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CPT "Legacy" Case Histories

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CAL POLY

Civil and Environmental Engineering

Pacific Earthquake Engineering Research Center (PEER)

UC Berkeley Caltech Stanford UC Irvine UCLA UC Davis UCSD USC University of Washington

Previous PEER Funded Work:

SPT, CPT, V_S

Liquefaction (Denali, Alaska)

Robb Moss, Fugro

Lateral Spreading (Bhuj, India)

Foundation Failure (Kocaeli, Turkey)

I. M. Idriss

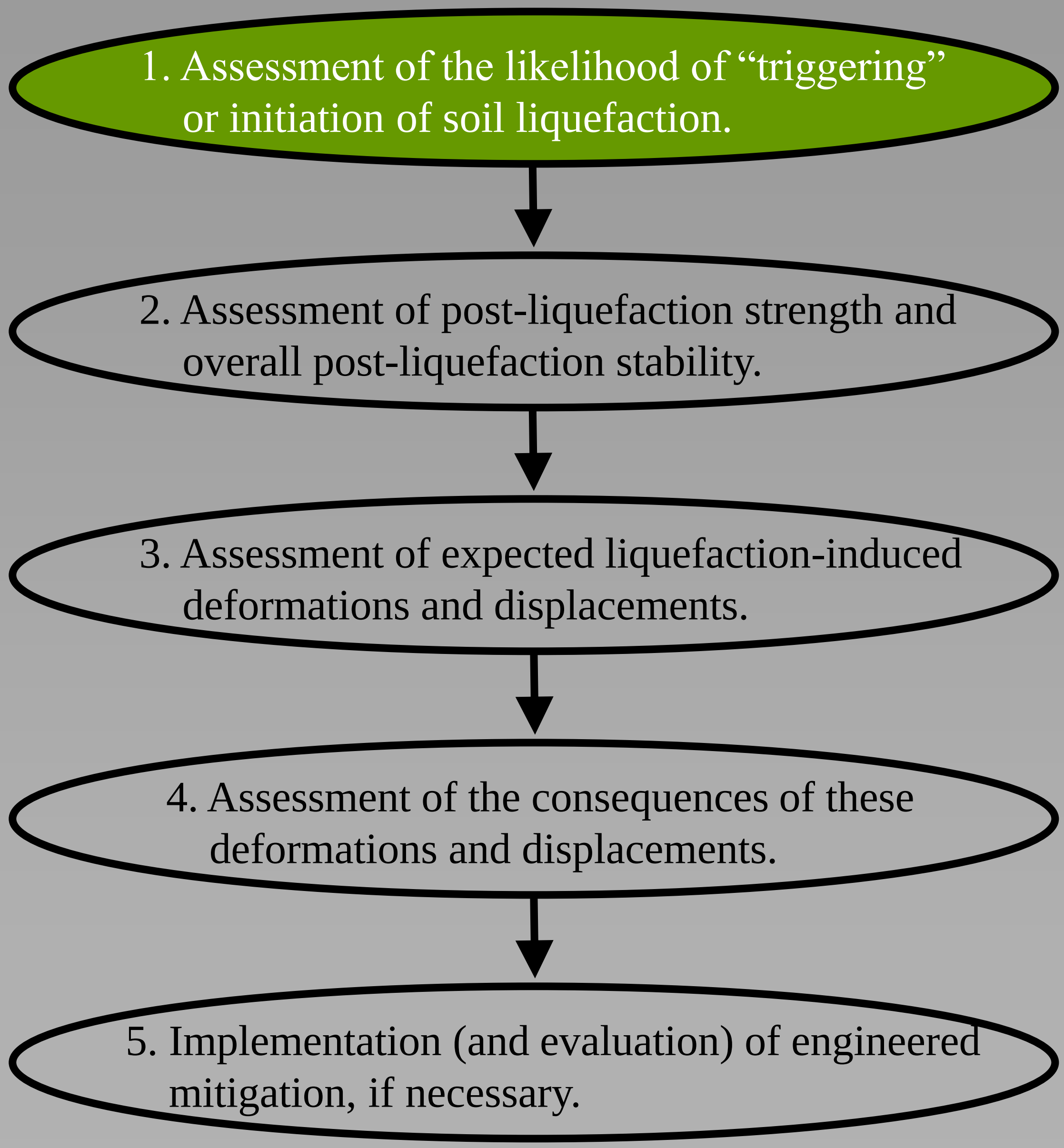
Dam Failure (Bhuj, India)

“Lifelines” Failure (Denali, Alaska)

Key Elements of Soil Liquefaction Engineering

1. Assessment of the likelihood of “triggering” or initiation of soil liquefaction.
2. Assessment of post-liquefaction strength and overall post-liquefaction stability.
3. Assessment of expected liquefaction-induced deformations and displacements.
4. Assessment of the consequences of these deformations and displacements.
5. Implementation (and evaluation) of engineered mitigation, if necessary.

Key Elements of Soil Liquefaction Engineering

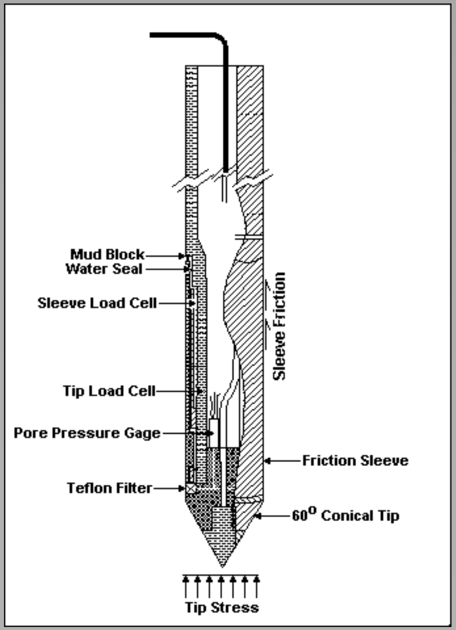


Evaluation of *In Situ* Resistance to Triggering of Cyclic Liquefaction

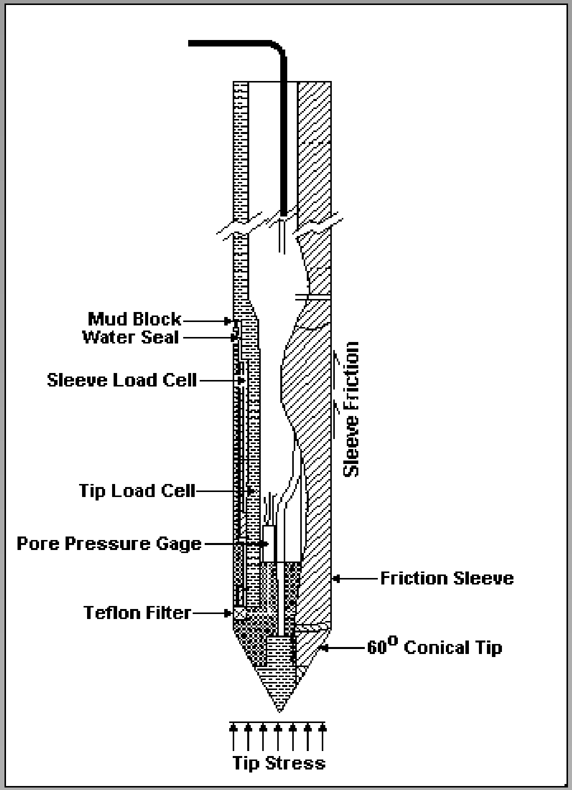
Two Basic Approaches:

1. ~~Laboratory Testing~~

2. In Situ Index Testing
   - -SPT
   - -CPT
   - -V_s
   - -BPT
   - -others



Data Source



LEGACY EVENTS EVALUATED:

1999 Kocaeli, Turkey
1999 Chi-Chi, Taiwan
1995 Dinar, Turkey
1995 Kobe, Japan
1994 Northridge, USA
1992 Erzincan, Turkey
1989 Loma Prieta, USA
1988 Saguenay, Canada
1987 Edgecumbre, New Zealand
1987 Superstition Hills, USA
1987 Elmore Ranch, USA
1983 Nihonkai-Chubu, Japan
1983 Borah Peak, USA
1981 Westmorland, USA
1980 Mexicali, Mexico
1979 Imperial Valley, USA
1977 Vrancea, Romania
1976 Tangshan, China
1975 Haicheng, China
1971 San Fernando, USA
1968 Inanguahua, New Zealand
1964 Niigata, Japan

LEGACY SUMMAY

Moss (2003) - worldwide CPT database

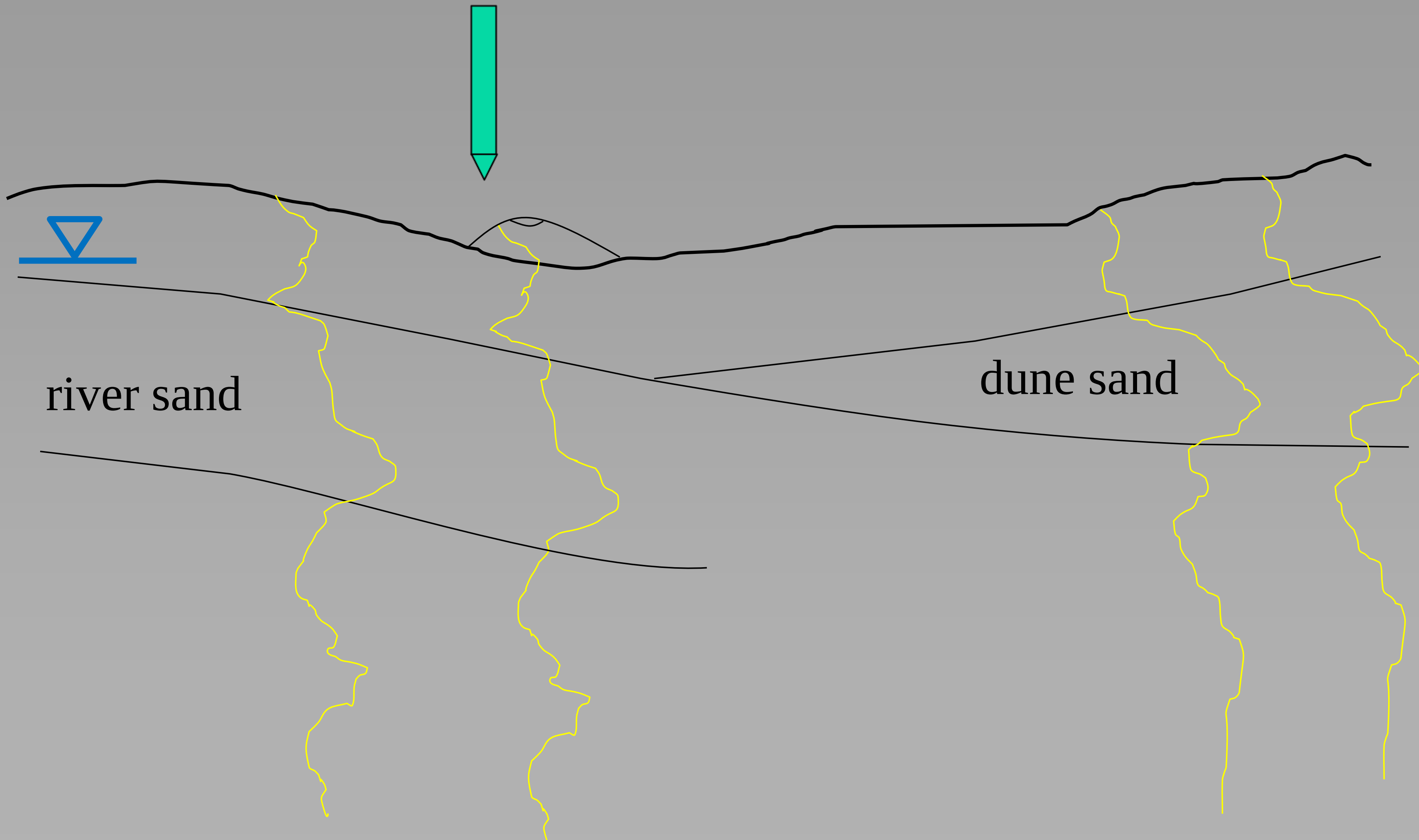
- 139 liquefied and
- 43 nonliquefied cases recorded from
- 18 different earthquakes spanning 5 decades.

Reinvestigations of:

- 1979 Imperial Valley, 1981 Westmoreland, 1987 Superstition Hills (Moss et al. 2005)
- 1976 Tangshan (Moss et al., 2011)

Total = 146 + 54

Objective vs. Subjective - gray areas and nuances and correlations and ….


river sand
dune sand

What constitutes a “**Good**” case history:

- detailed observations of ground failure or non-failure that is both relative and global
- well quantified ground shaking (low CoV)
- well quantified water table (other than CPTu)
- modern CPT measurements (non-trivial in other countries)
- multiple measurements of critical layer(s)
- co-located with SPT and V_S (downhole)
- consideration of spatial variability/correlation
- other: ageing, thin/thick layer, deformations, severity, timing, confining layer, fines/plasticity, …

Case History Statistics

μ

σ

ρ

(layer specific)

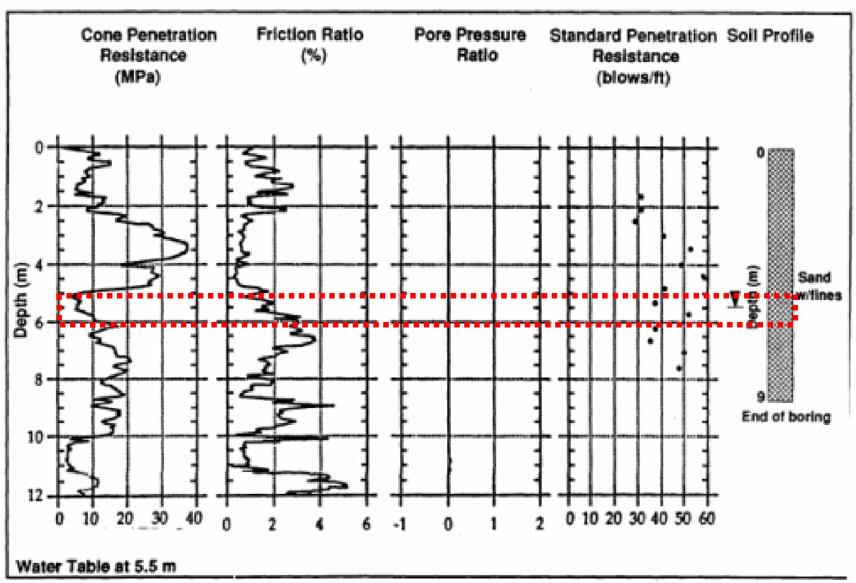


Figure 53: Cone and Standard Penetration Resistance Logs at Alameda Bay Farm Island (Dike Location)

Earthquake: 1989 Loma Prieta

Magnitude: M_s=7.1

Location: Alameda Bay Farm Island (Dike Location)

References: Mitchell et al. (1994), Kayen & Mitchell (1997)

Nature of Failure: No failure, DDC improved site.

Comments: Western portion consists of sandy Hydraulic fill, underlain by bay mud and deeper stiffer soil.

Liquefaction occurred along the western and northern sections of the island.

Deep Dynamic Compaction was performed in the western perimeter dike to prevent liquefaction.

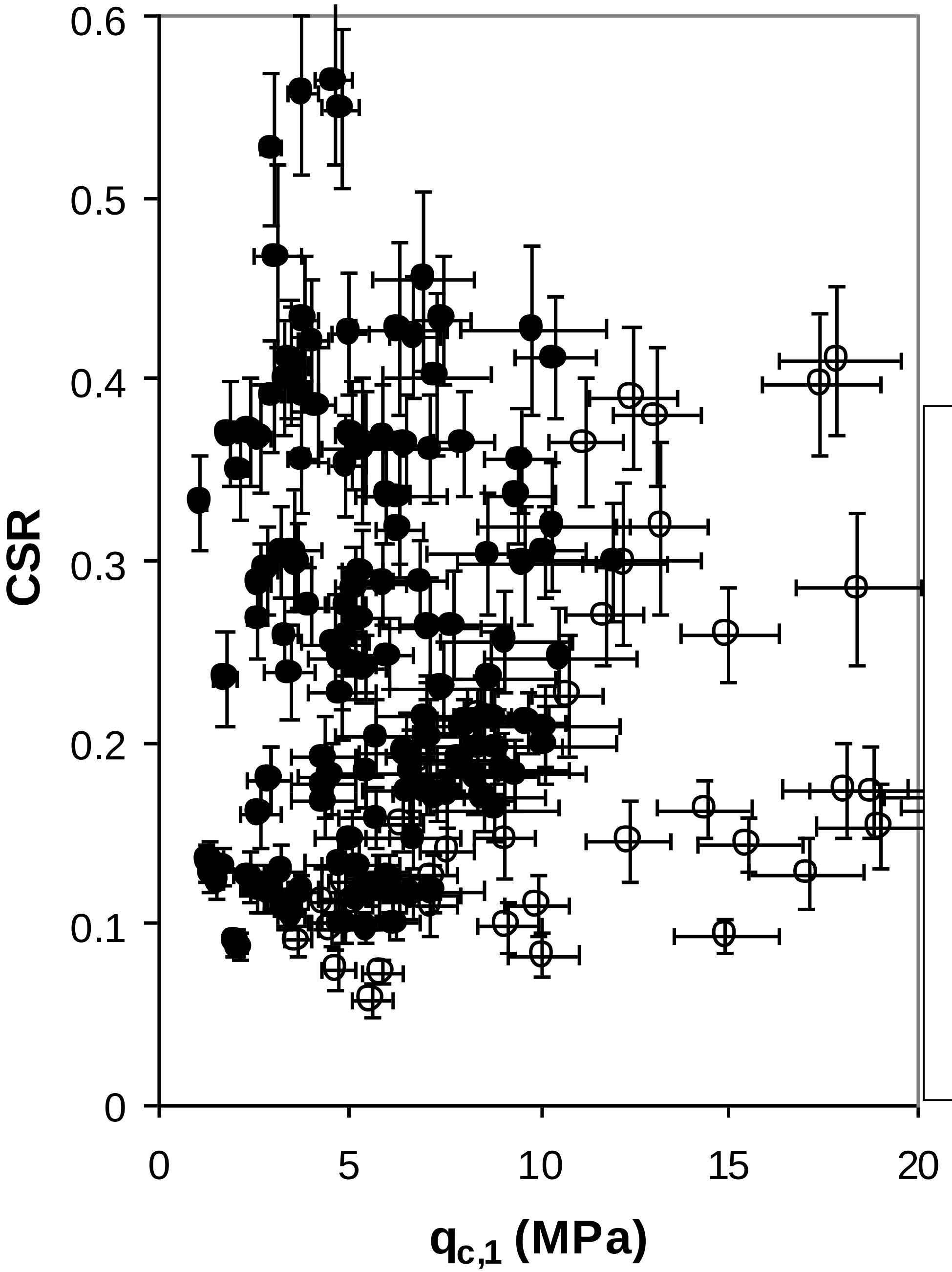
PGA was recorded at 0.27 & 0.21 at the Alameda Naval Air Station.

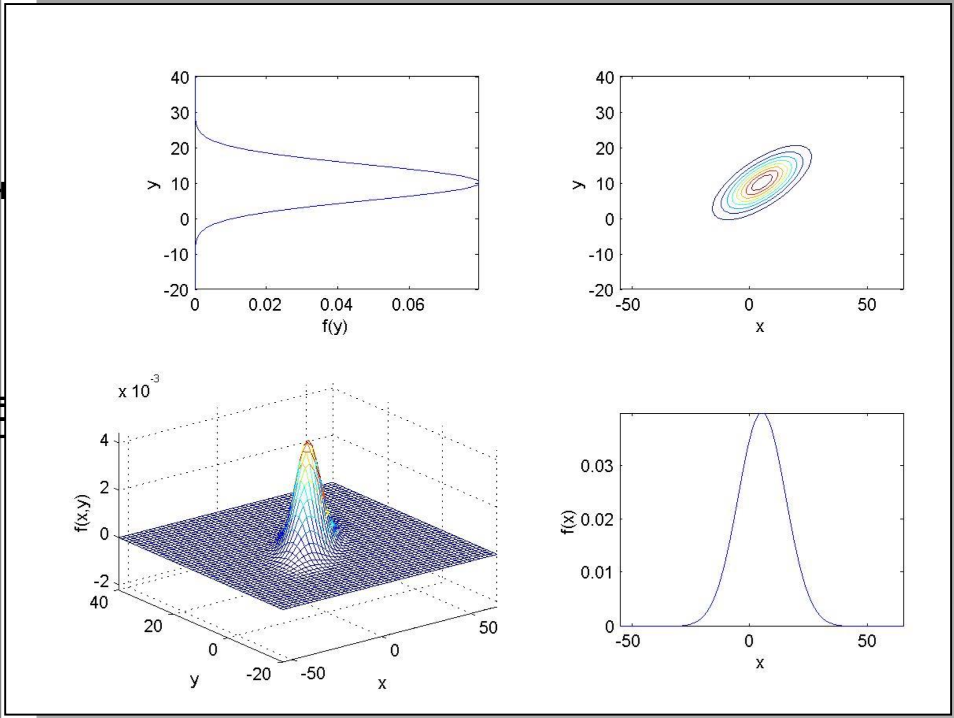
Correlated with SPT from Cetin et al. (2000)
Corrected water table from 97 reference.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class		Soil Class	SP-SM
Critical Layer (m)	5 to 6	D_{50} (mm)	0.28
Median Depth (m)	5.50	%Fines	7
st.dev.	0.17	%PI	
Depth to GWT (m)	2.50		
st.dev.	0.30		
σ_v (kPa)	103.75	q_c (MPa)	7.10
st.dev.	4.23	st.dev.	2.70
σ_v' (kPa)	74.32	f_s (kPa)	152.37
st.dev.	3.56	st.dev.	25.35
a_{max} (g)	0.24	norm. exp.	0.34
st.dev.	0.02	C_q, C_f	1.11
r_d	0.95	C_{thin}	1.00
st.dev.	0.09	f_{s1} (kPa)	168.54
Corrected Magnitude	7.00	st.dev.	28.04
st.dev.	0.12	q_{c1} (MPa)	7.85
CSR_{eq}	0.16	st.dev.	2.98
st.dev.	0.03	R_{f1}(%)	2.15
$C.O.V._{CSR}$	0.15	stdev	0.89

Parameter Uncertainty





Data Screening and Vetting

Class A

1. Original CPT trace with q_c and f_s/R_f, using a ASTM D3441 & D5778 spec. cone.
2. No thin layer correction required
3. $\delta_{CSR} \leq 0.20$

Class B

1. Original CPT trace with q_c and f_s/R_f, using a ASTM D3441 & D5778 spec. cone.
2. Thin layer correction required.
3. $0.20 < \delta_{CSR} \leq 0.35$

Class C

1. Original CPT trace with q_c and f_s/R_f, but using a non-standard cone (e.g. Chinese cone or mechanical cone).
2. No sleeve data but FC ≤ 5% (i.e. "clean" sand).
3. $0.35 < \delta_{CSR} \leq 0.50$

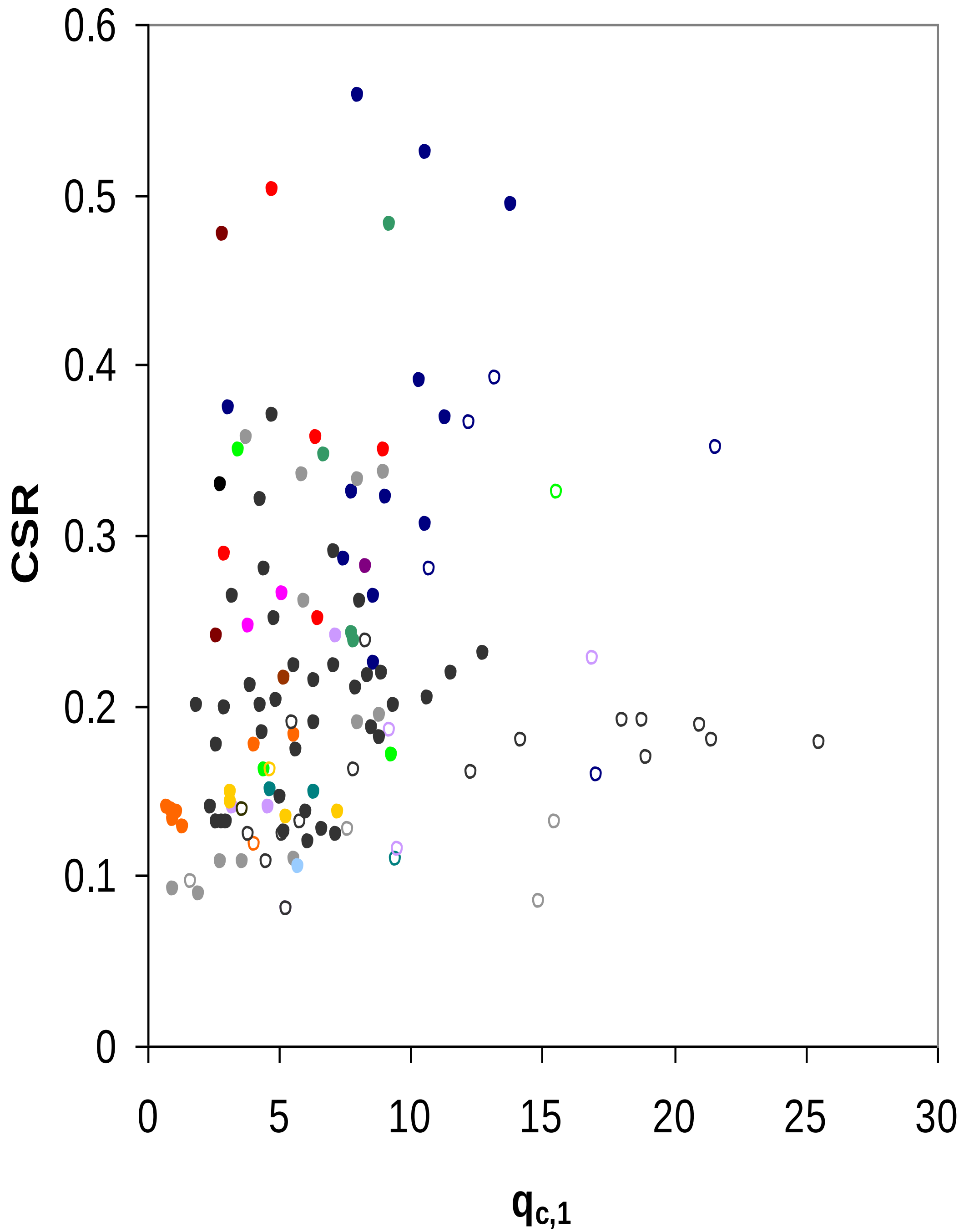
Class D

1. Not satisfying the criteria for Classes A, B, or C.

Expert Panel Review

Data

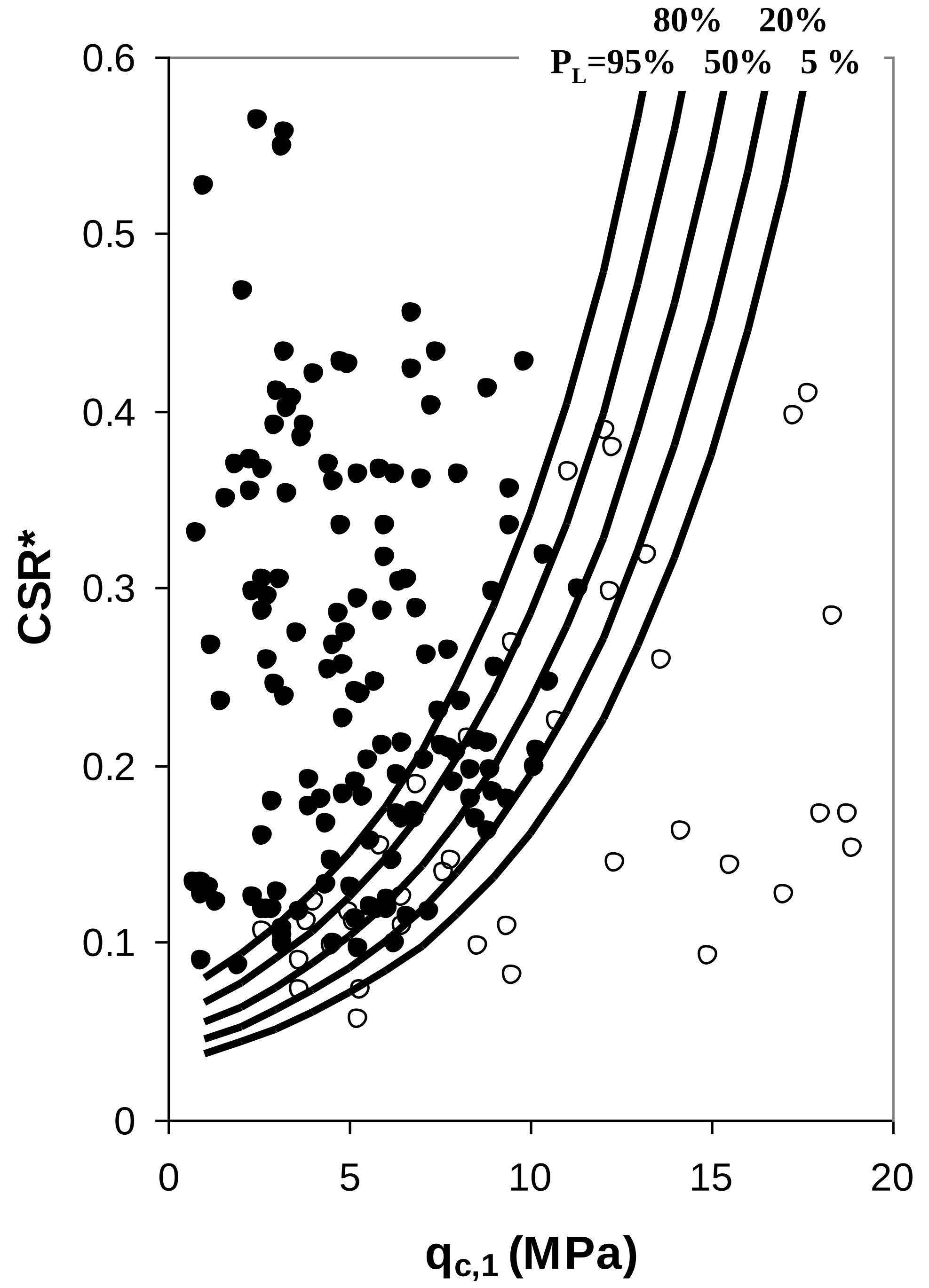
- Data points passing the screening and vetting process (class A,B, & C)



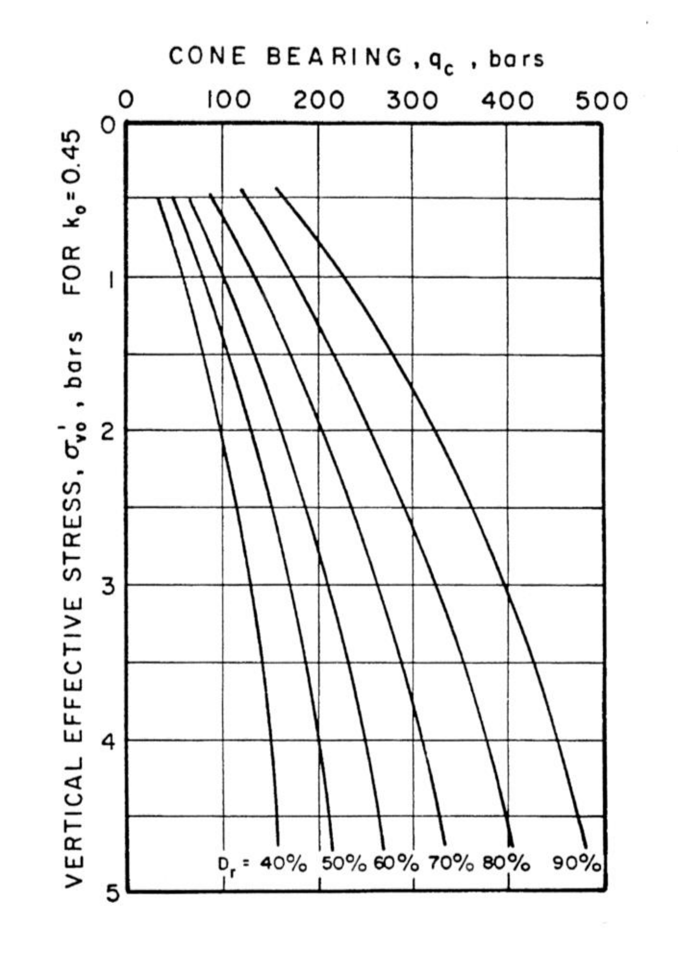
Modeling

Equivalent Clean Sand

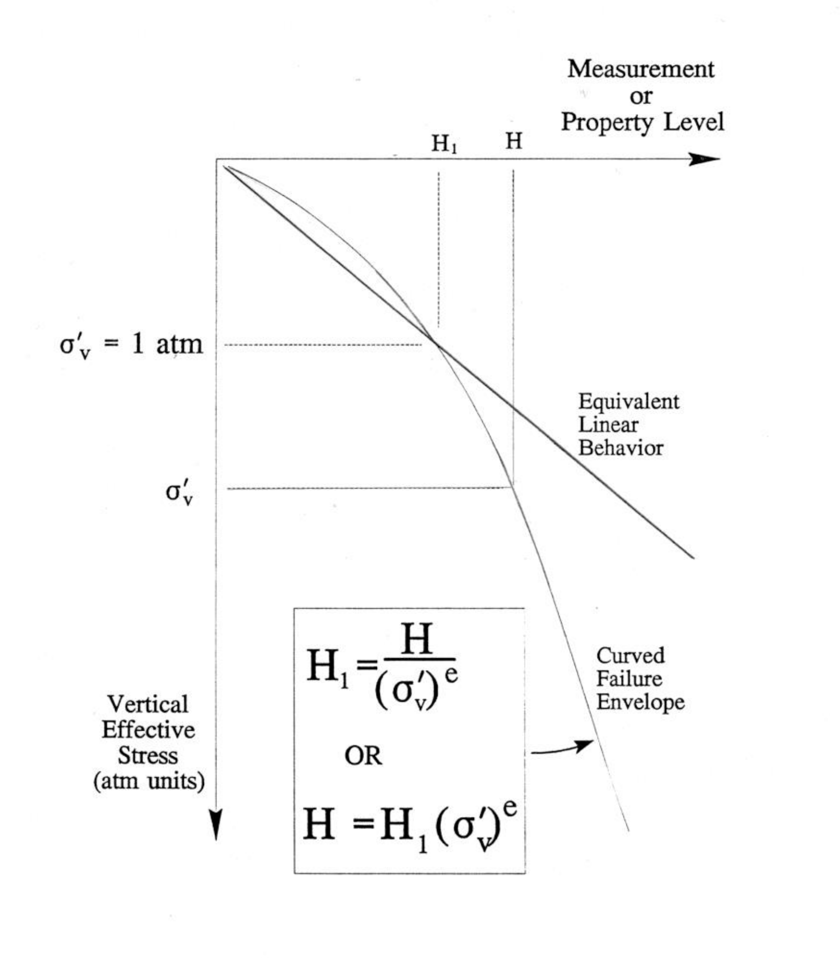
M_w=7.5 σ_v'=1 atm



NORMALIZATION



Ticino Sand, Baldi et al. (1981)



Olsen (1995)

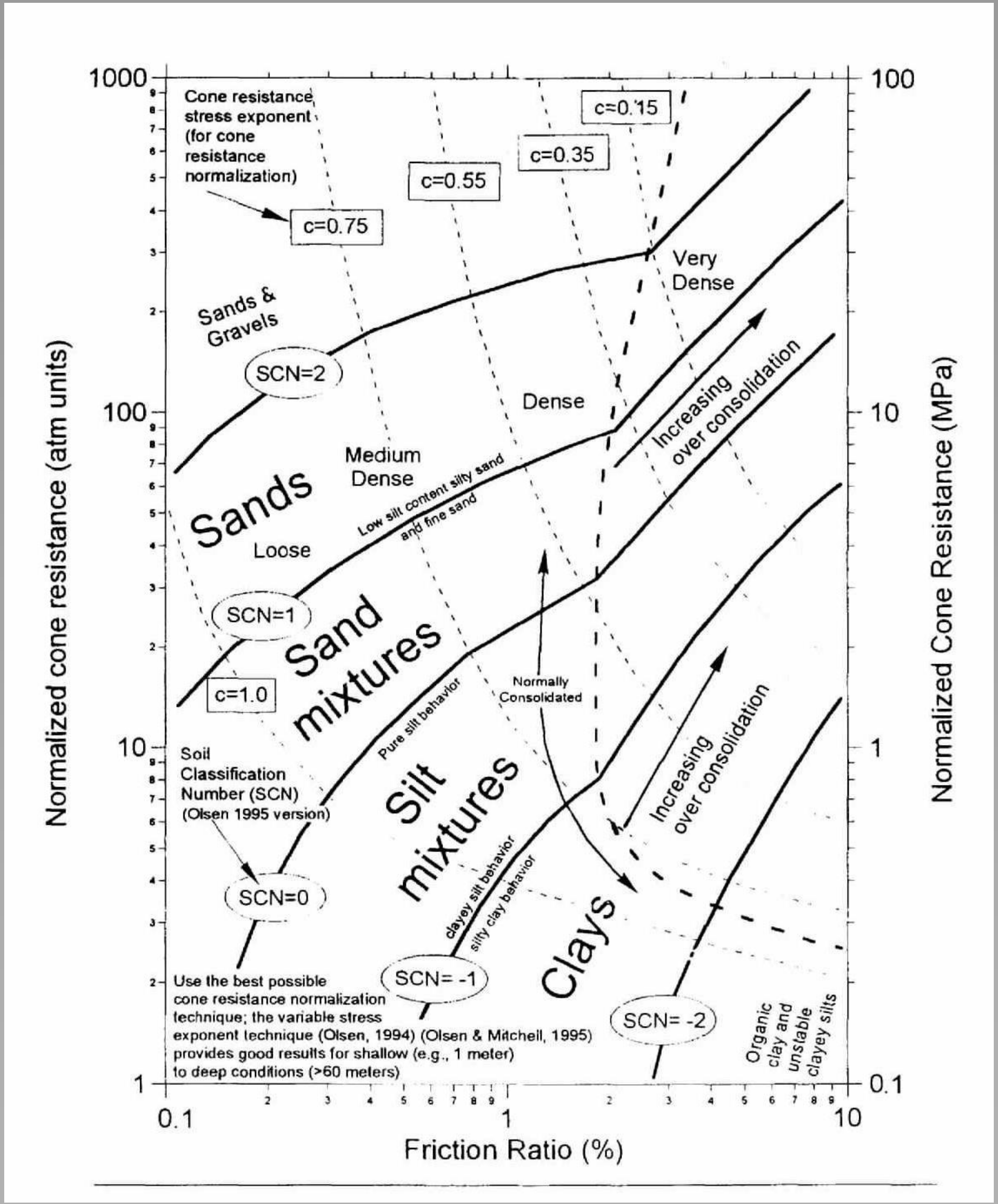
Field and Lab Data

$$q_{c,1} = q_c \cdot C_q$$

$$C_q = \left(\frac{P_a}{\sigma_v'}\right)^c$$

$$f_{s,1} = f_s \cdot C_f$$

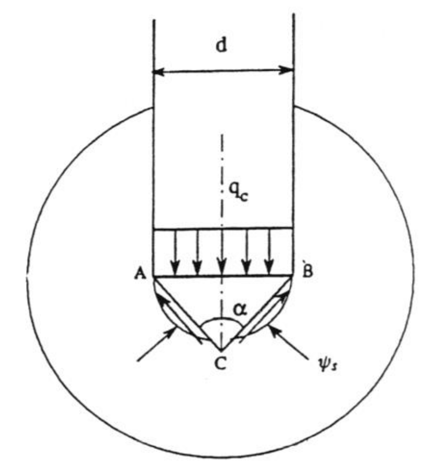
$$C_f = \left(\frac{P_a}{\sigma_v'}\right)^s$$



Olsen & Mitchell (95)

Theoretical Approaches for Predicting Cone and/or Sleeve Resistance

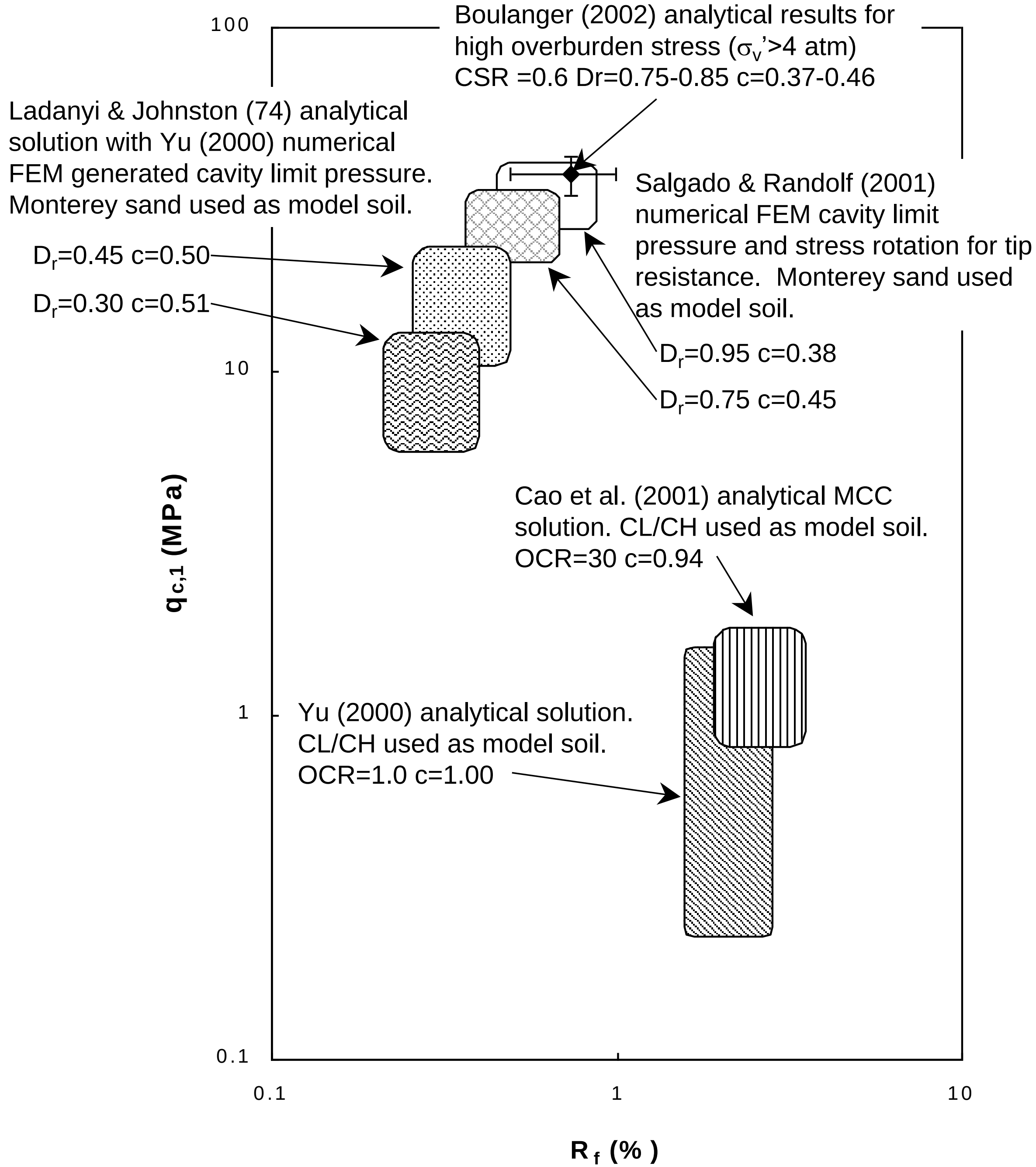
- Bearing Capacity
- Cavity Expansion
- Strain Path
- Steady State
- Discrete Element



(a). Ladanyi & Johnston (1974)

Calibrated and Utilized to Predict Resistance as a Function of Pressure and D_r, K_o, and OCR.

Theoretical Results



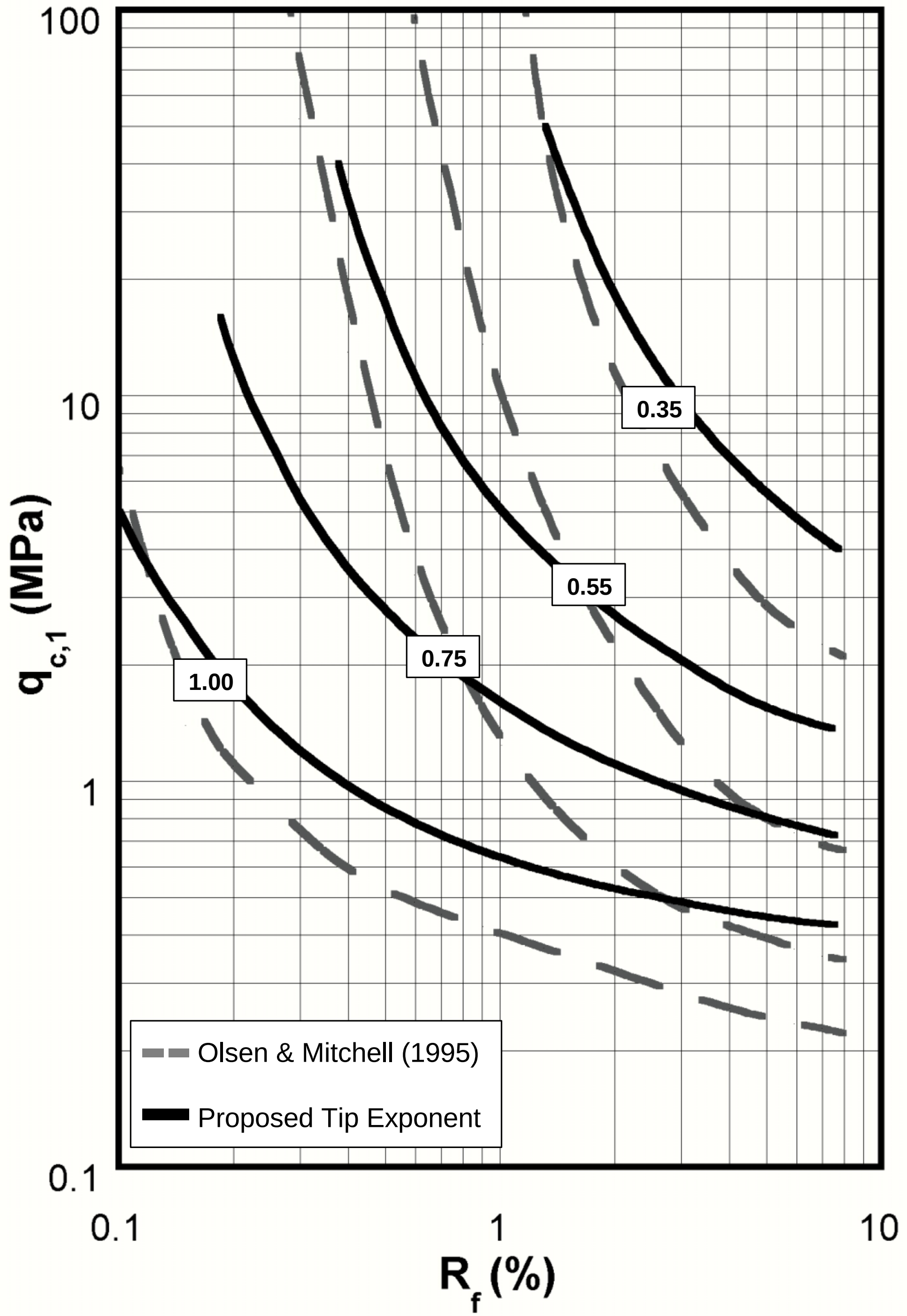
Iterative Normalization Procedure

$$c = f_1 \cdot \left(\frac{R_f}{f_3} \right)^{f_2}$$

where $f_1 = x_1 \cdot q_c^{\,x_2}$

$f_2 = -(y_1 \cdot q_c^{\,y_2} + y_3)$

$f_3 = abs(\log(10 + qc))^{z_1}$

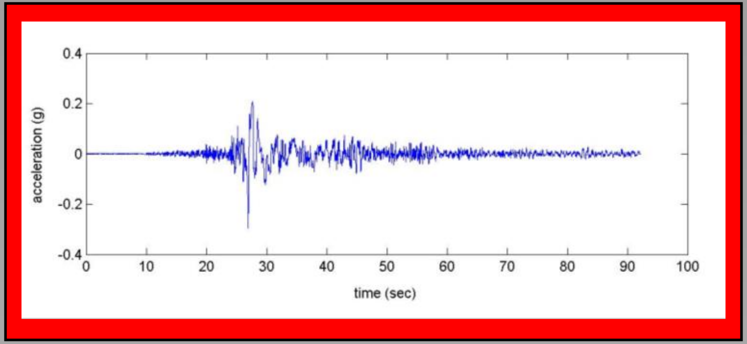


Other Processing Issues Addressed

- ✓ thin layer correction
- ✓ screening for other failure mechanisms
- ✓ pre- vs. post-event CPT measurements
- ✓ non-linear shear mass participation (r_d)
- ✓ magnitude-correlated duration weighting (DWF_M)
- ✓ “fines” adjustment

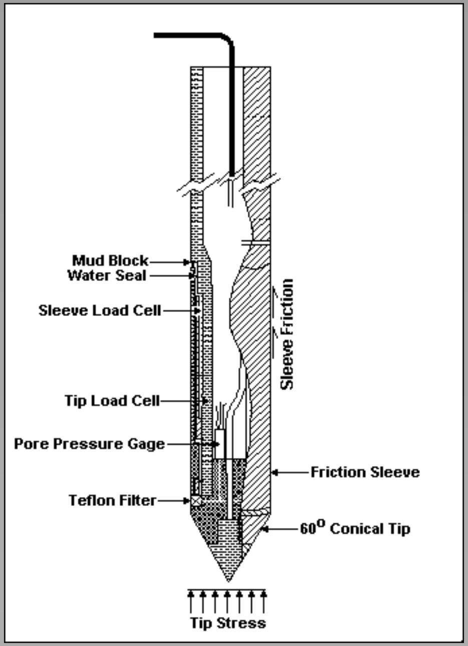
PROBABILISTIC METHODOLOGY

Reliability = f("Load" vs. "Resistance")



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

Uniform Cyclic Stress Ratio



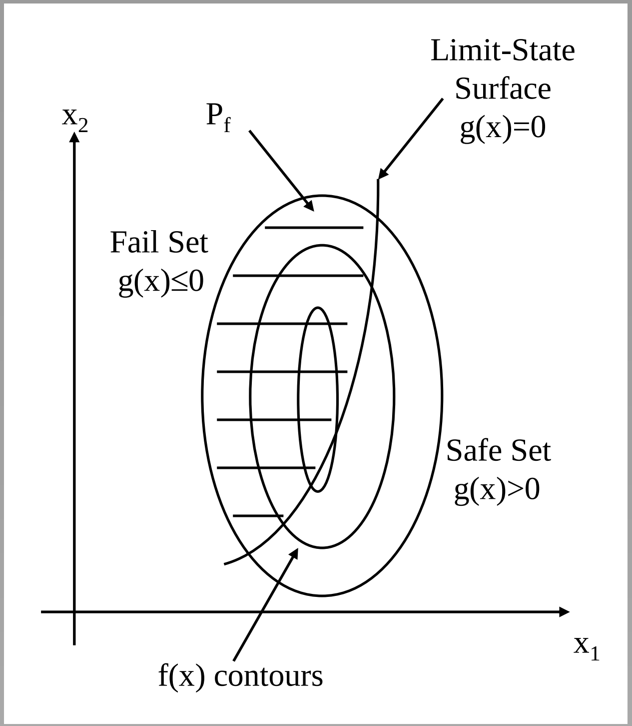
Cone Penetration Test

Basic Limit-State Model

$$\hat{g}(q_{c,1}, CSR) = q_{c,1} - \ln(CSR)$$

Model Parameters

$$\hat{g}(q_{c,1}, CSR, \theta) = q_{c,1} - \theta_1 \ln(CSR) + \theta_2$$



Optimized Model

$$g = q_{c,1}(1+\theta_1 R_f) + (1+\theta_2 R_f) + c(1+\theta_3 R_f) - \theta_4 \ln(CSR) - \theta_5 \ln(M_w) - \theta_6 \ln(\sigma_v') - \theta_7 + \varepsilon$$

Accounting for Model Error

$$g(q_{c1}, CSR, \theta, \varepsilon) = \hat{g}(q_{c1}, CSR, \theta) + \varepsilon$$

$$\varepsilon = N(0, \sigma_\varepsilon)$$

Accounting for Parameter Uncertainty

$$g(Q, S, \theta, \varepsilon) = \hat{g}(Q, S, \theta) + \varepsilon$$

$$Q = q_{c1} + e_{q_{c1}}$$

$$e_{q_{c1}} = N(0, \sigma_{q_{c1}})$$

$$S = \ln(CSR) + e_{\ln(CSR)}$$

$$e_{\ln(CSR)} = N(0, \sigma_{\ln(CSR)})$$

BAYESIAN UPDATING

Bayes' Rule → $f(\Theta) = c \cdot L(\Theta) \cdot p(\Theta)$

Posterior distribution $f(\Theta)$

Likelihood function $L(\Theta)$

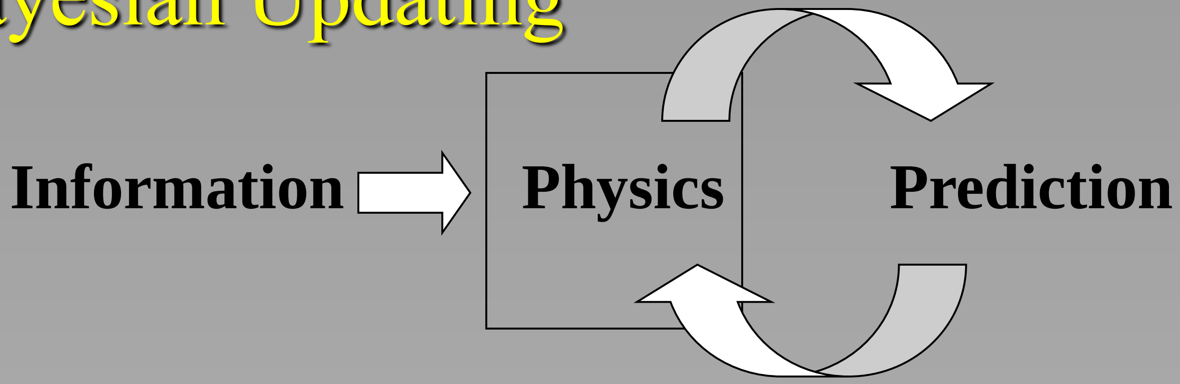
Prior distribution (non-informative) $p(\Theta)$

Normalizing constant $c = [\int L(\Theta) \cdot p(\Theta) \cdot d(\Theta)]^{-1}$

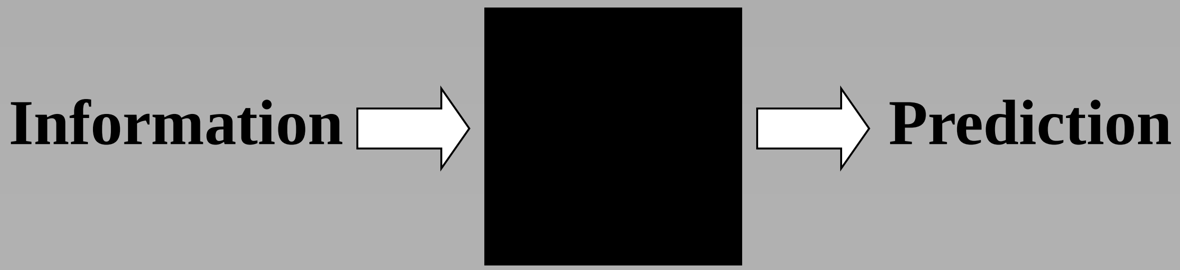
Application -- Estimating Model Parameters

Model Formulation and Parameter Estimation Techniques

- Bayesian Updating



- Artificial Neural Networks
- System Identification



RELIABILITY ANALYSIS

probability of liquefaction = summation of the probabilities of all possible combinations of parameters that will define liquefaction

$$P\left[\hat{g}(Q,S,\theta)+\varepsilon\leq 0\right]=\int_{\hat{g}(Q,S,\theta)+\varepsilon\leq 0}\varphi(\varepsilon|\sigma_{\varepsilon})\cdot f(\theta,\sigma_{\varepsilon})\cdot d\varepsilon\cdot d\theta\cdot d\sigma_{\varepsilon}$$

MVFOSM

FORM

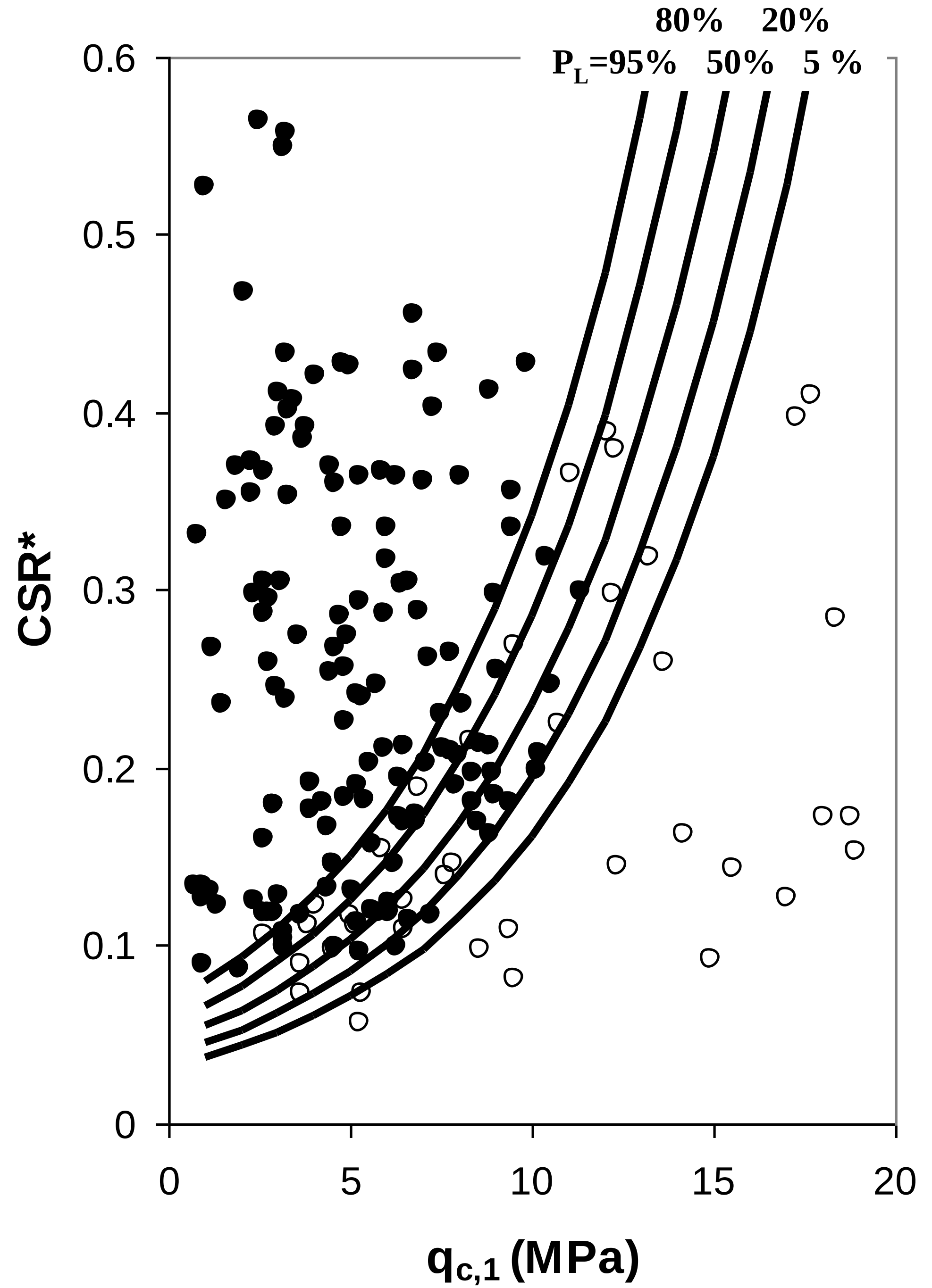
SORM

Monte Carlo Simulation

CORRELATION

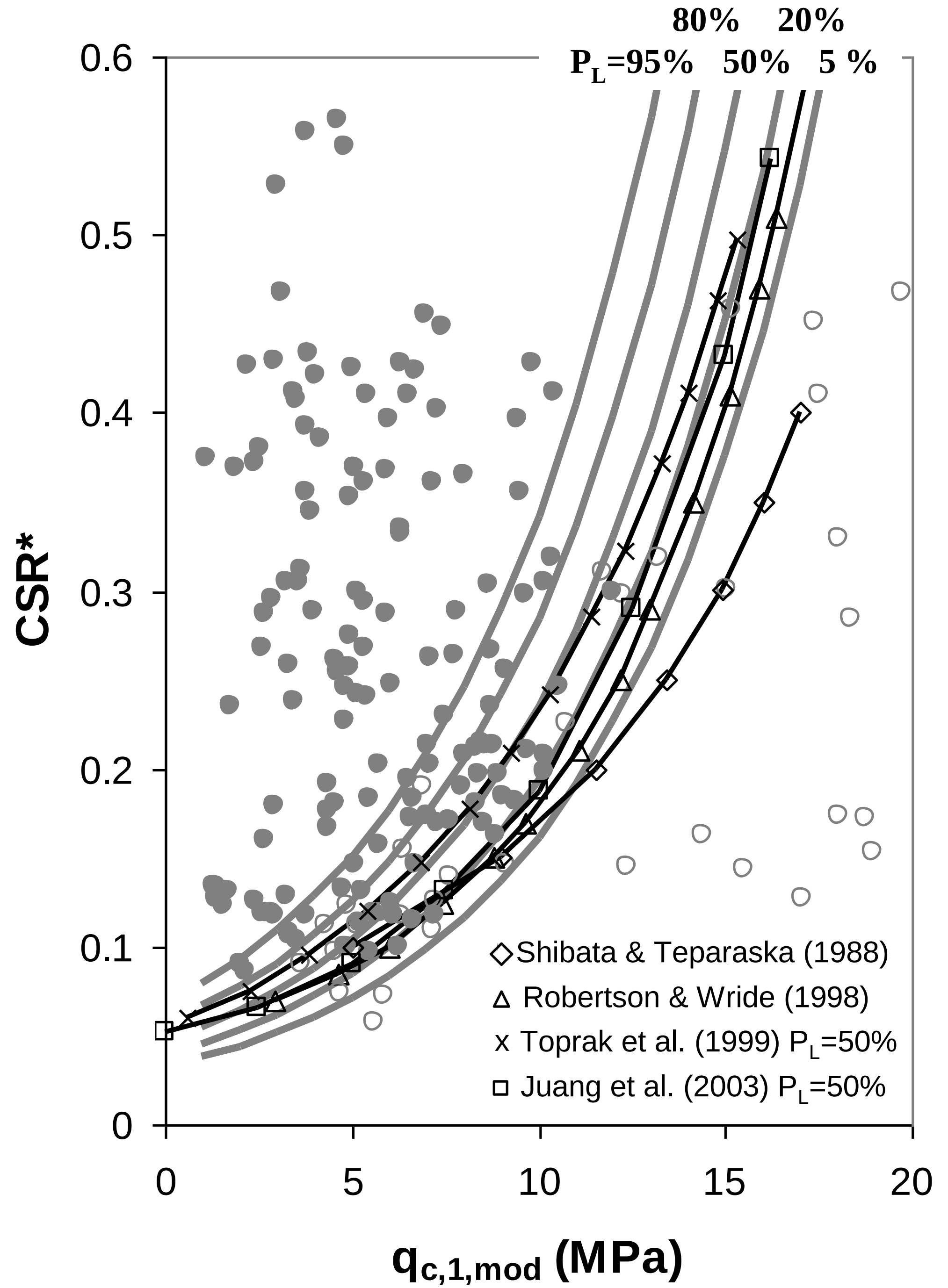
Equivalent Clean Sand

M_w=7.5 σ_v'=1 atm



Comparison with other studies (deterministic and probabilistic)

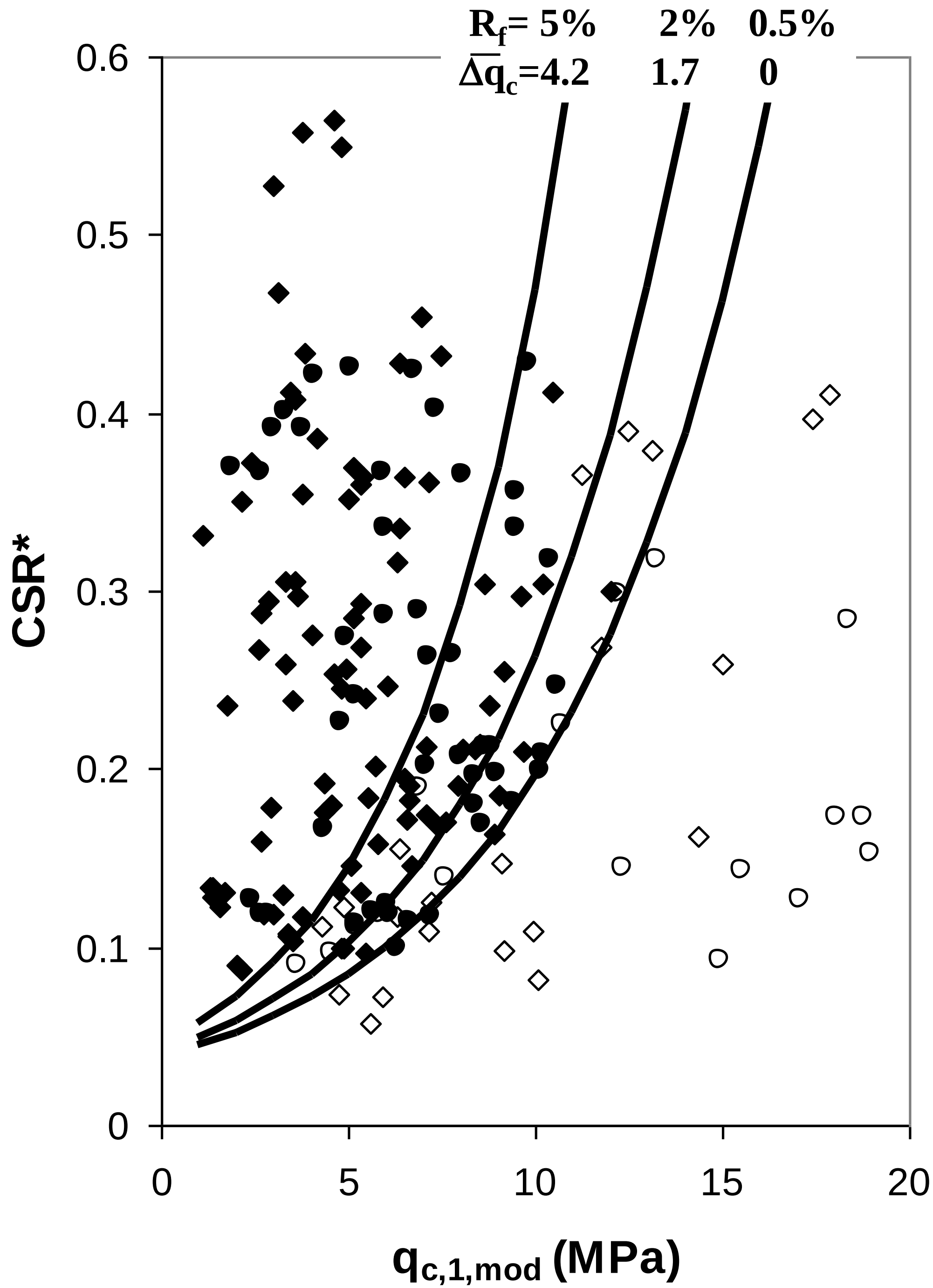
$$q_{c,1,mod} = q_{c,1} + \Delta q_{c,1}$$



"Fines" Adjusted

M_w=7.5 σ_v'=1 atm
P_L=20%

Note: $R_f \leq 0.5\%$ is an equivalent clean sand

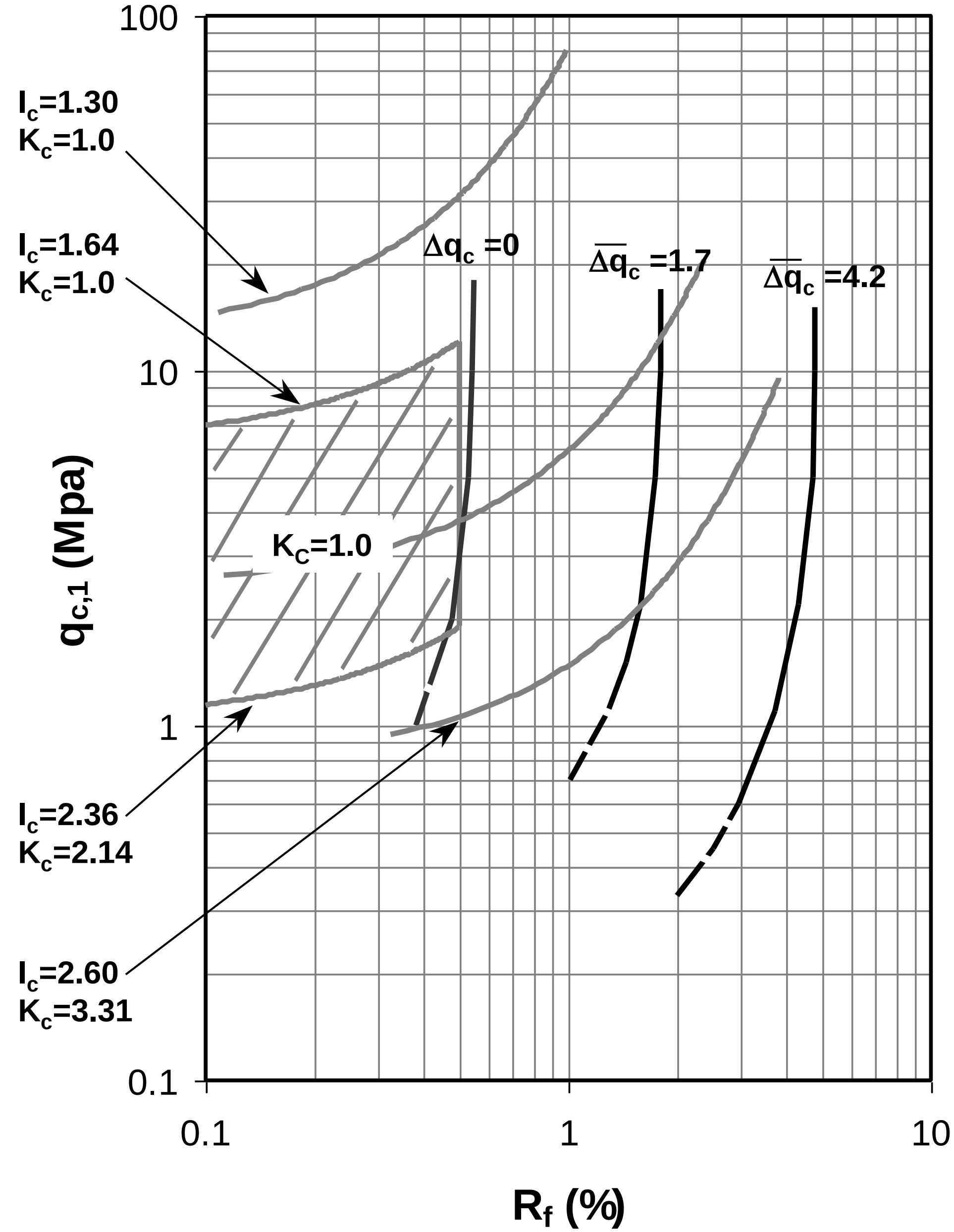


Proposed correction

$q_{c,1,mod} = q_{c,1} + \Delta q_{c,1}$

Robertson's correction

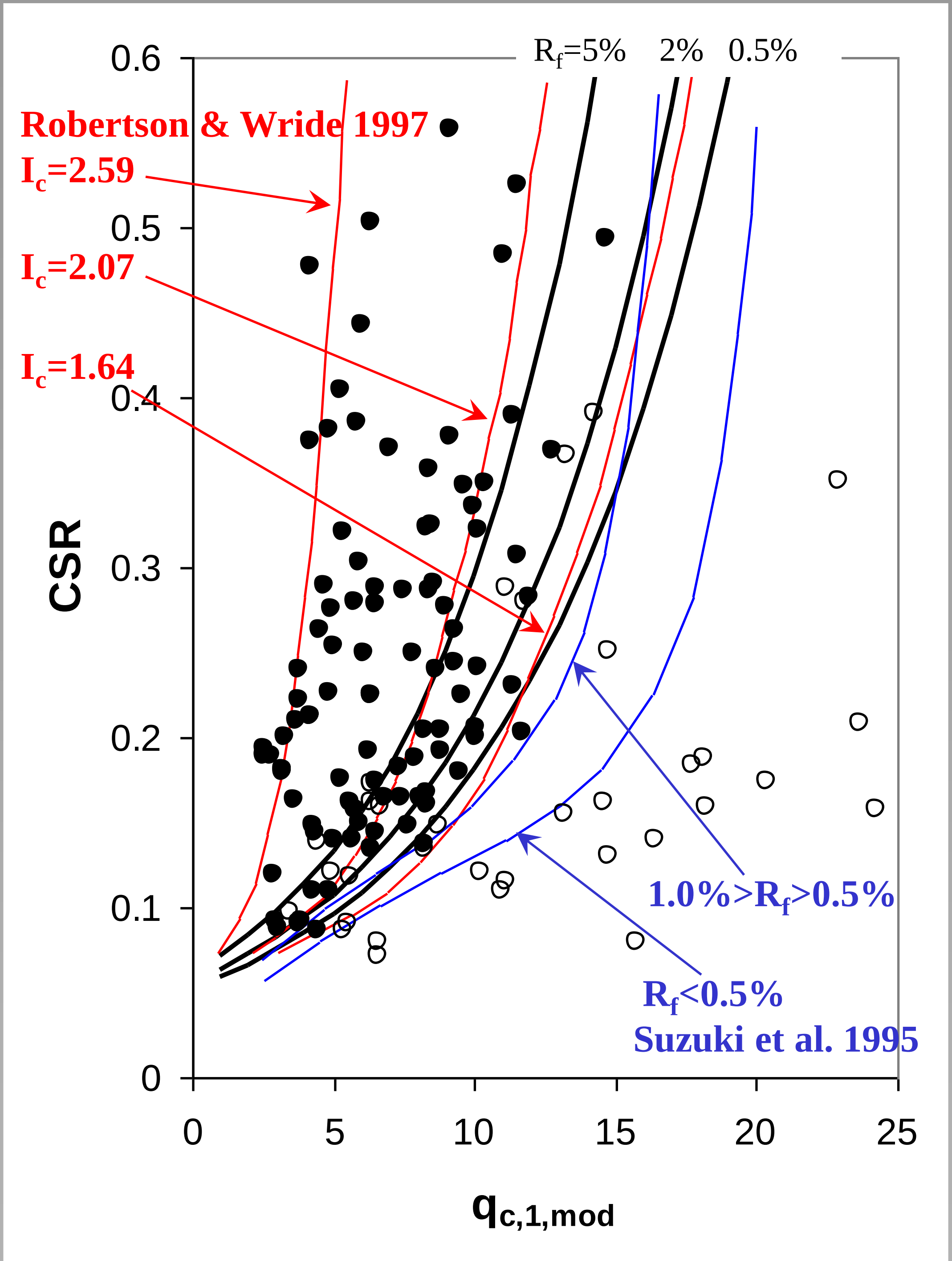
$q_{c,1,cs} = K_c \cdot q_{c,1}$



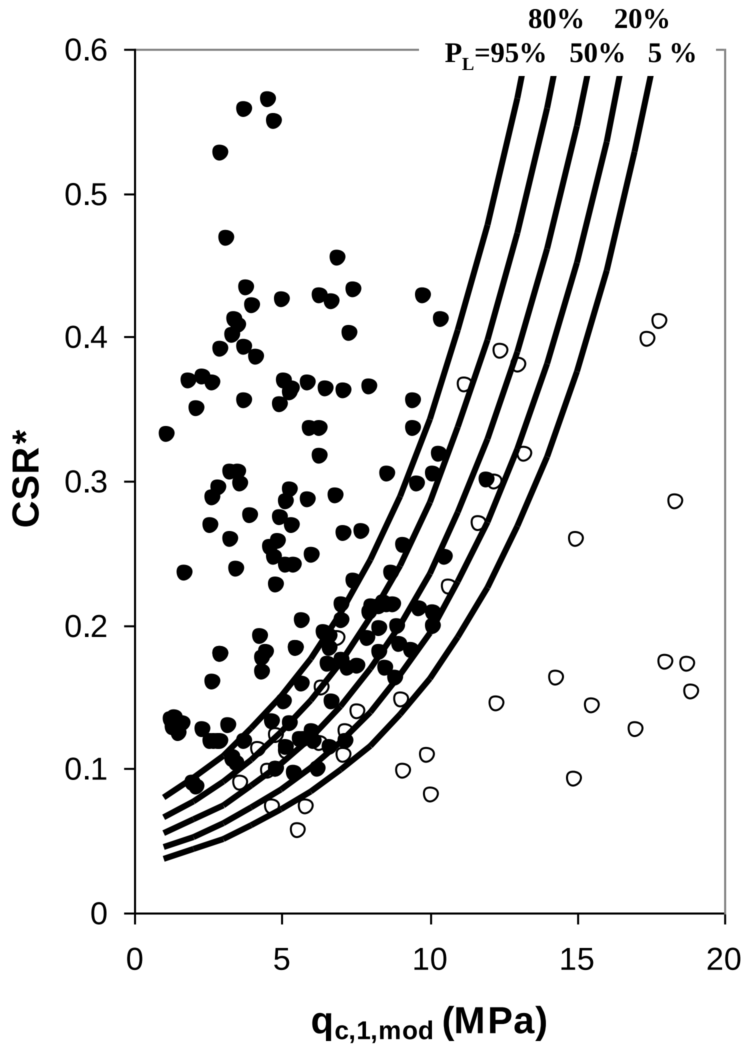
“Fines” Adjusted

P_L=20%
M_w=7.5
σ_v’=1 atm

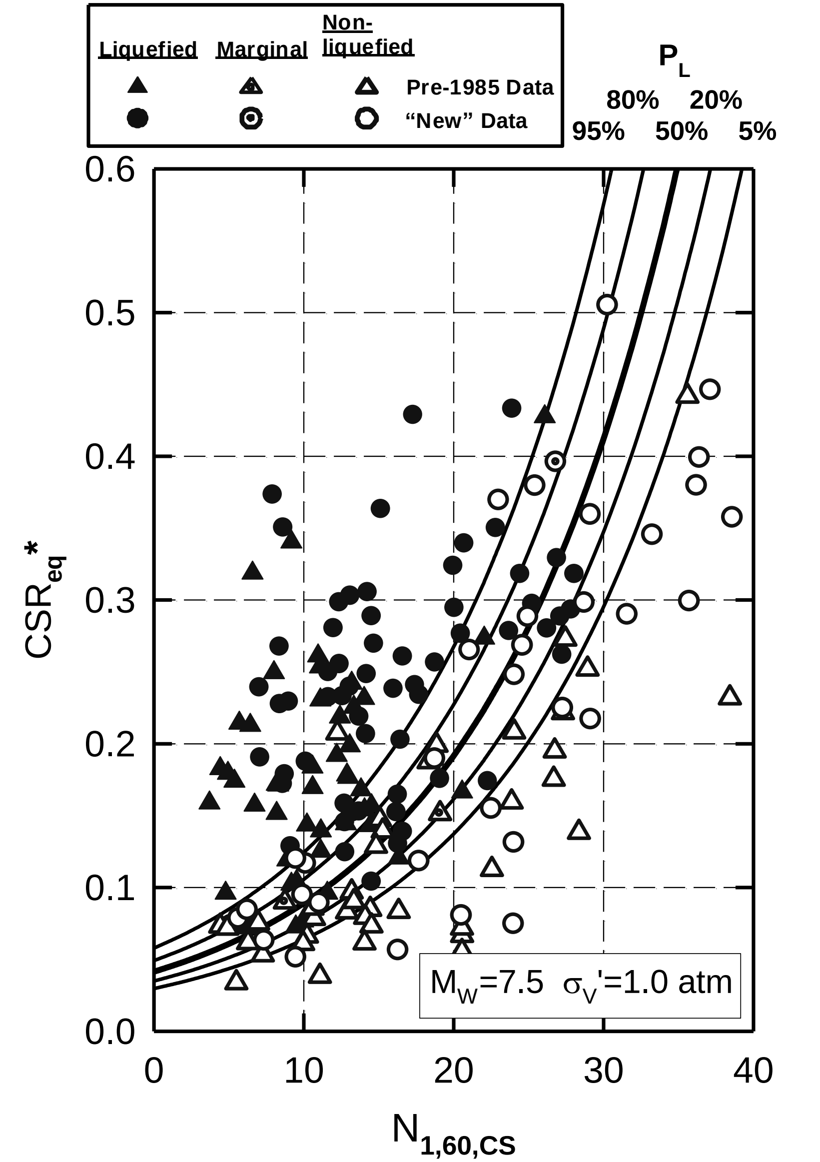
Note: Rf ≤ 0.5% is an equivalent clean sand



Probabilistic Liquefaction Triggering Correlations for the CPT and SPT at M_w=7.5 and σ_v'=1 atm.

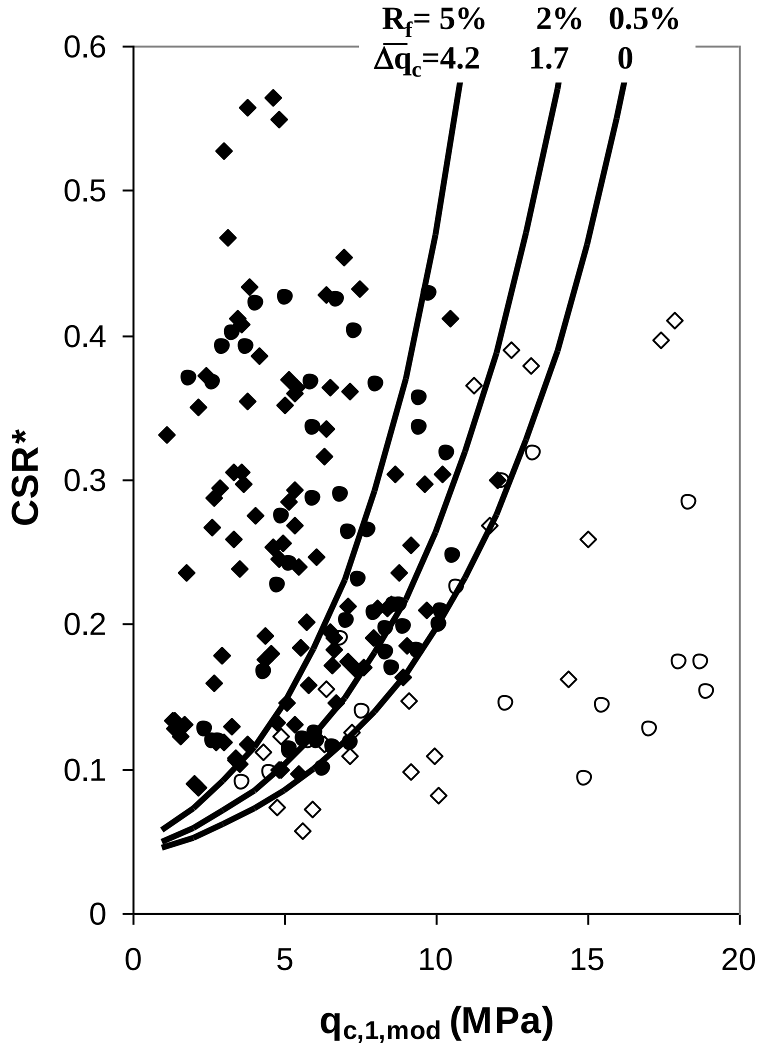


This Study



Cetin et al. (2004)

Deterministic Liquefaction Triggering Correlations for the CPT and SPT at M_w=7.5 and σ_v'=1 atm.



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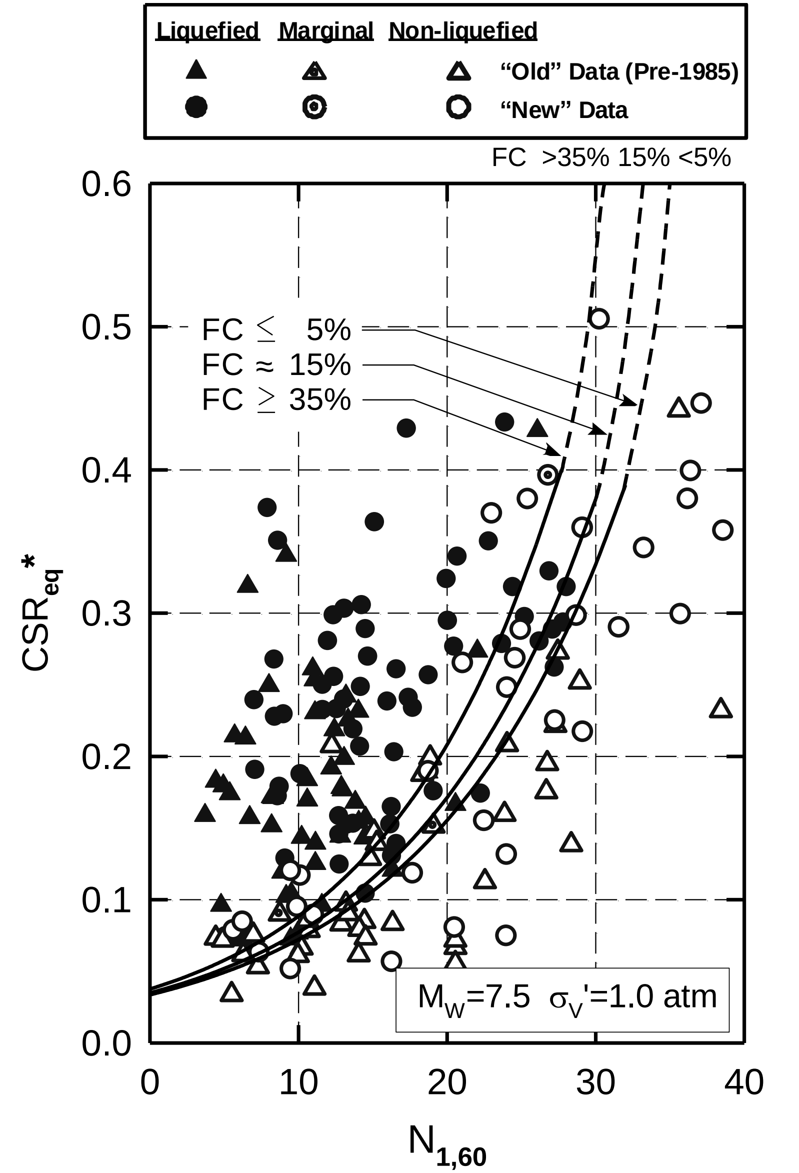

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