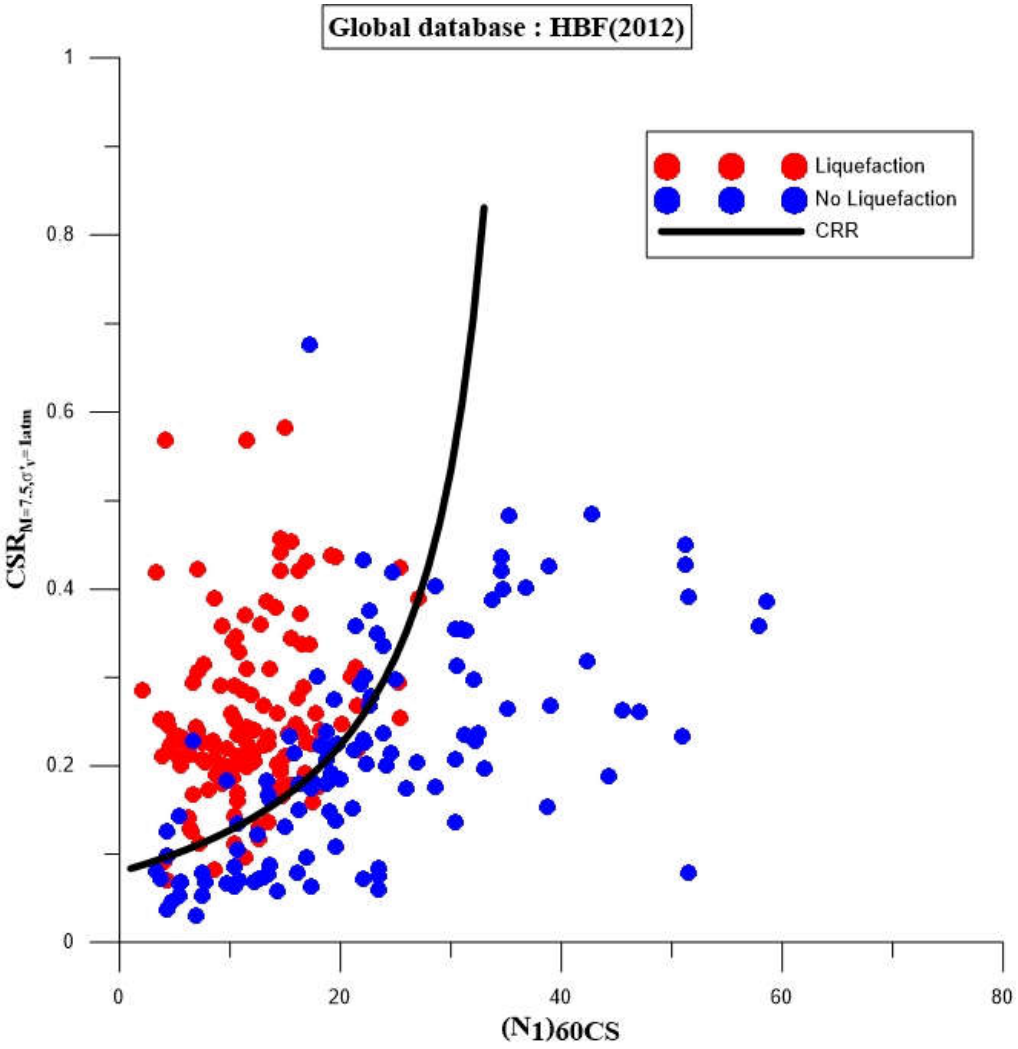
Fm	NCEER(2001)	Cetin(2004)	HBF (2012)	Boulanger and Idriss (2014)
液化案例	0.14	0.13	0.26	0.14
非液化案例	0.26	0.38	0.26	0.27
Total	0.24	0.37	0.26	0.25

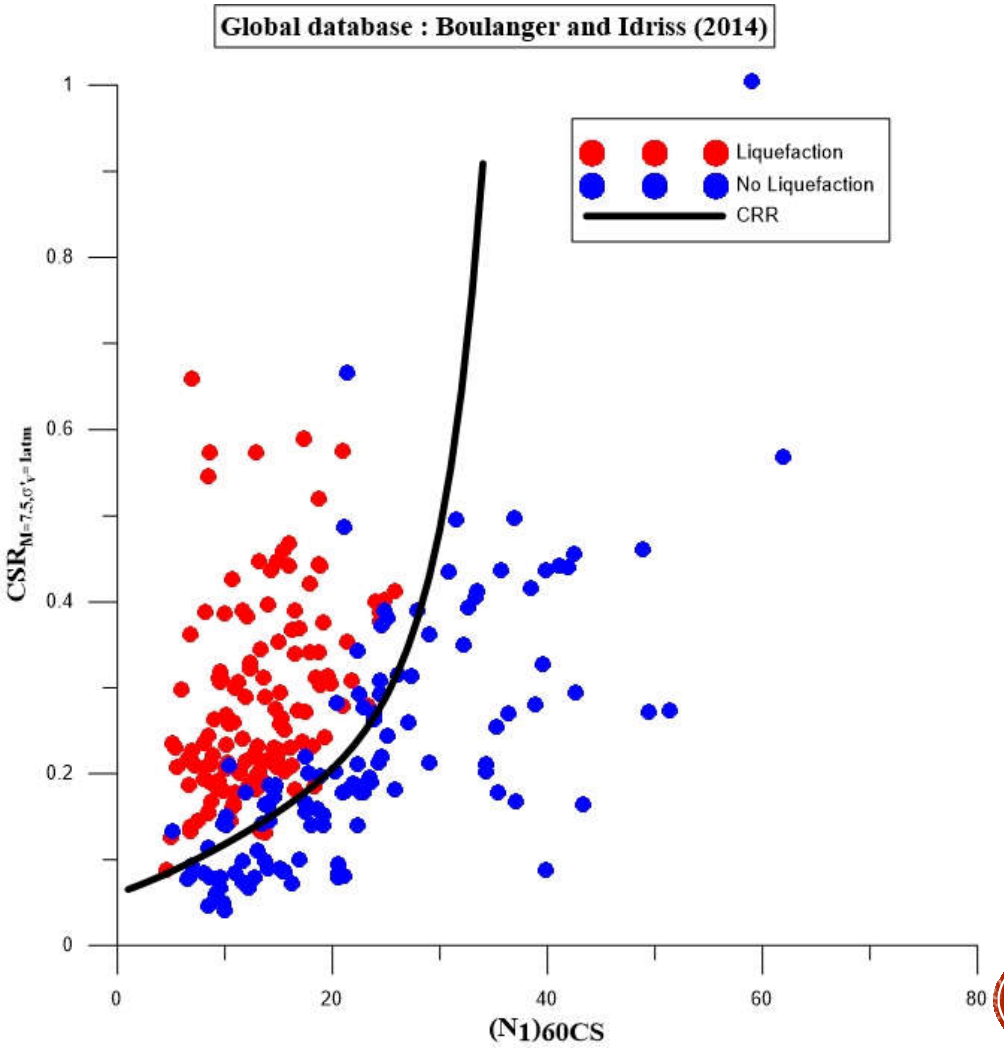
Comparisons of $CSR_{M,\sigma'v}$ v.s $(N_1)_{60CS}$ for Global Database (1/2)



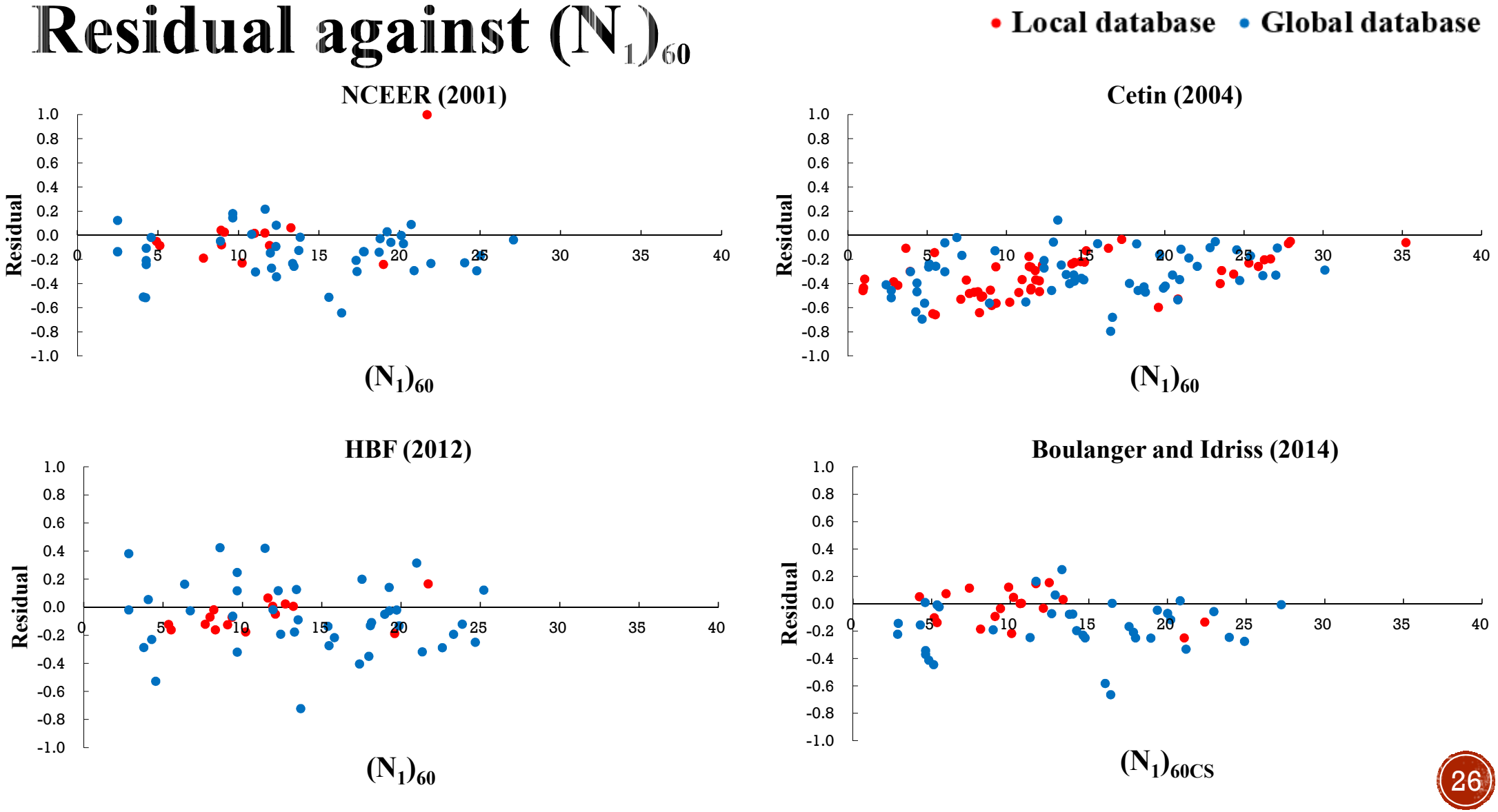


Comparisons of $CSR_{M,\sigma'v}$ v.s $(N_1)_{60CS}$ for Global Database (2/2)

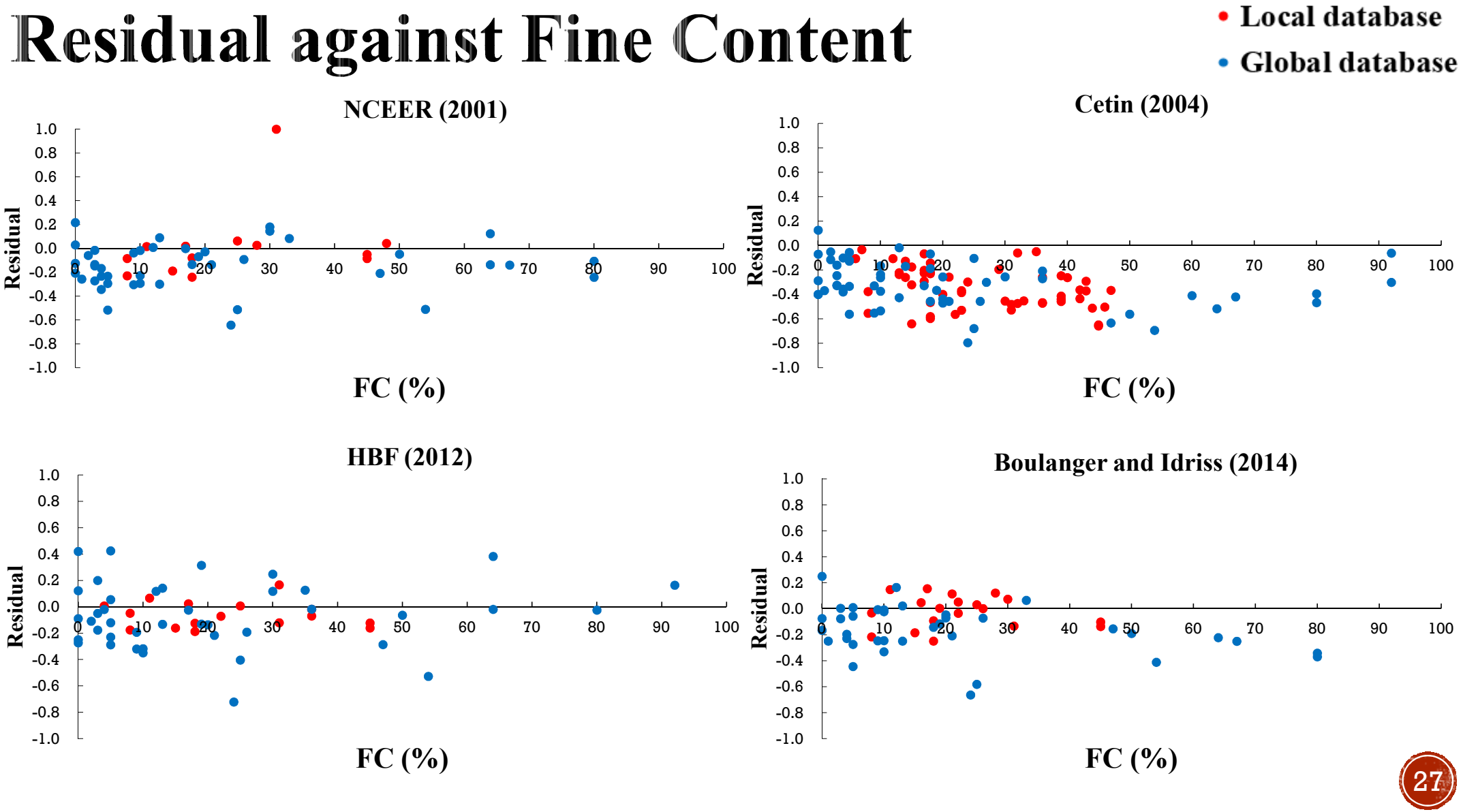




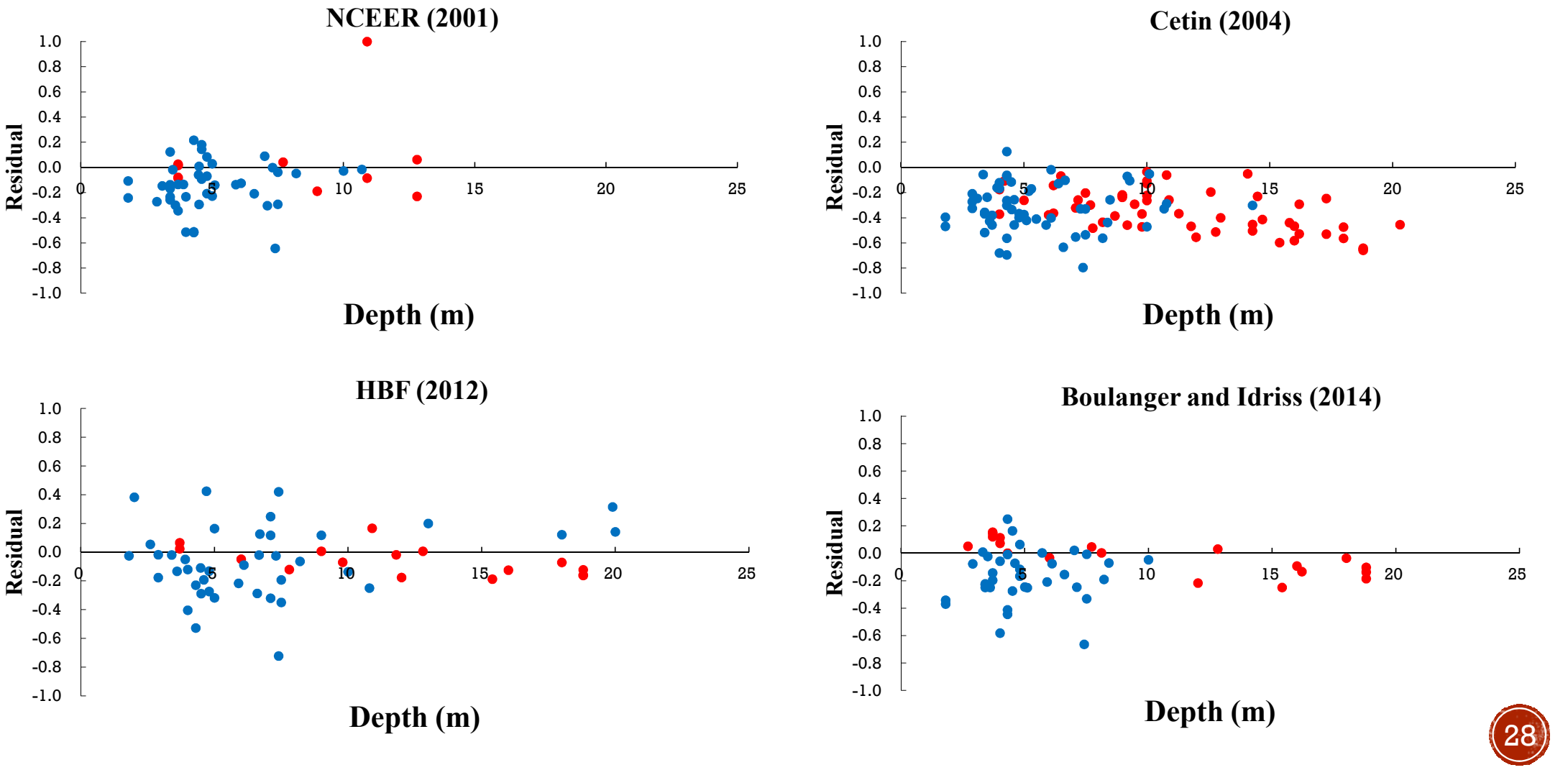
Residual against $(N_1)_{60}$



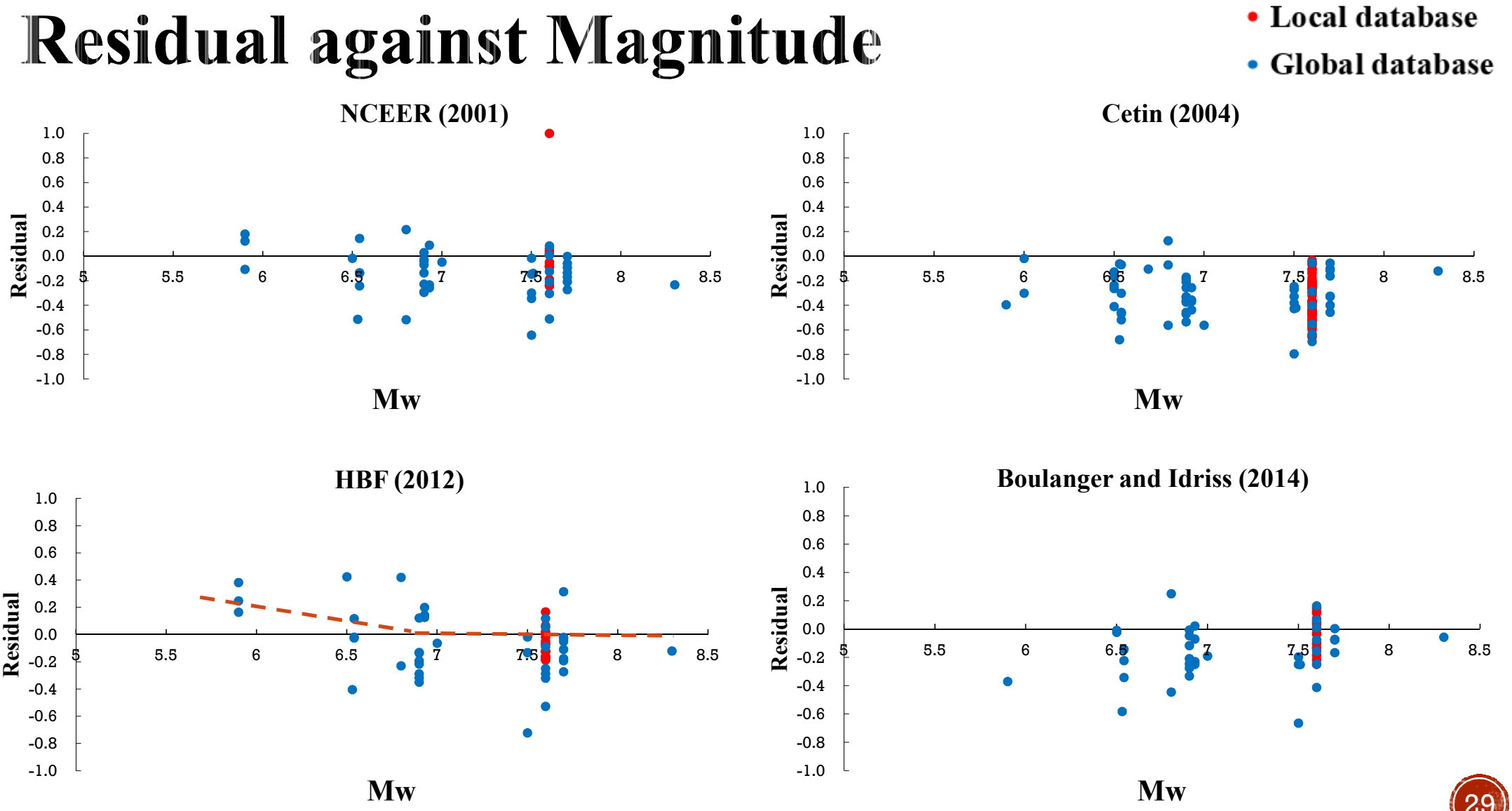
Residual against Fine Content



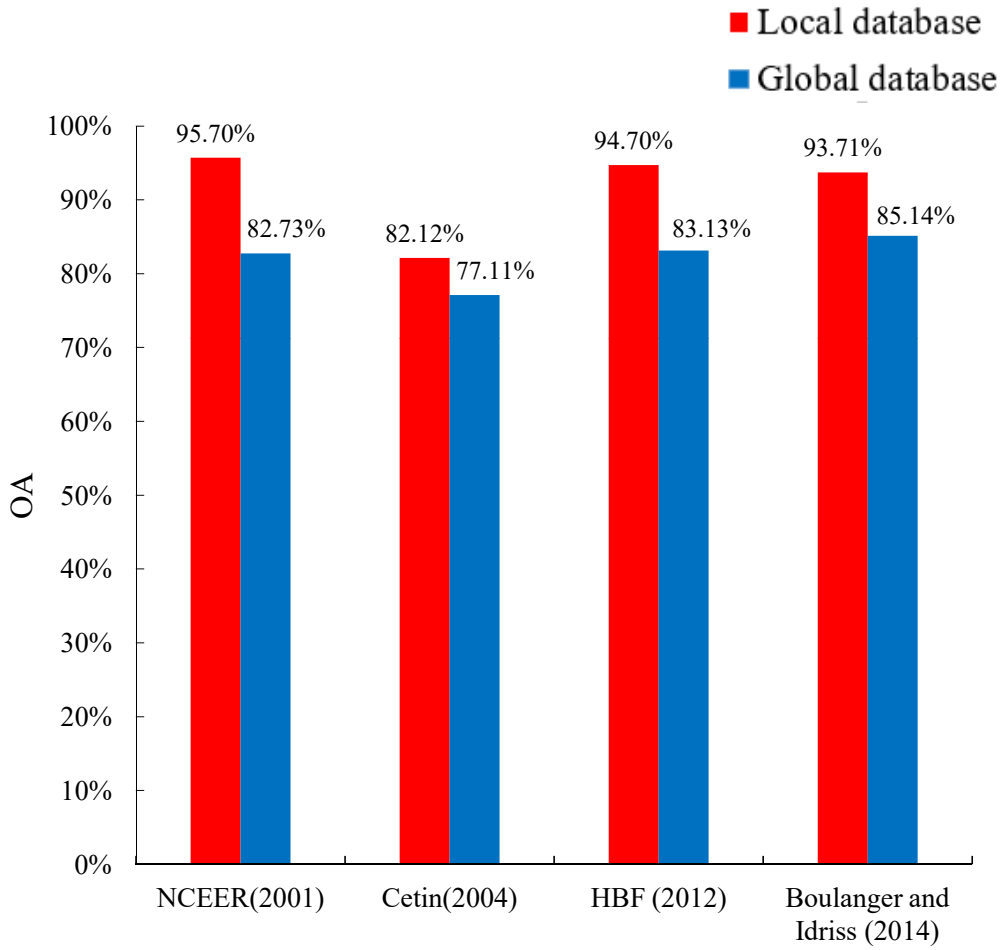
Residual against of Depth

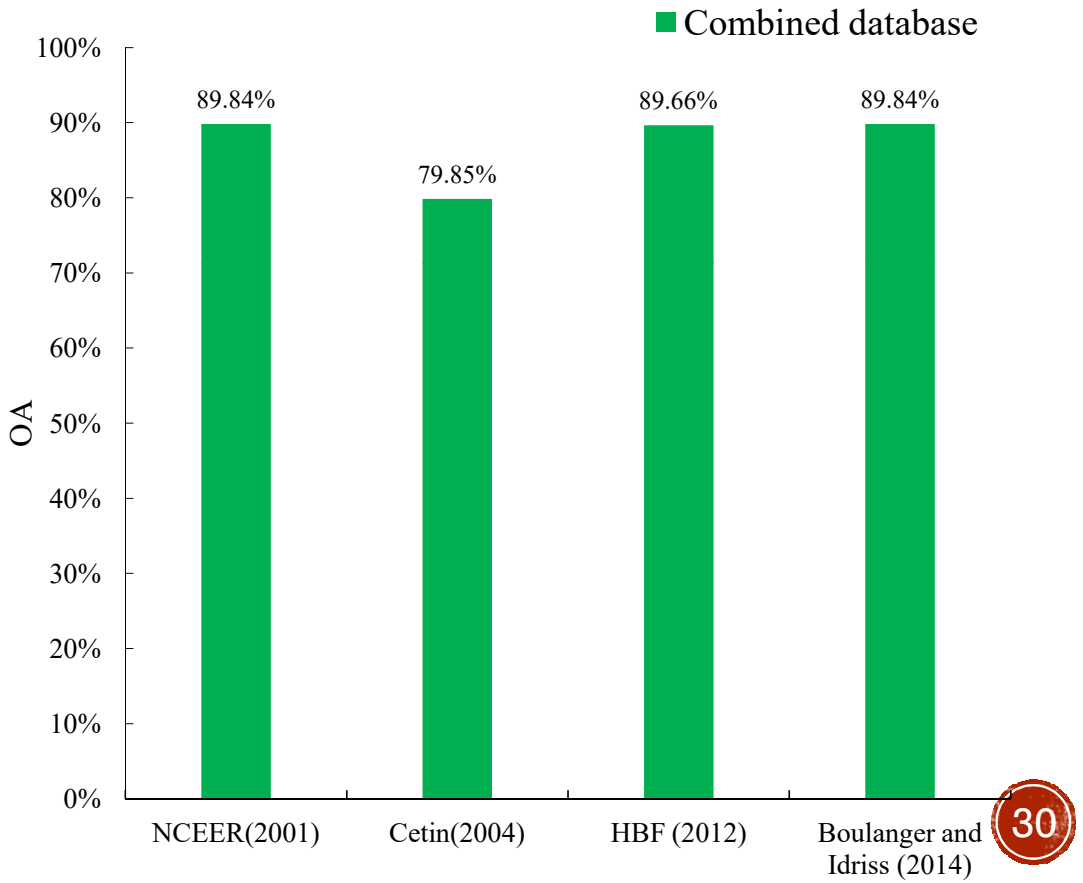


Residual against Magnitude

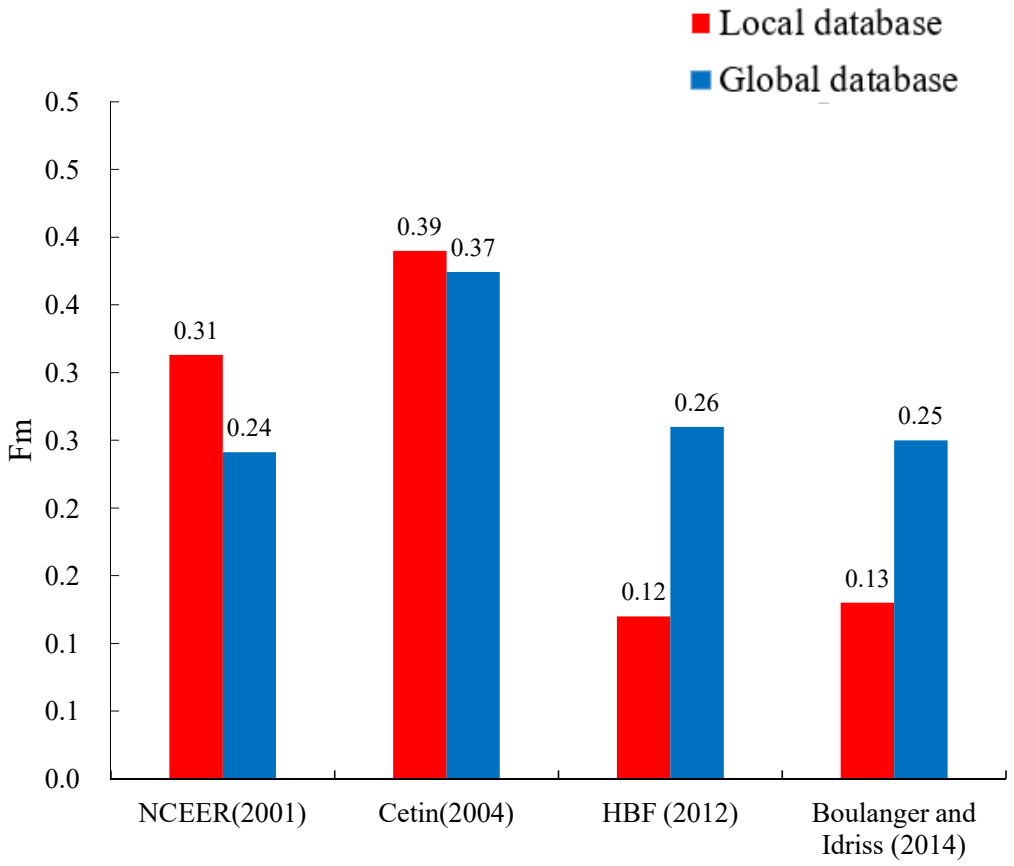


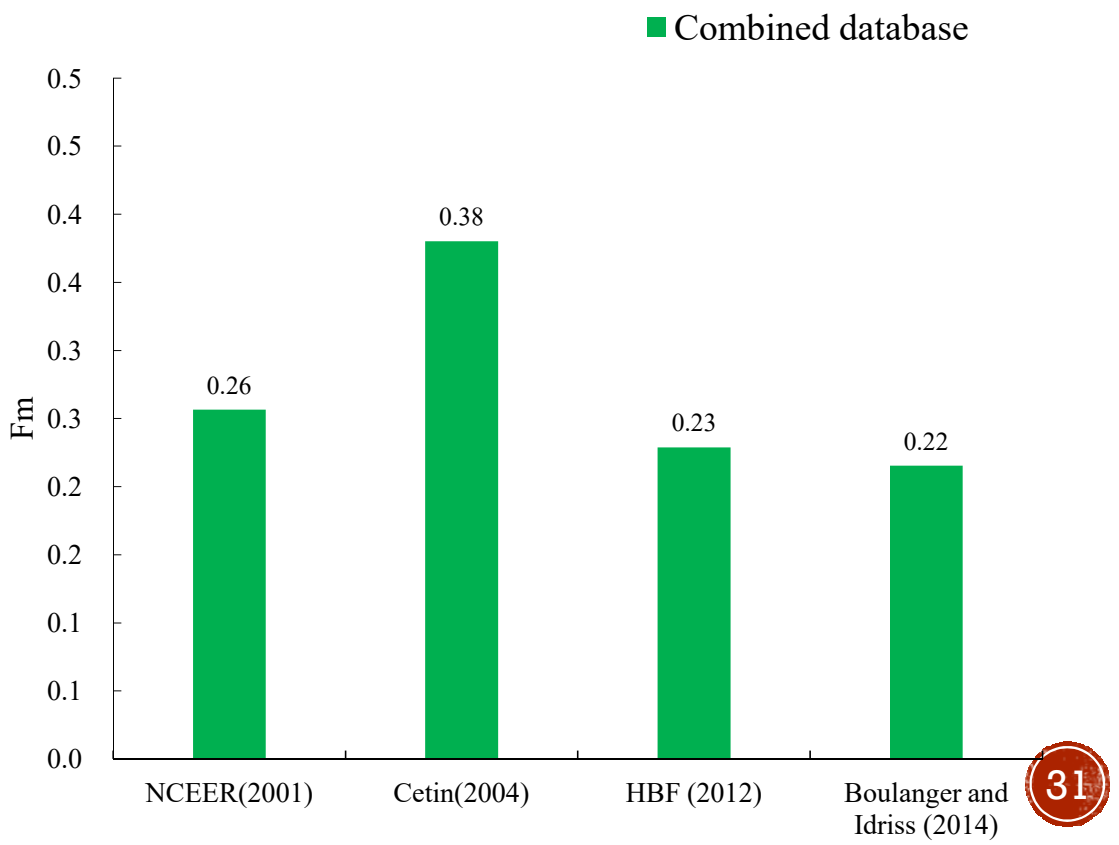
Performance of Different Liquefaction Analysis Methods





Performance of Different Liquefaction Analysis Methods





Sensitivity Analysis of N Correction

$$N_{60} = C_E C_B C_R C_S N_m$$

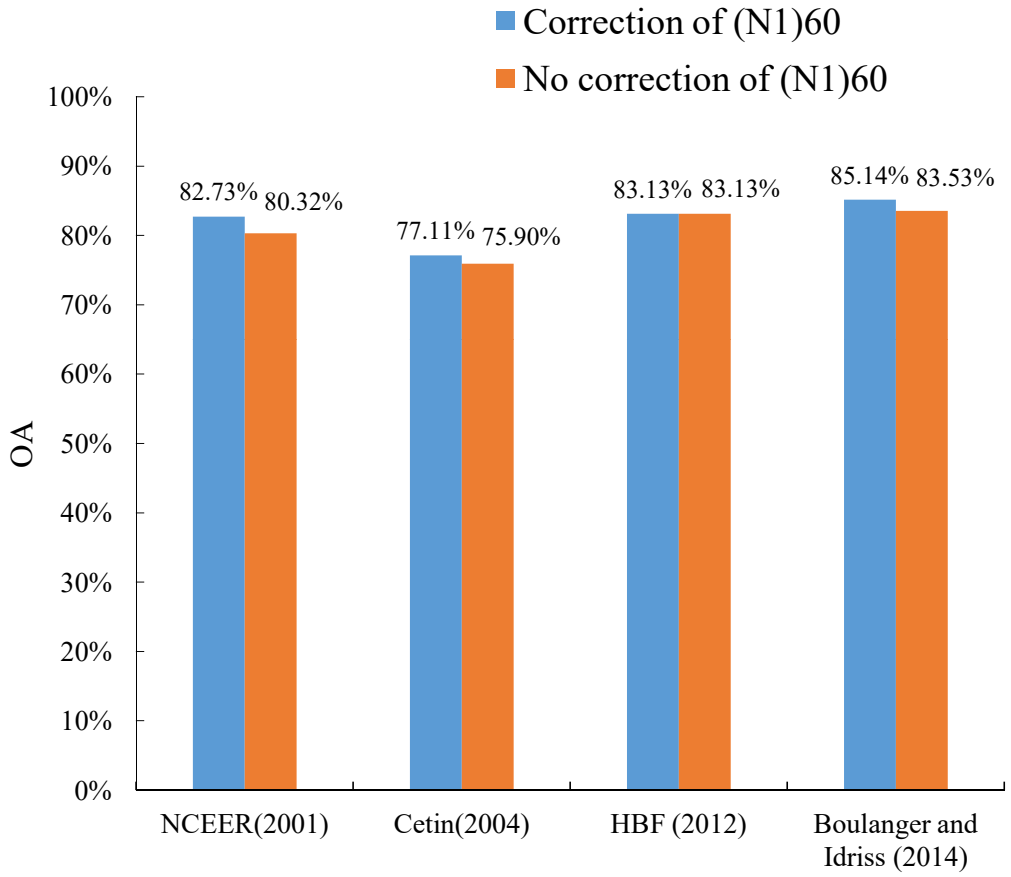
C_E is the energy ratio correction factor,
C_B is a correction factor for borehole diameter,
C_R is a correction factor for rod length,
C_S is a correction factor for a sampler that had room for liners but was used without the liners.

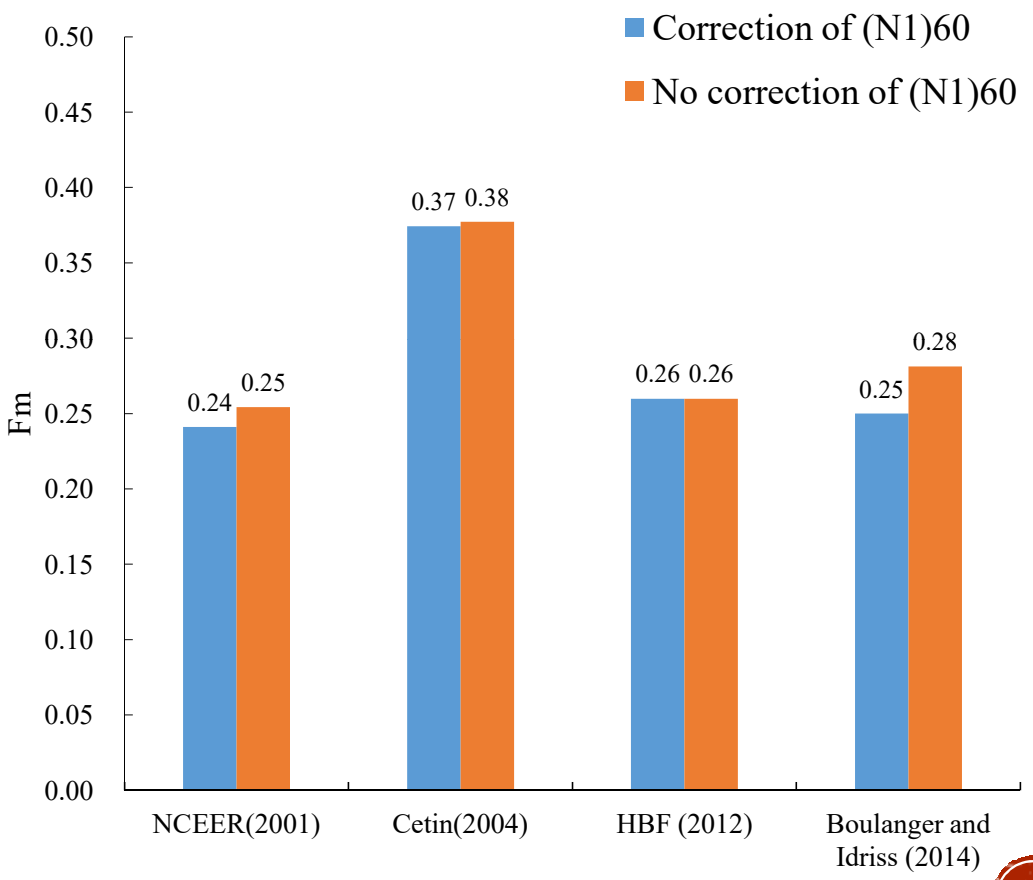
Assume C_E, C_B, C_R, C_S as 1 (i.e. no correction) and recheck the performance

C_B	C_E	C_N	C_R	C_S
1	1.17	1.25	0.95	1
1	1.17	1.32	0.95	1
1	1.17	1.70	0.85	1
1	1.17	1.48	0.85	1
1	1.30	0.99	0.95	1

Global database

Sensitivity Analysis -Correction of $(N_1)_{60}$





Comparison of Formula

Shear stress reduction coefficient, r_d	
NCEER (2001)	Cetin et al. (2004)
$r_d = \frac{(1.0 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.0 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^{2})}$	$d < 20m, \quad r_d = \frac{[1 + \frac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_W + 0.0525 \cdot V^*_{S,12m}}{16.258 + 0.201 \cdot e^{0.341(-d + 0.0785 V^*_{S,12m} + 7.586)}}]}{[1 + \frac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_W + 0.0525 \cdot V^*_{S,12m}}{16.258 + 0.201 \cdot e^{0.341(0.0785 V^*_{S,12m} + 7.586)}}]}$ Avaliable when $V^*_{S,12m}$ ranges from $120 m/s \sim 250 m/s$
HBF (2012)	Boulanger and Idriss (2014)
$r_d = 1 - 0.01z \quad \text{for } z(m) \le 10$ $r_d = 1.2 - 0.03z \quad \text{for } 10 \le z(m) \le 20$	$r_d = \exp[\alpha(z) + \beta(z) \cdot M]$ $\alpha(z) = -1.012 - 1.126 \sin(\frac{z}{11.73} + 5.133)$ $\beta(z) = 0.106 + 0.118 \sin(\frac{z}{11.28} + 5.142)$

Adjustment of fine content, C_{fin}	
NCEER (2001)	Cetin et al. (2004)
$(N_1)_{60CS} = \alpha + \beta (N_1)_{60}$ $\alpha = 0$ for FC ≤ 5% $\beta = 0$ for FC ≤ 5% $\alpha = \exp[1.76 - (190/FC^2)]$ for 5%<FC<35% $\beta = [0.99 + (FC^{4.5}/1000)]$ for 5%<FC<35% $\alpha = 5.0$ for FC ≥ 35% $\beta = 1.2$ for FC ≥ 35%	$C_{FINES} = (1 + 0.004 \cdot FC) + 0.05 \cdot \left(\frac{FC}{N_{1,60}}\right)$ $\lim: 5\% \le FC \le 35\%$
HBF (2012)	Boulanger and Idriss (2014)
$(N_1)_{60,CS} = K_s \times (N_1)_{60}$ $K_s = 1.0 \quad \text{for } FC(\%) \le 10$ $K_s = 1 + 0.07 \times \sqrt{FC - 10} \quad \text{for } FC(\%) > 10$	$(N_1)_{60CS} = (N_1)_{60} + \Delta(N_1)_{60}$ $\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right)$

Cyclic resistance ratio, CRR	
NCEER (2001)	Cetin et al. (2004)
$CRR_{7.5} = \frac{1}{34 - (N_1)_{60CS}} + \frac{(N_1)_{60CS}}{135} + \frac{50}{[10 \cdot (N_1)_{60CS} + 45]^2} - \frac{1}{200}$	$CRR((N_1)_{60}, M_W, \sigma'_v, FC, P_L = 15\%):$ $\exp[\frac{((N_1)_{60} \cdot (1 + 0.004 \cdot FC) - 29.53 \cdot \ln(M_W) - 3.7 \cdot \ln(\frac{\sigma'_v}{P_a}) + 0.05 \cdot FC + 16.85 + 2.7 \cdot \Phi^{-1}(0.15, 0.1))}{13.32}]$
HBF (2012)	Boulanger and Idriss (2014)
$CRR_{7.5} = A + \frac{B \times (N_1)_{60CS}}{1 - (N_1)_{60CS}/C}$ $A = CRR_{min} = 0.08$ $B = \text{increasing slope of } (N_1)_{60,CS} = 0.0035$ $C = \text{upper bound of } (N_1)_{60,CS} = 39$	$CRR_{M=7.5, \sigma'_{v0} = 1atm}:$ $\exp(\frac{(N_1)_{60CS}}{14.1} + (\frac{(N_1)_{60CS}}{126})^2 - (\frac{(N_1)_{60CS}}{23.6})^3 + (\frac{(N_1)_{60CS}}{25.4})^4 - 2.8)$

Overburden correction factor, K_σ	
NCEER (2001)	Cetin et al. (2004)
$K_\sigma = (\sigma'_{v0}/P_a)^{(f-1)}$ $D_r = 40\% \sim 60\%, \quad f = 0.7 \sim 0.8$ $D_r = 60\% \sim 80\%, \quad f = 0.6 \sim 0.7$	$K_\sigma = (\sigma'_{v0}/P_a)^{(f-1)}$ $K_\sigma \le 1$
HBF (2012)	Boulanger and Idriss (2014)
Not required	$K_\sigma = 1 - C_\sigma \ln(\frac{\sigma'_{v0}}{P_a}) \le 1.1$ $C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60CS}}} \le 0.3$

Conclusions (I)

- Four methods (Youd et al, 2001, Cetin et al, 2004, HBF, 2012, and Boulanger and Idriss, 2014) are evaluated by local and global database.
- Global database cover a wide range of earthquake magnitudes while local database is based on only one earthquake but includes more cases of high fines content and more reliable data.
- Overall performance is assessed by accuracy of prediction, Fm, and residual analysis.
- All methods have better performance for local database with OA over 94% but worse performance for global database with OA between 75~84%.
- SPT-N correction do influence the accuracy of prediction but impact is minor.

Conclusions (II)

- Cetin et al. (2004) is overly conservative and is not recommended.
- Youd et al. (2001), HBF (2012), and Boulanger and Idriss (2014) have similar performance, in which Boulanger and Idriss (2014) has highest OA and lowest Fm for the combined database while HBF (2012) has the best performance for the local database that mostly reflects the local condition.
- HBF (2012) exhibits minor bias against small magnitude according to the residual analysis. However, such bias will not affect the liquefaction analyses in Taiwan because the design earthquake magnitude is mostly high.
- HBF (2012) is recommended due to it's simplicity yet good performance.

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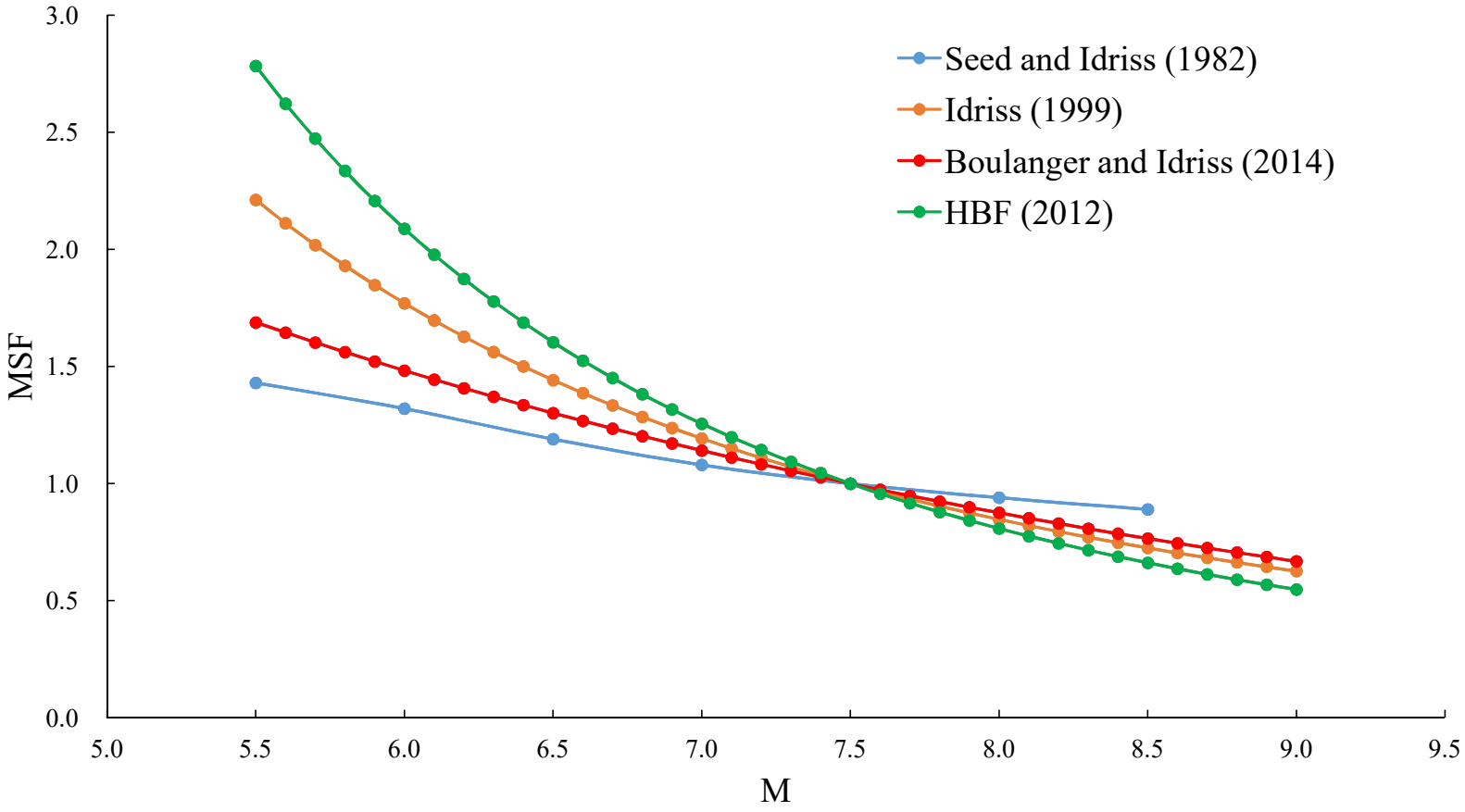
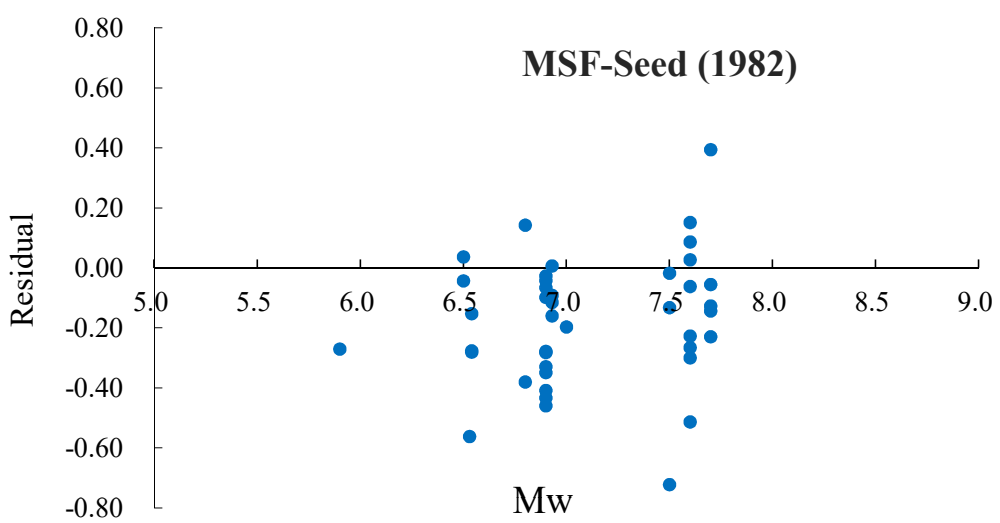
Thank you for your patience!

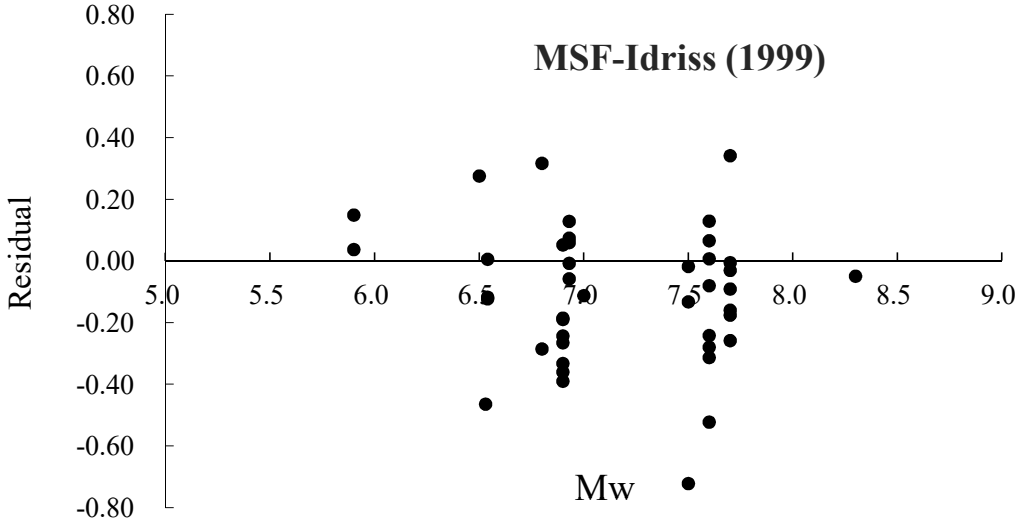
Comparison of MSF

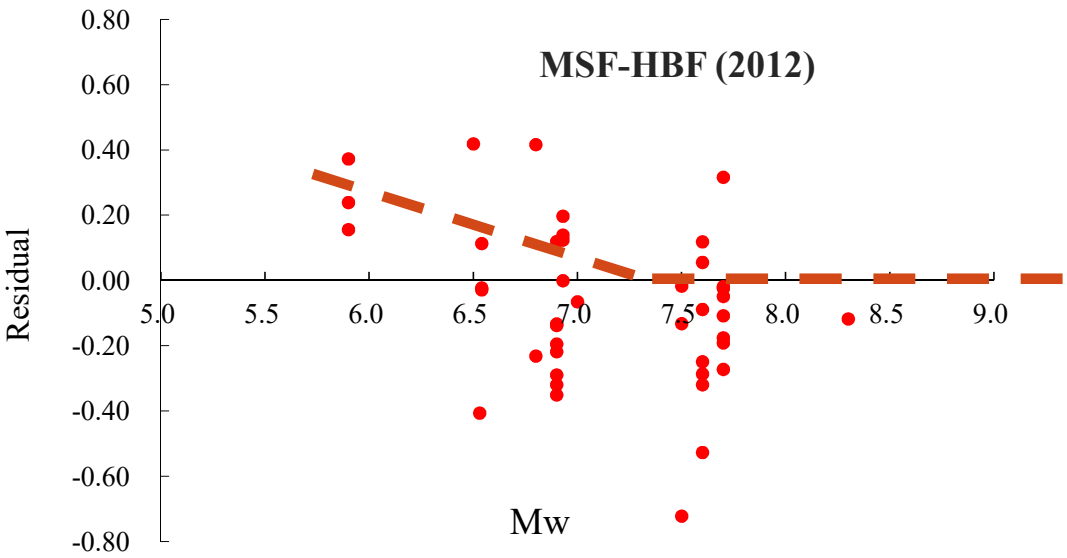


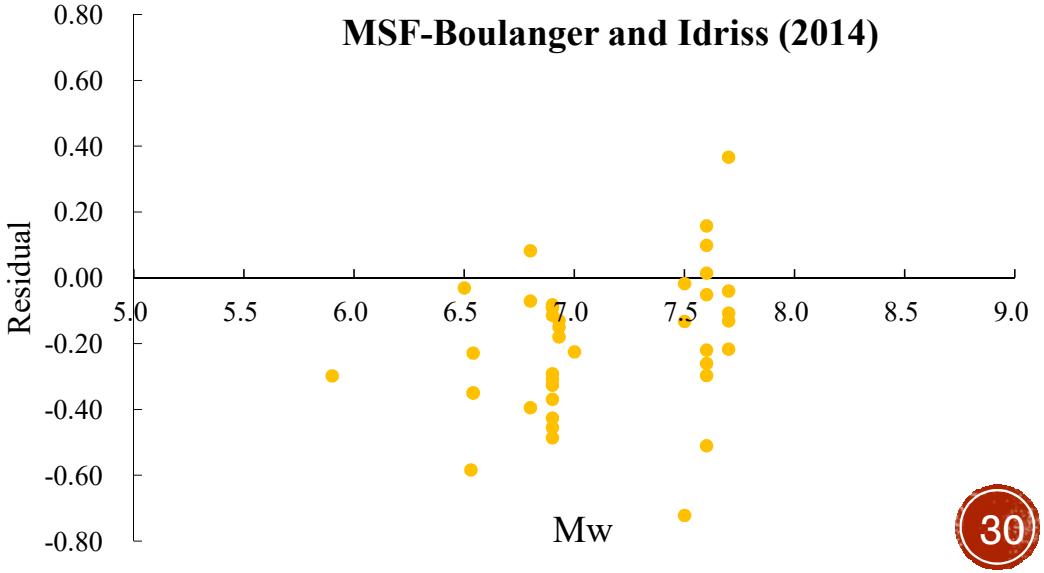
MSF_{max} is determined as 1.8 for sandy layer in this comparison.

Performance of Different MSF









Performance of Different MSF

Global database			Liquefied Cases :133				No Liquefied Cases :116	
MSF 修正	Seed and Idriss (1982)		Idriss (1991)		HBF (2012)		Boulanger and Idriss (2014)	
	液化案例	非液化案例	液化案例	非液化案例	液化案例	非液化案例	液化案例	非液化案例
正判	126	82	120	87	120	88	128	81
誤判	7	34	13	29	13	29	5	35
正判率	94.74%	70.69%	90.23%	75.00%	90.23%	75.00%	96.24%	69.83%
OA	83.53%		83.13%		83.13%		83.53%	
Fm	0.187	0.295	0.175	0.275	0.26	0.26	0.21	0.31
Total Fm	0.278		0.246		0.257		0.29	