

## Chapter 6

# Liquefaction Triggering Correlations

### 6.1 Background

Liquefaction triggering correlations were first developed following the 1964 Niigata and Anchorage earthquakes. Laboratory experimentation was used in discerning trends of the phenomena of liquefaction but failed to capture important *in situ* characteristics such as soil fabric and the effects of aging. Researchers in Japan and the U.S. began characterizing the susceptibility of liquefiable material in relation to the standard penetration test (SPT). The development of the simplified procedure for evaluation of seismically induced shear stresses (Seed & Idriss, 1971) allowed for a concise assessment of stresses within a particular soil layer. Based on SPT data from past events of seismic liquefaction/non-liquefaction, correlations were developed.

#### 6.1.1 Deterministic Correlations

The advent of the cone penetrometer gave rise to another index test that could be used for correlation purposes. The advantages of the CPT are the continuous reading that it acquires of the soil profile and the high degree of standardization of testing equipment and procedures. The first CPT triggering correlation was presented by Seed, Idriss, and Arrango (1983) and used an SPT-to-CPT conversion to present the results of the SPT correlation in CPT space. The mapping of SPT to CPT was done because of the paucity of CPT triggering data. This method was used in subsequent studies with the addition of empirical data from other events, laboratory data, and the use of refined SPT-to-CPT

conversions (e.g. Robertson & Campanella, 1983; Olsen, 1984; Ishihara, 1985; Jamiolkowski et al., 1985; Seed & DeAlba, 1986; Franklin, 1986; Olsen & Koester, 1995).

The first work that used CPT directly as the primary index test was by Shibata & Teparaska (1988). By this time there existed a sufficiently large field case history database for an independent CPT correlation, however the fines content and grain size analysis derived from SPT sampling was still used to group the data into appropriate bins. Subsequent studies followed this pattern of using CPT tip resistance and SPT fines measurements (e.g. Rongxiang & Zhaoji, 1995; Stark & Olson, 1995).

The first wholly independent CPT-based correlation was presented by Suzuki et al. (1995). This work used both tip and sleeve resistance measurements from the CPT to determine the threshold for seismic liquefaction triggering. Follow-on studies by other researchers expanded the database and further developed the method of relying on CPT only measurements (e.g. Suzuki et al., 1997; Robertson and Wride, 1998). This approach avoids using SPT-to-CPT conversions (which are rough approximations at best), and does not require additional fines content or grain size data from other forms of sub-surface sampling.

On the theoretical side, Mitchell & Tseng (1990), presented a correlation that was based on cavity expansion analyses, validated with laboratory cyclic simple shear and cyclic

triaxial testing data. This work is valuable for bounding empirical results and providing a theoretical backbone.

### **6.1.2 Probabilistic Correlations**

All the correlations discussed so far are of a deterministic nature. However, the uncertainties associated with liquefaction can be large and the most accurate way to present the threshold of liquefaction initiation and the associated uncertainties is in a probabilistic manner. The first researchers to explore the probability associated with the phenomena of liquefaction were Christian & Swiger (1975) using SPT data converted to relative density and a form of discriminant analysis. Other researchers have assessed the probability of liquefaction triggering using SPT data and probabilistic methods such as logistic regression, artificial neural networks, and Bayesian analysis (e.g. Liao et al., 1988; Youd & Noble, 1997; Toprak et al., 1999; Juan et al., 2000; and Cetin et al., 2003). The Bayesian work by Cetin et al. (2003) was a precursor to the CPT-based assessment presented herein.

A probabilistic assessment of CPT-based triggering was first carried out by Reyna (1991) using discriminant analysis. Further work using artificial neural networks has been presented by Goh (1996) and Juang et al. (2000 & 2003).

### **6.2 Database**

This CPT-based liquefaction field case history database consists of sites conforming to data classes A, B, and C which have been processed according to the techniques outlined

in prior chapters. This database contains sites from 18 different earthquakes around the world that occurred from 1964 to 1999. This comprises the most extensive collection of field case history data for CPT-based liquefaction correlations to date.

More than 600 cases were studied, and 185 conforming to data classes A, B, and C were selected for use in development for use in development of the new correlations. Cases of high uncertainty, and cases with other significant potential deficiencies were deleted from further consideration (see Chapter 4). Table 6.1 presents the key variables for the 185 cases carried forward. Fuller descriptions of each case are presented in the Appendix.

The data is arranged by chronological order with all pertinent variables included. The variance of each parameter is included as a  $\pm 1$  standard deviation. The mean water table measurements are shown, not shown is the variance of the water tables which was assumed to be 0.3 m for all sites. Sites are described as liquefied or non-liquefied. The normalization exponent is shown in the column labeled c; this variable was treated deterministically and therefore no variance is given.

**Table 6.1 CPT-Based Liquefaction Triggering Database**

EVENT		M <sub>w</sub> ±											
1964 Niigata		7.50	0.11										
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR ±	q <sub>c,1</sub> (MPa) ±	R <sub>f</sub> (%) ±	c	σ <sub>v</sub> ' (kPa) ±	q <sub>c,1,mod</sub> (MPa)	CSR*
Site D	Y	B	2.7 to 6.0	2.70	0.55	1.12	0.15 0.05	6.24 1.73	1.14 0.65	0.45	32.44 4.16	6.70	0.15
Site E	Y	B	1.8 to 4.8	3.80	0.67	1.40	0.15 0.04	4.56 1.13	1.22 0.60	0.47	44.46 4.94	5.09	0.15
Site F	N	B	1.7 to 2.2	1.95	0.08	1.70	0.11 0.02	9.39 8.97	1.40 1.81	0.38	29.50 2.38	9.95	0.11
EVENT		M <sub>w</sub> ±											
1968 Inangahua		7.40	0.11										
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR ±	q <sub>c,1</sub> (MPa) ±	R <sub>f</sub> (%) ±	c	σ <sub>v</sub> ' (kPa) ±	q <sub>c,1,mod</sub> (MPa)	CSR*
Three Channel Flat	Y	C	0.5 to 2.5	1.50	0.33	0.10	0.48 0.19	2.84 0.96	1.39 0.70	0.53	15.27 3.37	3.89	0.47
Reedy's Farm	Y	B	1.0 to 1.8	1.38	0.13	0.10	0.24 0.08	2.62 0.69	0.79 0.52	0.65	14.10 2.51	2.88	0.24
EVENT		M <sub>w</sub> ±											
1975 Haicheng		7.30	0.11										
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR ±	q <sub>c,1</sub> (MPa) ±	R <sub>f</sub> (%) ±	c	σ <sub>v</sub> ' (kPa) ±	q <sub>c,1,mod</sub> (MPa)	CSR*
Chemical Fiber Site	Y	C	7.8 to 12.0	9.90	0.75	1.52	0.13 0.06	1.37 0.64	0.76 0.43	0.85	97.14 7.28	1.55	0.12
Const. Com. Bldg.	Y	C	5.5 to 7.5	6.50	0.33	1.52	0.14 0.05	0.77 0.14	1.37 0.27	0.92	67.60 4.94	1.39	0.13
Guest House	Y	C	8.0 to 9.5	8.75	0.25	1.52	0.13 0.05	0.97 0.18	1.08 0.41	0.86	87.15 5.42	1.38	0.13
17th Middle School	Y	C	4.5 to 11.0	7.75	1.08	1.52	0.14 0.06	0.92 0.29	1.02 0.44	0.87	75.34 8.40	1.29	0.13
Paper Mill	Y	C	3 to 5	4.00	0.33	1.52	0.14 0.05	1.16 0.31	1.28 0.56	0.77	45.87 4.44	1.71	0.13
EVENT		M <sub>w</sub> ±											
1976 Tangshan		8.00	0.09										
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR ±	q <sub>c,1</sub> (MPa) ±	R <sub>f</sub> (%) ±	c	σ <sub>v</sub> ' (kPa) ±	q <sub>c,1,mod</sub> (MPa)	CSR*
Tientsin Y24	Y	C	3.5 to 4.5	4.00	0.17	0.20	0.11 0.05	3.64 0.32	0.72 0.15	0.70	38.12 3.34	3.77	0.12
Tientsin Y28	Y	C	1 to 3	2.00	0.33	0.20	0.11 0.05	2.78 0.87	0.78 0.33	0.68	19.74 3.13	2.96	0.12
Tientsin Y21	Y	C	4.5 to 5.25	4.88	0.13	1.00	0.09 0.04	0.97 0.42	2.50 1.84	0.76	51.61 4.02	2.08	0.10
Tientsin Y29	Y	C	2.8 to 3.8	3.30	0.17	1.00	0.09 0.04	1.93 0.22	0.91 0.59	0.74	37.14 2.80	2.16	0.10
T1 Tangshan District	Y	C	4.1 to 5.8	4.95	0.45	3.70	0.26 0.11	5.95 1.29	0.38 0.38	0.75	70.69 4.26	7.04	0.29

EVENT	$M_w$	$\pm$
1976 Tangshan	8.00	0.09

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Tientsin Y21	Y	C	4.5 to 5.25	4.88	0.13	1.00	0.09	0.04	0.97	0.42	2.50	1.84	0.76	51.61	4.02	2.08	0.10
Tientsin Y29	Y	C	2.8 to 3.8	3.30	0.17	1.00	0.09	0.04	1.93	0.22	0.91	0.59	0.74	37.14	2.80	2.16	0.10
T1 Tangshan District	Y	C	4.1 to 5.8	4.95	0.45	3.70	0.26	0.11	5.95	1.29	0.38	0.38	0.75	70.69	4.26	7.04	0.29
T2 Tangshan District	Y	C	2.3 to 4.3	3.30	0.23	1.30	0.36	0.15	3.79	1.56	0.38	0.38	0.78	39.18	2.93	3.79	0.39
T8 Tangshan District	Y	C	4.5 to 6.0	5.25	0.25	2.00	0.33	0.14	8.03	3.68	0.38	0.38	0.72	61.87	3.54	8.03	0.36
T10 Tangshan District	Y	C	6.5 to 9.8	8.15	0.55	1.45	0.34	0.15	5.90	1.01	0.38	0.38	0.75	84.77	5.92	5.90	0.37
T19 Tangshan District	Y	C	2.0 to 4.5	3.25	0.42	1.10	0.19	0.08	8.00	1.74	0.38	0.38	0.69	38.17	3.71	8.00	0.21
T22 Tangshan District	Y	C	7.0 to 8.0	7.50	0.17	0.80	0.19	0.08	8.83	2.21	0.38	0.38	0.70	76.25	4.90	8.83	0.21
T32 Tangshan District	Y	C	2.6 to 3.9	3.25	0.23	2.30	0.11	0.05	5.63	0.75	0.38	0.38	0.74	50.13	3.63	5.63	0.12
Tientsin F13	N	C	3.1 to 5.1	4.10	0.33	0.70	0.10	0.04	1.63	0.35	2.62	0.74	0.60	42.45	3.66	2.85	0.11
T21 Tangshan District	N	C	3.1 to 4.0	3.55	0.15	3.10	0.13	0.05	15.52	1.21	0.38	0.38	0.72	55.51	3.03	15.52	0.14
T30 Tangshan District	N	C	5.0 to 8.0	6.50	0.50	2.50	0.08	0.04	14.92	1.64	0.38	0.38	0.65	76.76	4.78	14.92	0.09
T36 Tangshan District	N	C	5.7 to 9.0	7.35	0.55	2.30	0.13	0.06	7.61	1.10	0.38	0.38	0.72	83.21	5.33	7.61	0.14

EVENT	$M_w$	$\pm$
1977 Vrancea	7.20	0.11

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Site 2	N	C	6.5 to 9.0	7.75	0.42	1.00	0.13	0.06	3.45	1.82	0.38	0.38	0.55	78.03	5.47	3.45	0.12

EVENT	$M_w$	$\pm$
1979 Imperial Valley	6.50	0.13

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Radio Tower B1	Y	A	3.0 to 5.5	4.25	0.42	2.01	0.16	0.03	4.38	2.21	0.96	0.58	0.52	52.75	4.53	4.74	0.13
McKim Ranch A	Y	A	1.5 to 4.0	2.75	0.42	1.50	0.44	0.07	4.61	1.48	1.13	0.40	0.52	35.49	4.38	5.34	0.36
Kornbloom B	N	A	2.6 to 5.2	3.90	0.43	2.74	0.09	0.01	3.65	2.48	2.45	1.87	0.44	54.50	4.58	4.72	0.07
Wildlife B	N	B	3.7 to 6.7	5.20	0.50	0.90	0.13	0.04	6.45	3.83	1.50	1.00	0.40	56.52	4.90	7.15	0.11
Radio Tower B2	N	A	2.0 to 3.0	2.50	0.17	2.01	0.12	0.02	8.59	5.47	1.41	1.12	0.40	36.66	3.71	9.18	0.10

EVENT	$M_w$	$\pm$
1980 Mexicali	6.20	0.14

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Delta Site2	Y	B	2.2 to 3.2	2.70	0.17	2.20	0.14	0.04	7.28	1.33	0.04	0.01	0.90	39.30	4.19	7.28	0.10
Delta Site3	Y	B	2.0 to 3.8	2.90	0.30	2.00	0.15	0.04	3.14	0.56	0.78	0.20	0.65	39.37	4.46	3.35	0.11
Delta Site3p	Y	B	2.2 to 3.8	3.00	0.27	2.20	0.14	0.04	3.19	0.96	0.93	0.31	0.58	41.75	4.40	3.50	0.11
Delta Site4	Y	B	2.0 to 2.6	2.30	0.10	2.00	0.13	0.04	5.28	0.46	0.81	0.10	0.53	34.46	4.08	5.49	0.10
Delta Site1	N	B	4.8 to 5.3	5.05	0.08	2.30	0.16	0.05	4.68	0.00	1.96	1.12	0.43	59.32	4.33	5.81	0.12

EVENT	$M_w$	$\pm$
1981 Westmorland	5.90	0.15

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Wildlife B	Y	B	2.7 to 6.7	4.72	0.67	0.91	0.24	0.06	6.80	3.13	1.38	0.77	0.43	51.93	5.94	7.60	0.17
Kornbloom B	Y	B	2.8 to 5.8	4.30	0.50	2.74	0.14	0.03	3.20	1.88	2.78	1.79	0.40	58.18	4.86	4.82	0.10
Radio Tower B1	Y	A	3.0 to 5.5	4.25	0.42	2.00	0.14	0.02	4.61	1.99	0.88	0.42	0.52	50.43	4.92	4.88	0.10
McKim Ranch A	N	B	1.5 to 5.2	3.35	0.61	1.50	0.08	0.02	5.29	1.35	1.13	0.32	0.50	39.15	5.56	5.60	0.06
Radio Tower B2	N	A	2 to 3	2.50	0.17	2.01	0.12	0.02	9.52	4.57	1.36	0.73	0.40	36.17	4.17	10.07	0.08

EVENT	$M_w$	$\pm$
1983 Nihonkai-Chubu	7.70	0.10

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Akita A	Y	C	0.8 to 6.5	3.50	0.97	0.78	0.18	0.08	5.44	3.38	2.01	2.66	0.40	37.48	6.60	6.64	0.18
Akita B	Y	B	3.3 to 6.7	5.00	0.67	1.03	0.17	0.06	3.93	1.84	1.05	1.28	0.52	52.96	5.30	4.36	0.18
Akita C	N	B	2.0 to 4.0	3.00	0.33	2.40	0.12	0.04	4.04	0.96	1.77	0.91	0.48	43.91	3.31	4.86	0.12

EVENT	$M_w$	$\pm$
1983 Borah Peak	6.90	0.12

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	$\pm$	w.t. (m)	CSR	$\pm$	$q_{c,1}$ (MPa)	$\pm$	$R_f$ (%)	$\pm$	c	$\sigma_v'$ (kPa)	$\pm$	$q_{c,1,mod}$ (MPa)	CSR*
Pence Ranch	Y	B	1.5 to 4.0	2.75	0.42	1.55	0.24	0.07	7.54	2.24	1.38	0.76	0.43	37.98	3.92	8.34	0.21
Whiskey Springs Site 1	Y	B	1.6 to 3.2	2.40	0.27	0.80	0.46	0.12	8.87	5.04	1.83	1.89	0.35	29.10	3.13	10.43	0.41

EVENT	M <sub>w</sub>	±
1983 Borah Peak	6.90	0.12

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Whiskey Springs Site 2	Y	B	2.4 to 4.3	3.35	0.32	2.40	0.34	0.09	6.60	3.03	3.90	3.11	0.32	50.01	3.57	10.18	0.30
Whiskey Springs Site 3	Y	B	6.8 to 7.8	7.30	0.17	6.80	0.24	0.07	7.80	2.07	2.58	1.65	0.33	120.45	5.03	9.70	0.21

EVENT	M <sub>w</sub>	±
1987 Edgecumbe	6.60	0.13

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Robinson Farm E.	Y	B	2.0 to 5.5	3.75	0.58	0.76	0.51	0.16	10.54	4.38	0.37	0.19	0.60	28.03	4.29	10.54	0.43
Robinson Farm W.	Y	C	1.0 to 2.8	1.90	0.30	0.61	0.48	0.19	13.84	1.97	0.10	0.00	0.73	16.19	3.13	13.84	0.40
Gordon Farm	Y	B	1.2 to 4.2	2.70	0.50	0.47	0.55	0.19	8.05	2.68	0.65	0.25	0.53	19.50	3.82	8.23	0.45
Brady Farm	Y	C	6.4 to 8.0	7.70	0.27	1.65	0.37	0.13	3.09	1.07	0.97	0.37	0.52	58.35	4.97	3.60	0.31
Morris Farm	Y	B	7.0 to 8.5	7.75	0.25	1.63	0.38	0.11	10.39	1.17	0.37	0.06	0.58	58.46	4.98	10.39	0.32
Awaroa Farm	Y	B	2.3 to 3.3	2.80	0.17	1.15	0.36	0.09	11.36	2.20	1.10	0.25	0.38	26.06	3.04	12.01	0.30
Keir Farm	Y	B	6.5 to 9.5	8.00	0.50	2.54	0.26	0.08	8.61	1.24	0.31	0.06	0.43	67.90	5.23	8.61	0.21
James St. Loop	Y	B	3.4 to 6.8	5.10	0.57	1.15	0.31	0.09	9.08	3.00	0.56	0.24	0.53	39.15	4.58	9.14	0.26
Landing Rd. Bridge	Y	B	4.8 to 6.2	5.50	0.23	1.15	0.30	0.08	10.57	2.07	0.32	0.07	0.63	41.43	4.06	10.57	0.25
Whakatane Pony Club	Y	B	3.6 to 4.6	4.10	0.17	2.35	0.22	0.05	8.60	1.64	0.10	0.03	0.88	44.03	3.33	8.60	0.18
Sewage Pumping Station	Y	B	2.0 to 8.0	5.00	1.00	1.29	0.28	0.09	7.47	2.34	0.30	0.21	0.67	39.81	5.94	7.47	0.23
Whakatane Pipe Breaks	Y	B	5.0 to 5.9	5.45	0.15	2.50	0.32	0.08	7.77	1.57	0.39	0.12	0.40	53.04	3.69	7.77	0.26
Gordon Farm	N	B	1.7 to 1.9	1.80	0.03	0.90	0.34	0.09	21.57	3.81	0.50	0.26	0.50	18.17	2.77	21.57	0.28
Brady Farm	N	B	3.4 to 5.0	4.20	0.27	1.53	0.38	0.13	13.24	2.09	0.41	0.13	0.56	37.38	3.53	13.24	0.32
Morris Farm	N	B	5.2 to 6.6	5.90	0.23	2.10	0.36	0.12	12.23	2.08	0.31	0.12	0.65	52.07	3.99	12.23	0.30
Whakatane Hospital	N	B	4.4 to 5.0	4.70	0.10	4.40	0.15	0.04	17.05	2.25	0.49	0.09	0.50	65.51	3.90	17.05	0.13
Whakatane Board Mill	N	B	7 to 8	7.50	0.17	1.44	0.27	0.10	10.73	2.94	0.43	0.17	0.63	55.36	4.85	10.73	0.23

EVENT	M <sub>w</sub>	±
1987 Elmore Ranch	6.20	0.14

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Wildlife B	N	B	3.7 to 6.7	5.20	0.50	0.90	0.16	0.05	6.45	3.83	1.50	1.00	0.40	56.52	4.90	7.23	0.13

EVENT	M <sub>w</sub>	±
1987 Superstition Hills	6.60	0.13

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Wildlife B	Y	B	3.7 to 6.7	5.20	0.50	0.90	0.20	0.06	6.45	3.83	1.50	1.00	0.40	56.52	4.90	7.31	0.17

EVENT	M <sub>w</sub>	±
1989 Loma Prieta	7.00	0.12

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
SFOBB-1	Y	A	6.25 to 7.0	6.75	0.13	2.99	0.17	0.01	5.63	0.73	0.66	0.13	0.66	90.64	3.90	5.76	0.16
SFOBB-2	Y	A	6.5 to 8.5	7.50	0.34	2.99	0.18	0.01	8.84	1.95	0.55	0.23	0.62	96.79	4.72	8.88	0.16
P007-2	Y	B	5.5 to 6.8	6.15	0.66	2.30	0.22	0.05	7.09	0.84	0.45	0.06	0.70	73.41	5.50	7.09	0.20
P007-3	Y	B	7.1 to 8.1	7.60	0.17	2.30	0.22	0.05	10.84	1.20	0.25	0.05	0.67	85.51	4.35	10.84	0.20
POR-2	Y	B	5.3 to 7.6	6.45	0.38	2.40	0.13	0.03	2.66	0.76	0.63	0.20	0.74	74.42	4.17	2.75	0.12
POR-3	Y	B	5.0 to 7.0	6.00	0.33	2.40	0.13	0.03	2.64	1.15	0.48	0.23	0.78	71.48	4.01	2.64	0.12
POR-4	Y	B	6.0 to 7.0	6.50	0.17	2.40	0.13	0.03	2.88	0.59	0.43	0.10	0.80	76.08	3.81	2.88	0.12
Marine Lab. C4	Y	A	5.2 to 5.8	5.50	0.10	2.50	0.20	0.03	2.92	0.58	0.51	0.16	0.78	66.32	3.19	2.93	0.18
Marine Lab. UC-7	Y	B	7.6 to 9.8	8.30	0.50	2.00	0.20	0.05	4.90	1.53	1.20	0.57	0.55	86.75	5.68	5.49	0.18
Sandholdt Rd. UC-4	Y	A	2.4 to 4.6	3.50	0.37	2.70	0.23	0.03	11.66	8.81	0.44	0.36	0.60	48.55	2.99	11.66	0.21
Moss Landing State Beach 14	Y	A	2.4 to 4.0	3.20	0.27	2.40	0.21	0.03	7.91	1.15	0.55	0.10	0.65	44.55	3.86	7.95	0.19
Woodward Marine UC-11	Y	B	2.5 to 3.4	2.85	0.15	2.50	0.20	0.04	9.40	1.71	0.48	0.10	0.64	43.22	3.88	9.40	0.18
Harbor Office UC-12 & 13	Y	B	2.9 to 4.7	3.80	0.30	1.90	0.20	0.07	8.98	5.23	0.58	0.36	0.56	47.86	4.24	9.04	0.19
Marine Lab. C4	Y	A	5.2 to 5.8	5.50	0.10	2.50	0.20	0.03	2.92	0.58	0.51	0.16	0.78	66.32	3.19	2.93	0.18
Marine Lab. UC-7	Y	B	7.6 to 9.8	8.30	0.50	2.00	0.20	0.05	4.90	1.53	1.20	0.57	0.55	86.75	5.68	5.49	0.18
T.I. Naval Station	Y	B	3.5 to 7.0	5.25	0.58	1.50	0.14	0.04	5.05	1.91	0.85	0.50	0.60	60.64	4.67	5.30	0.13
Farris Farm Site	Y	A	6.0 to 7.0	6.50	0.17	4.50	0.28	0.05	4.44	0.52	0.71	0.10	0.67	87.13	3.87	4.64	0.25
Miller Farm CMF 8	Y	A	6.8 to 8.0	7.40	0.20	4.91	0.25	0.03	4.83	0.94	0.25	0.20	0.81	98.99	4.16	4.83	0.23
Miller Farm CMF 10	Y	A	7.0 to 9.7	8.65	0.45	3.00	0.37	0.06	4.80	2.41	1.93	0.99	0.45	99.92	5.36	6.34	0.34
Miller Farm CMF 5	Y	A	5.5 to 8.5	7.00	0.51	4.70	0.29	0.04	7.13	1.57	0.49	0.20	0.63	99.84	5.18	7.13	0.26
Miller Farm CMF 3	Y	A	5.75 to 7.50	6.50	0.29	3.00	0.26	0.04	3.27	1.44	0.72	0.44	0.71	95.70	4.46	3.47	0.24
Model Airport 18	Y	B	3.7 to 4.5	4.10	0.13	2.40	0.22	0.06	8.93	1.45	0.35	0.09	0.72	54.02	2.90	8.93	0.20
Model Airport 21	Y	B	3.4 to 4.7	4.05	0.22	2.40	0.22	0.06	8.38	2.54	0.30	0.11	0.74	53.56	3.07	8.38	0.20
Farris 58	Y	B	7.4 to 8.0	7.70	0.10	4.80	0.19	0.06	8.54	0.35	0.48	0.02	0.67	103.45	4.18	8.54	0.17

EVENT	M <sub>w</sub>	±
1989 Loma Prieta	7.00	0.12

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Farris 61	Y	B	6.0 to 7.3	6.65	0.22	4.20	0.20	0.06	4.27	0.58	0.81	0.12	0.64	86.39	3.92	4.53	0.18
Granite Const. 123	Y	B	7.2 to 7.8	7.50	0.10	5.00	0.18	0.06	4.36	0.28	0.50	0.16	0.73	102.98	4.17	4.36	0.17
Jefferson 121	Y	B	6.5 to 7.75	7.13	0.21	3.40	0.12	0.04	6.10	0.97	0.45	0.08	0.71	90.33	4.14	6.10	0.11
Jefferson 141	Y	B	3.1 to 4.5	3.80	0.23	2.10	0.13	0.04	3.02	0.75	0.83	0.26	0.70	50.27	3.20	3.25	0.12
Jefferson 148	Y	B	7.0 to 7.9	7.45	0.15	3.00	0.12	0.04	7.20	1.81	0.38	0.11	0.72	94.12	4.22	7.20	0.11
Jefferson Ranch 32	Y	B	2.3 to 3.1	2.70	0.13	1.80	0.13	0.03	5.22	0.77	0.31	0.05	0.79	37.07	2.55	5.22	0.11
Kett 74	Y	B	2.3 to 3.1	2.70	0.13	1.50	0.26	0.07	8.08	0.88	1.20	0.31	0.46	36.38	2.55	8.74	0.24
Leonardini 39	Y	B	2.3 to 4.7	3.50	0.40	1.90	0.14	0.04	6.07	1.88	0.16	0.05	0.87	45.10	3.58	6.07	0.12
Leonardini 51	Y	B	3.1 to 3.7	3.40	0.10	1.80	0.14	0.04	2.39	0.32	0.48	0.08	0.81	43.50	2.63	2.39	0.13
Leonardini 53	Y	B	2.7 to 3.6	3.15	0.15	2.10	0.13	0.03	6.65	0.82	0.28	0.11	0.78	44.82	2.73	6.65	0.11
Marinovich 65	Y	B	6.8 to 9.4	8.60	0.60	5.60	0.21	0.06	6.33	0.48	0.67	0.10	0.65	121.47	6.07	6.48	0.19
Radovich 99	Y	B	4.75 to 6.9	4.83	0.18	4.10	0.19	0.05	6.37	0.93	0.74	0.15	0.62	72.26	3.54	6.57	0.17
Sea Mist 31	Y	B	2.8 to 3.7	3.25	0.15	0.80	0.18	0.05	2.67	0.79	0.53	0.19	0.76	36.29	2.80	2.69	0.16
Silliman 68	Y	B	4.7 to 7.1	5.90	0.40	3.50	0.22	0.06	5.56	0.35	0.69	0.05	0.64	79.83	4.28	5.73	0.20
SP Bridge 48	Y	B	6.0 to 7.5	6.75	0.25	5.30	0.21	0.06	3.95	0.73	0.95	0.19	0.61	100.15	4.38	4.34	0.19
Alameda Bay Farm Is.	N	A	5 to 6	5.50	0.17	2.50	0.16	0.03	7.85	2.98	2.15	0.89	0.34	74.32	3.56	9.11	0.15
MBARI 3 RC-6	N	A	3.0 to 4.5	3.75	0.25	2.60	0.18	0.03	21.48	1.39	0.21	0.06	0.74	52.74	3.05	21.48	0.16
MBARI 3 RC-7	N	A	4.0 to 5.0	4.50	0.17	3.70	0.16	0.02	12.35	0.81	0.30	0.06	0.70	66.95	3.24	12.35	0.14
Sandholdt Rd. UC2	N	A	3.0 to 4.5	3.75	0.25	2.70	0.18	0.03	25.55	7.61	0.30	0.10	0.65	50.90	3.51	25.55	0.16
General Fish CPT-6	N	A	2.2 to 3.2	2.70	0.17	1.70	0.19	0.03	18.06	2.78	0.32	0.06	0.70	39.09	3.74	18.06	0.17
MBARI 4 CPT-1	N	A	2.3 to 3.5	2.90	0.20	1.90	0.19	0.03	18.79	1.99	0.28	0.06	0.70	38.27	3.28	18.79	0.17
Sandholdt Rd. UC-6	N	A	6.2 to 7.0	6.60	0.13	2.70	0.19	0.03	20.99	0.68	0.30	0.05	0.70	85.64	4.26	20.99	0.17
Moss Landing State Beach 18	N	A	2.4 to 3.4	2.90	0.17	2.40	0.17	0.03	18.94	1.38	0.27	0.05	0.72	43.50	3.32	18.94	0.15
Leonardini 37	N	B	2.9 to 6.1	4.50	0.53	2.50	0.13	0.04	5.81	1.34	0.35	0.09	0.74	58.38	4.39	5.81	0.12
Leonardini 52a	N	B	3.8 to 4.5	4.15	0.12	2.70	0.12	0.03	3.82	1.07	1.17	0.67	0.60	58.60	2.94	4.27	0.11
Martella 111	N	B	1.7 to 5.1	3.40	0.57	1.70	0.12	0.04	5.16	0.98	0.47	0.10	0.71	43.50	4.29	5.16	0.11
McGowan Farm 136	N	B	2.4 to 3.1	2.75	0.13	2.40	0.18	0.05	6.00	0.58	1.07	0.12	0.57	42.92	2.74	6.46	0.17
Marinovich 67	N	B	6.2 to 7.0	6.60	0.13	6.20	0.18	0.05	14.21	1.03	0.70	0.06	0.55	109.48	4.57	14.37	0.16
Radovich 98	N	B	5.1 to 8.75	6.93	0.61	3.50	0.24	0.07	8.33	1.74	0.68	0.30	0.60	90.94	5.53	8.50	0.21
Salinas River Bridge 117	N	B	6.4 to 7.4	6.90	0.17	6.40	0.08	0.02	5.31	0.79	1.64	0.39	0.46	109.07	4.71	5.89	0.07
Tanimura 105	N	B	4.2 to 6.8	5.50	0.43	4.20	0.11	0.03	4.56	0.41	0.41	0.05	0.75	79.54	4.35	4.56	0.10

EVENT	M <sub>w</sub>	±
1994 Northridge	6.70	0.13

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Balboa Blvd. Unit C	Y	A	8.3 to 9.8	9.00	0.25	7.19	0.36	0.04	6.43	3.63	2.58	1.62	0.33	144.99	5.59	8.65	0.30
Malden St.t Unit D	Y	B	9.2 to 10.7	9.95	0.25	3.90	0.29	0.09	2.98	1.42	2.36	1.28	0.45	110.45	5.45	4.81	0.25
Potrero Canyon Unit C1	Y	A	6 to 7	6.50	0.17	3.30	0.25	0.04	6.52	2.51	1.08	0.49	0.50	91.27	3.92	7.06	0.21
Wynne Ave. Unit C1	Y	A	5.8 to 6.5	6.13	0.13	4.30	0.35	0.03	8.96	5.77	1.13	0.87	0.42	94.85	3.38	9.63	0.30
Rory Lane	Y	A	3 to 5	4.00	0.33	2.70	0.50	0.10	4.78	0.59	1.80	0.90	0.45	53.85	3.66	6.34	0.43

EVENT	M <sub>w</sub>	±
1995 Hyogoken-Nanbu	7.20	0.11

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Dust Management Center	Y	B	6 to 8	7.00	0.33	2.00	0.31	0.11	7.83	2.53	0.49	0.20	0.64	70.45	4.92	7.83	0.29
Imazu Elementary School	Y	C	8.0 to 12.0	10.00	0.67	1.40	0.40	0.17	0.80	0.19	0.80	0.34	0.90	101.43	7.23	1.14	0.37
Koyo Junior High School	Y	B	6.5 to 7.5	7.00	0.17	4.00	0.28	0.10	8.03	0.54	1.24	0.87	0.50	95.07	3.96	8.76	0.27
Kobe Customs Maya Office A	Y	B	4 to 9	6.50	0.17	1.80	0.45	0.16	2.93	0.34	0.40	0.13	0.78	75.24	3.97	2.93	0.43
Kobe Customs Maya Office B	Y	B	3 to 6	4.50	0.17	1.80	0.48	0.15	6.98	0.73	0.87	0.17	0.54	55.86	3.12	7.41	0.45
Kobe Port Const. Office	Y	B	3 to 5	4.00	0.13	2.50	0.42	0.13	5.99	1.15	0.29	0.11	0.76	55.79	2.91	5.99	0.40
Koyo Pump Station	Y	B	5 to 6	5.50	0.17	2.60	0.33	0.11	2.38	0.57	1.75	0.82	0.65	71.00	3.41	3.68	0.31
Kobe Wharf Public Co.	Y	B	4.0 to 5.5	4.75	0.25	2.10	0.35	0.12	6.03	0.74	0.78	0.40	0.65	60.33	3.41	6.33	0.33
Koyo Elementary School	Y	B	6.5 to 7.0	6.75	0.17	4.20	0.28	0.10	2.93	1.44	2.17	1.50	0.54	94.01	3.91	4.56	0.26
Mizukasa Park	Y	C	6.9 to 7.9	7.40	0.17	2.00	0.45	0.16	1.63	0.60	0.99	0.48	0.75	85.33	4.36	2.19	0.43
Shiporex Kogyo Osaka Factory	Y	B	4.0 to 7.0	5.50	0.33	1.50	0.37	0.12	3.93	2.18	0.41	0.24	0.74	54.71	4.44	3.93	0.34
Hamakoshienn Housing Area	Y	B	2.5 to 5.0	3.75	0.42	2.00	0.38	0.13	7.00	1.51	0.65	0.22	0.59	49.96	3.85	7.16	0.36
Taito Kobe Factory	Y	B	3.2 to 4.2	3.70	0.17	1.60	0.39	0.13	4.85	0.86	0.39	0.12	0.75	42.13	3.38	4.85	0.36
Tokuyama Concrete Factory	Y	B	4.0 to 4.8	4.40	0.13	2.00	0.40	0.13	2.55	0.88	0.40	0.19	0.80	50.98	3.48	2.55	0.38
Nisseki Kobe Oil Tank A	Y	B	4.8 to 6.1	5.45	0.22	2.40	0.43	0.14	5.30	1.31	0.61	0.36	0.72	69.15	3.53	5.42	0.41
Nisseki Kobe Oil Tank B	Y	B	5.0 to 6.0	5.50	0.17	2.40	0.43	0.14	6.25	1.34	0.74	0.27	0.70	69.64	3.42	8.65	0.41
New Port No. 6 Pier	Y	B	3.5 to 5.5	4.00	0.33	2.50	0.42	0.14	9.47	1.60	0.43	0.11	0.70	55.79	3.55	4.81	0.40
Minatojima Junior High	Y	B	4.0 to 4.5	4.25	0.08	2.70	0.32	0.10	4.71	1.35	0.94	0.42	0.65	59.57	2.91	7.06	0.30
New Wharf Const.Offices	Y	B	3.2 to 3.8	3.50	0.10	2.60	0.31	0.10	3.56	0.81	0.93	0.64	0.64	51.62	2.78	9.63	0.29

EVENT	M <sub>w</sub>	±
1995 Hyogoken-Nanbu	7.20	0.11

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Fukuzumi Park	N	C	11.0 to 12.5	11.75	0.33	3.10	0.35	0.18	17.09	3.45	1.42	0.57	0.40	115.94	6.85	18.06	0.33
Honjyo Central Park	N	B	4.0 to 6.0	5.00	0.33	2.50	0.48	0.16	17.30	3.75	0.60	0.25	0.56	70.48	3.98	17.42	0.45
Kobe Art Institute	N	B	3.5 to 3.8	3.65	0.05	3.00	0.32	0.10	13.64	5.38	1.90	1.31	0.33	57.62	2.86	15.08	0.30
Yoshida Kogyo Factory	N	B	3 to 5	4.00	0.33	3.00	0.33	0.11	9.43	7.22	2.71	2.73	0.34	59.19	3.64	11.72	0.31
Shimonakajima Park	N	B	3.0 to 4.5	3.75	0.17	2.00	0.50	0.16	19.49	0.80	0.73	0.43	0.53	46.11	3.38	19.77	0.47
Sumiyoshi Elementary	N	B	2.4 to 3.2	2.80	0.13	1.90	0.43	0.14	17.35	4.20	0.66	0.31	0.54	38.09	3.15	17.53	0.41
Nagashi Park	N	B	1.1 to 1.8	1.45	0.12	1.00	0.49	0.16	14.51	4.31	1.05	0.49	0.51	21.59	2.32	15.16	0.46

EVENT	M <sub>w</sub>	±
1999 Kocaeli	7.40	0.11

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Hotel Spanca SH-4	Y	B	1.2 to 2.0	1.60	0.13	0.50	0.41	0.12	3.25	1.41	0.45	0.29	0.70	17.31	2.31	3.25	0.40
Soccer Field SF-5	Y	B	1.2 to 2.4	1.80	0.20	1.00	0.34	0.10	2.97	1.84	1.17	0.86	0.55	22.45	2.48	3.66	0.33
Police Station Site	Y	B	1.8 to 2.8	2.30	0.17	1.00	0.36	0.10	2.33	0.47	1.89	0.55	0.54	26.80	2.48	3.82	0.35
Yalova Harbor YH-3	Y	B	3.0 to 4.5	3.75	0.25	1.00	0.39	0.11	8.10	0.66	0.43	0.07	0.57	39.40	3.12	8.10	0.38
Adapazari Site B	Y	B	3.3 to 4.3	3.80	0.17	3.30	0.25	0.07	5.77	2.62	0.77	0.42	0.65	55.50	3.10	6.03	0.25
Adapazari Site C2	Y	B	3.3 to 4.8	4.05	0.25	0.44	0.44	0.13	3.22	1.87	1.03	0.76	0.64	38.19	3.41	3.84	0.43
Adapazari Site D	Y	B	1.8 to 2.5	2.15	0.12	1.50	0.30	0.08	3.54	1.82	0.58	0.40	0.75	28.90	2.39	3.61	0.29
Adapazari Site E	Y	B	1.5 to 3.0	2.25	0.25	0.50	0.43	0.13	5.95	2.76	0.41	0.27	0.73	22.96	2.75	5.95	0.42
Adapazari Site F	Y	B	6.8 to 8.0	7.40	0.20	0.50	0.38	0.12	4.13	1.44	0.91	0.39	0.53	67.71	5.01	4.58	0.38
Adapazari Site G	Y	B	1.5 to 2.7	2.10	0.20	0.45	0.43	0.13	5.03	1.28	0.32	0.17	0.84	21.31	2.58	5.03	0.43
Adapazari Site H	Y	B	2 to 3	2.50	0.17	1.72	0.30	0.08	5.55	2.03	0.58	0.31	0.68	33.44	2.56	5.63	0.29
Adapazari Site I	Y	B	3.0 to 3.5	3.25	0.08	0.71	0.42	0.11	3.85	1.04	0.56	0.32	0.72	33.08	2.69	3.92	0.41
Adapazari Site J	Y	B	2.5 to 3.5	3.00	0.17	0.60	0.43	0.12	3.77	1.41	0.80	0.46	0.65	30.16	2.75	4.11	0.42
Adapazari Site K	Y	B	2 to 3	2.50	0.17	0.80	0.39	0.11	4.19	1.64	0.91	0.49	0.62	27.17	2.55	4.64	0.39
Adapazari Site L	Y	B	2.0 to 2.8	2.38	0.13	1.72	0.29	0.08	2.61	1.24	0.57	0.36	0.75	32.35	2.46	2.68	0.29

EVENT	M <sub>w</sub>	±
1999 Chi-Chi	7.60	0.10

SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	q <sub>c,1</sub> (MPa)	±	R <sub>f</sub> (%)	±	c	σ <sub>v</sub> ' (kPa)	±	q <sub>c,1,mod</sub> (MPa)	CSR*
Nantou Site C	Y	B	2.0 to 4.5	3.25	0.42	1.00	0.36	0.10	4.46	2.07	1.11	0.62	0.56	36.68	3.65	5.11	0.37
WuFeng Site B	Y	B	2.5 to 5.0	4.25	0.42	1.12	0.59	0.15	3.22	1.19	0.96	0.61	0.55	46.68	3.92	3.80	0.61
WuFeng Site C	Y	B	2.5 to 5.5	4.00	0.50	1.20	0.59	0.16	3.16	0.73	1.84	1.33	0.65	44.93	4.19	4.85	0.60
WuFeng Site A	Y	B	5.5 to 8.5	7.00	0.50	0.80	0.56	0.16	0.99	0.38	2.14	0.66	0.75	69.78	5.46	3.01	0.57
Yuanlin C-19	Y	B	4.0 to 5.8	6.50	0.30	0.57	0.25	0.07	2.78	0.54	1.08	0.29	0.67	63.62	4.71	3.33	0.26
Yuanlin C-2	Y	B	2.5 to 4.0	3.25	0.25	0.56	0.27	0.07	4.95	1.55	0.49	0.28	0.75	33.68	3.11	4.95	0.27
Yuanlin C-22	Y	B	2.8 to 4.2	3.50	0.23	1.13	0.24	0.06	5.17	0.70	0.46	0.17	0.70	39.86	3.01	5.17	0.24
Yuanlin C-24	Y	B	5.2 to 7.8	6.20	0.33	1.20	0.24	0.06	5.33	1.24	0.60	0.26	0.75	65.15	4.39	5.42	0.24
Yuanlin C-25	Y	B	9.5 to 12	10.75	0.42	3.52	0.17	0.06	6.83	0.97	0.80	0.19	0.61	122.76	6.11	7.07	0.17
Yuanlin C-32	Y	B	4.5 to 7.5	6.00	0.50	0.74	0.25	0.07	4.83	1.49	0.62	0.27	0.70	60.18	5.03	4.95	0.26
Yuanlin C-4	Y	B	3 to 6	4.50	0.50	0.66	0.26	0.07	4.60	1.09	1.30	1.34	0.55	45.85	4.47	5.36	0.27
WuFeng Site C-10	Y	B	2.5 to 7.0	4.75	0.75	1.00	0.60	0.18	2.52	1.36	2.18	2.16	0.58	50.46	5.65	4.65	0.61
Nantou Site C-8	Y	B	5 to 9	7.00	0.67	1.00	0.35	0.10	3.31	0.34	2.08	0.40	0.55	71.14	6.03	4.98	0.35
Nantou Site C-7	Y	B	2.5 to 4.5	3.50	0.33	1.00	0.37	0.09	2.31	0.87	0.57	0.43	0.76	38.98	3.38	2.39	0.37
Nantou Site C-3 & C-16	Y	C	12 to 16	14.00	0.67	1.00	0.26	0.11	1.21	0.23	1.96	1.13	0.74	135.47	9.53	2.60	0.27
Yuanlin C-3	N	C	10 to 13	11.50	0.50	1.79	0.19	0.07	6.74	0.83	0.30	0.14	0.77	123.62	7.44	6.74	0.19

### 6.3 Probabilistic Presentation of Results

A probabilistic triggering correlation was developed using the Bayesian updating methodology described in Chapter 5. Thirty seven different models for adjustment of CPT tip resistance for effects of “fines” were carried forward, including all previously existing models, and the final model selected was the one providing optimal overall “fit” (and least variance) based on the field case history database.

The overall results are presented in Figure 6.1. This plot shows contours of equal probability in  $q_{c,1}$  vs. CSR space, for  $M_w=7.5$  and  $\sigma_v'=1$  atm. The median line is the limit-state or threshold, equivalent to a 50% probability of liquefaction.

It has been recognized that a disparity exists between the number of liquefied vs. non-liquefied data points exists. This disparity can bias the resultant limit-state. Cetin et al. (2002) explored this bias and presented a consistent method to account for what is called choice-based sampling bias as applied to the problem of liquefaction triggering. The same methodology was used in this study. Figure 6.2 shows the shift in the limit-state when accounting for this choice-based sampling bias.

Figure 6.3 shows the same contours, at this time plotted in  $q_{c,1,mod}$  vs. CSR space, again for  $M_w=7.5$  and  $\sigma_v'=1$  atm . In this plot the data points have been adjusted for the effects that the “fines” have on the limit-state, in other words this is a “clean-sand-based” representation of the results. The word “fines” is in quotes because, for the CPT, it is not a measure of the fines content of the soil, rather the effect of increasing sleeve frictional

resistance on soil liquefiability. The frictional resistance is assessed by a combination of the friction ratio ( $R_f$ ) and the normalization constant ( $c$ ). The parameter  $q_{c,1,mod}$  is essentially analogous to a fines corrected SPT blow count ( $N_{1,60,CS}$ ).

Comparison of the probabilistic results against some of the more common CPT correlations is shown in Figures 6.4 and 6.5.

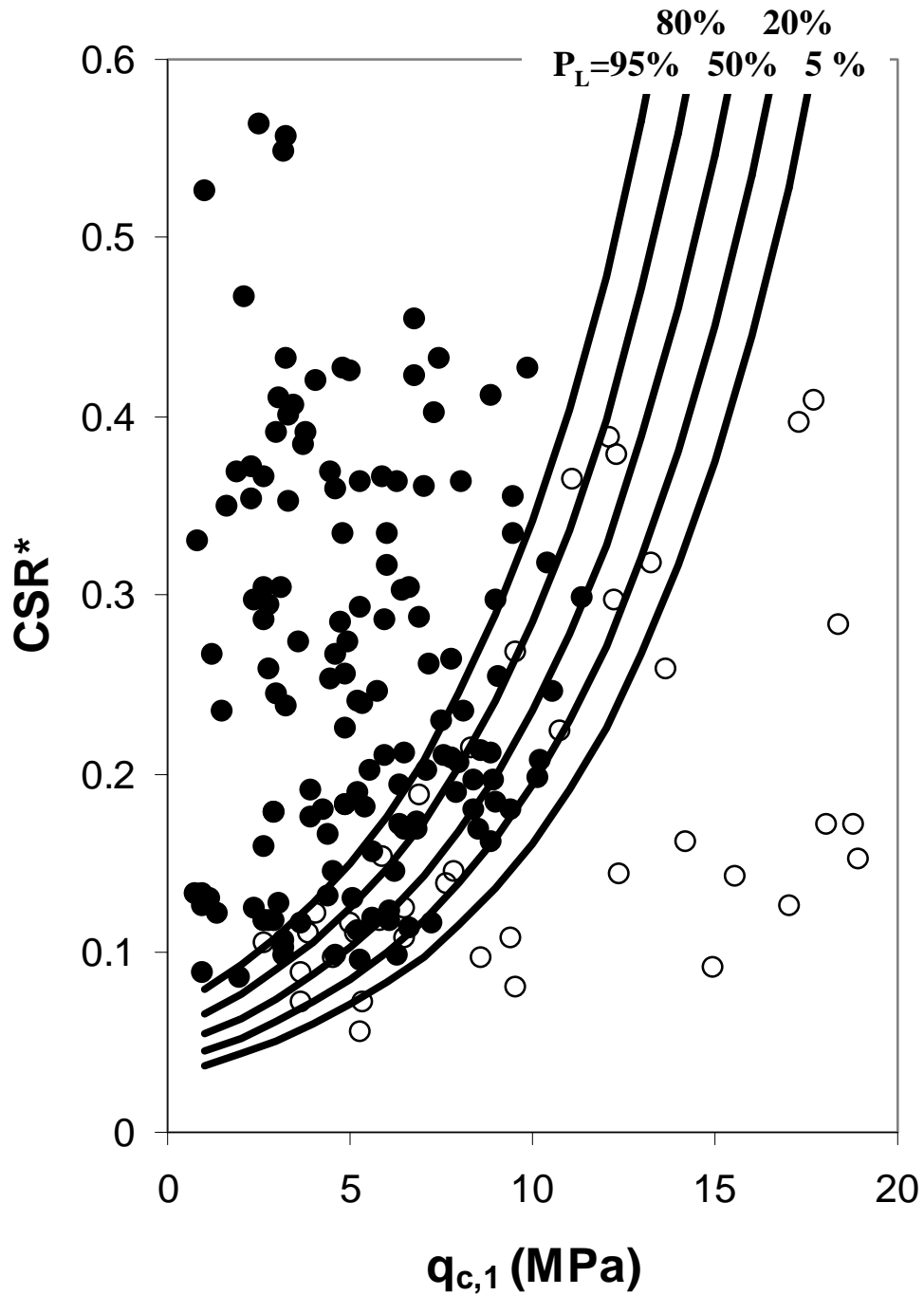
#### 6.4 Deterministic Presentation of Results

Shown in Figure 6.6 is plot of constant friction ratio ( $R_f$ ) contours, at  $P_L=15\%$  for  $M_w=7.5$  and  $\sigma'_v=1$  atm. Data with  $R_f \leq 0.5\%$  are shown as circles and dots, and  $R_f > 0.5\%$  are shown as solid and hollow diamonds, this separates the database into “clean” and “dirty” soils. This figure is a simplified deterministic representation of the effect that increasing friction ratio has on the limit-state. (The parameters that participate in this are both the friction ratio ( $R_f$ ) and the normalization exponent ( $c$ ) in various combinations, as seen in the limit-state function (Chapter 5), but can be represented by a variable friction ratio at a mean normalization exponent.) Increasing the friction ratio ( $R_f$ ) suppresses the liquefiability of a material systematically. Through numerical experimentation (see Chapter 5) an optimum limit-state function was used to elicit the nature of this suppression. This effect can be approximated by the equation,

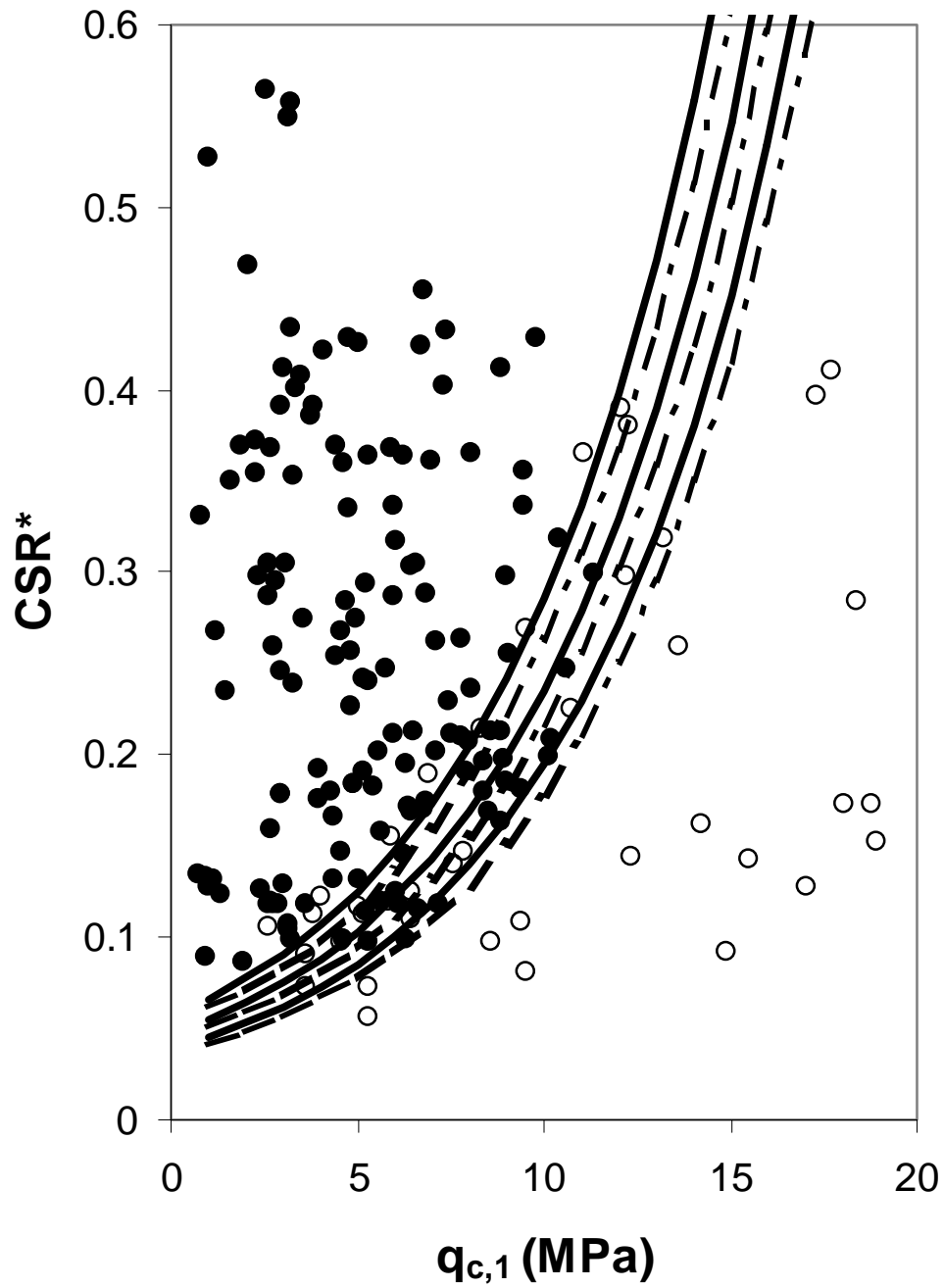
$$q_{c,1,mod} = q_{c,1} + \Delta q_c \quad (6.1)$$

$$\text{where } \Delta q_c = x_1 \cdot \ln(CSR) + x_2$$

$$\text{and } x_1 = 0.38 \cdot (R_f) - 0.19 \text{ and } x_2 = 1.46 \cdot (R_f) - 0.73$$



**Figure 6.1 Probabilistic liquefaction triggering curves shown for  $P_L=5,20,50,80,$  and 95%. Dots indicate liquefied data points and circles non-liquefied.**



**Figure 6.2** Plot showing the correction for the choice-based sampling bias.  $P_L=20,50$ , and 80% contours are shown uncorrected (dashed) and corrected (solid).

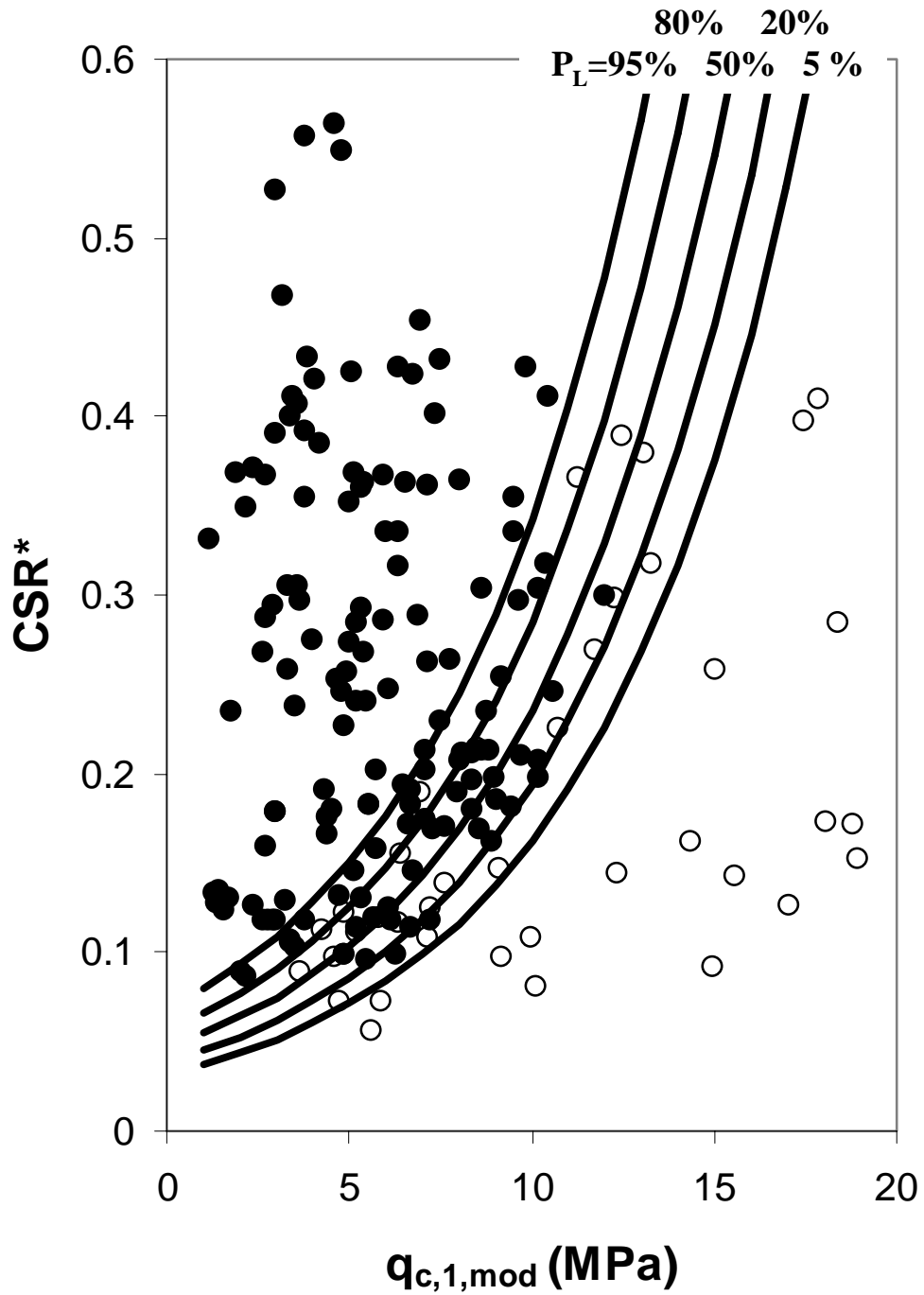


Figure 6.3 Triggering curves shown against data modified for friction ratio.

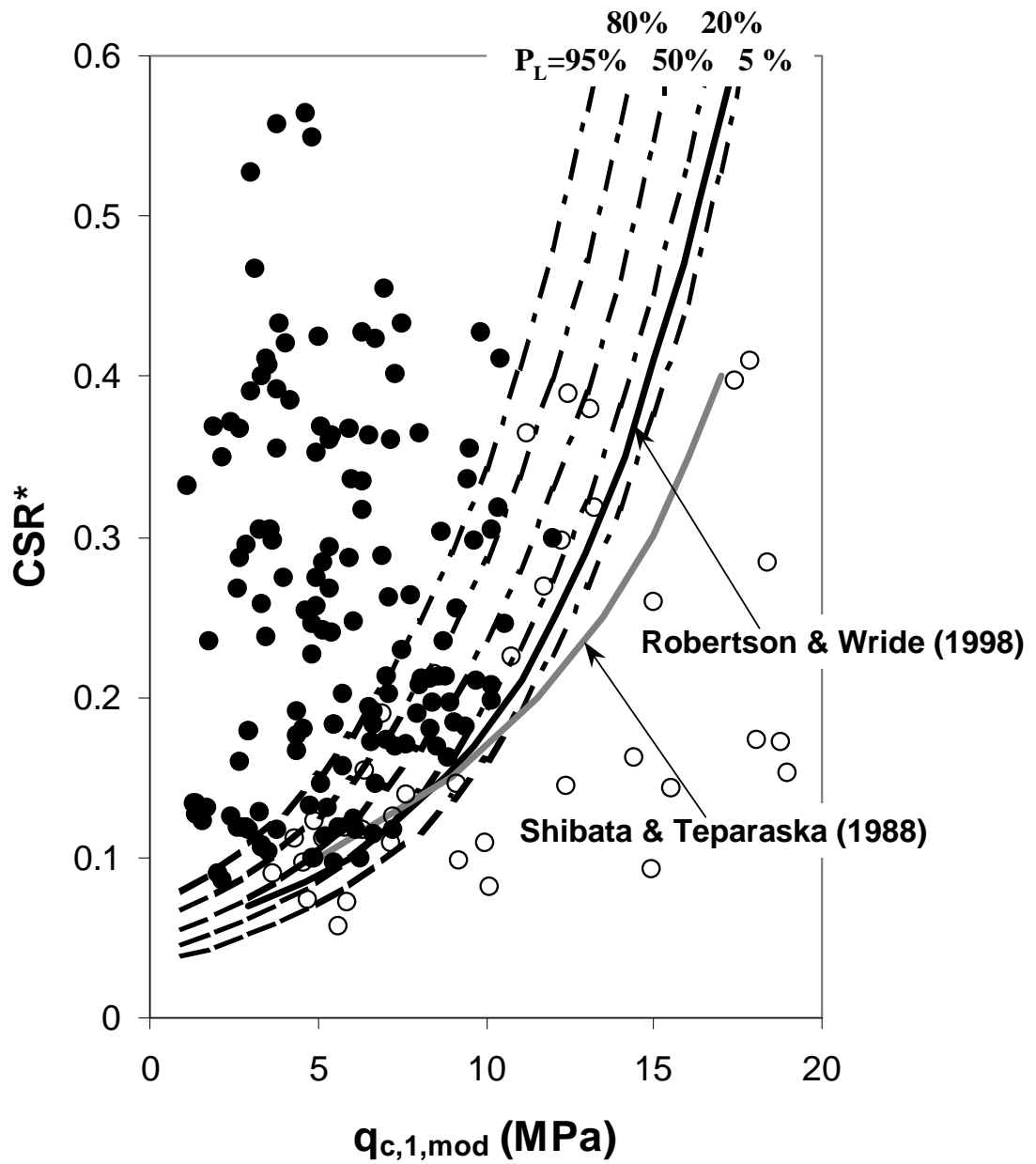


Figure 6.4 Comparison of triggering curves with previous deterministic studies.

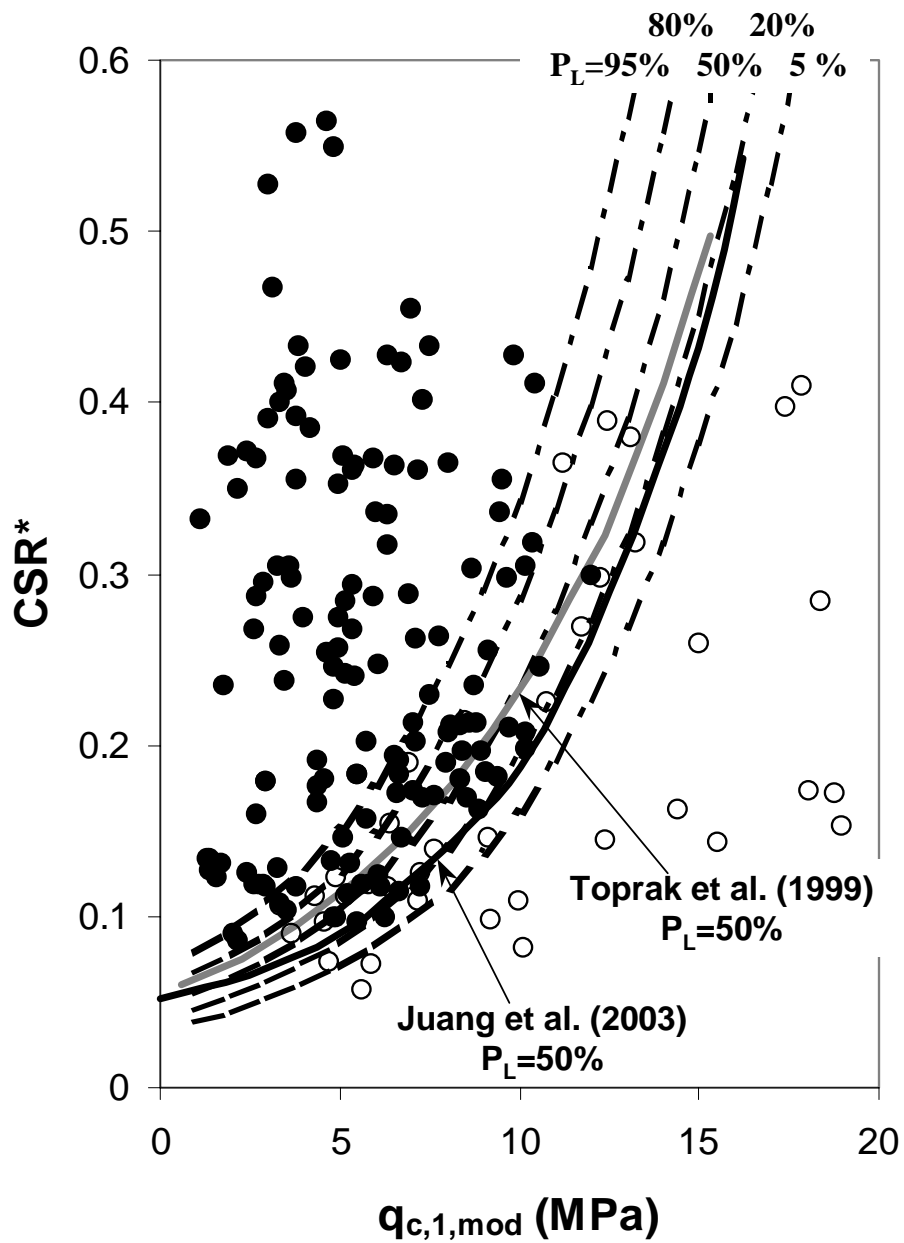
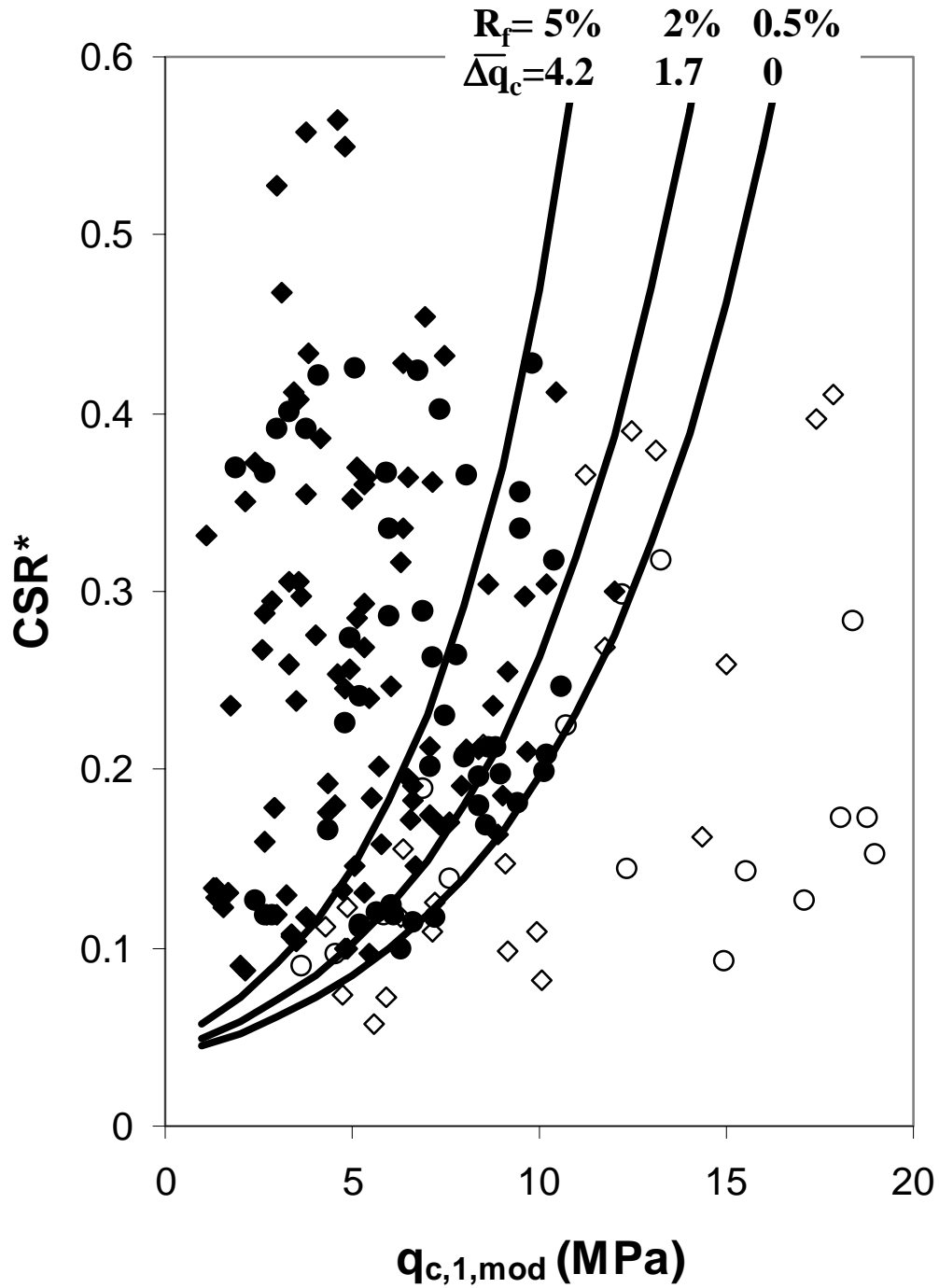


Figure 6.5 Comparison of triggering curves with previous probabilistic studies.



**Figure 6.6** Constant friction ratio triggering curves all shown for  $P_L=15\%$ . The round data points indicate “clean” sands and the diamond data points indicate soils of higher fines content.

The bounds of  $\Delta q_c$  are from  $R_f = 0.5$  to  $5.0$ , where  $\Delta q_c = 0$  when  $R_f \leq 0.5$ ,  $\Delta q_c$  reaches its maximum at  $R_f = 5.0$ , and no data exists for  $R_f > 5.0$ . This term was regressed from the liquefaction database and represents the change in liquefiability correlated to a change in friction ratio, as a function of CSR.

#### **6.4.1 Probability and Determinism**

The probability of liquefaction of  $P_L = 15\%$  was selected for the recommended deterministic boundary, based on prior thresholds both for CPT and the SPT-based analyses as well as judgement. Particularly for the CPT, the study by Juang et al. 2001 provided insight into where the deterministic threshold has been relatively located by prior researchers, either on purpose or by default. The SPT work by Seed et al. (1985) targeted the limit-state at a probability of  $\sim 10\text{-}15\%$ . The previous CPT-based deterministic correlations have mainly been hovering around a probability of  $\sim 10\text{-}35\%$ . The threshold at a probability of  $15\%$  was selected by expert consensus as a reasonable location for both design safety and for consistency with previous work.

#### **6.5 “Fines” Adjustment**

There is a body of literature that exists on the effects that fines content has on a soil's liquefaction resistance (e.g. Andrews & Martin, 2000; Andrianopoulos et al., 2001; Guo & Prakash, 1999; Perlea, 2000; Polito, 2001; Sancio et al., 2003; Yamamuro & Lade, 1998, Youd & Gilstrap, 1999; to name a few). These studies include both laboratory tests (cyclic triaxial, cyclic simple shear, torsion, etc.) and theoretical analyses. Within the

literature there is little consensus, and often one study completely contradicts another. Some of the more difficult laboratory issues in studying how fines content affects a soil's cyclic resistance include how to measure the void ratio (particularly when measuring minimum and maximum void ratios in “clean” sands is a difficult proposition in and of itself), how to create the sample in a consistent manner (pluviation, mixing, etc.), and what criteria are used to define “failure” and/or liquefaction.

These studies are germane to this research, but they only address one aspect of the effects captured by the parameter  $\Delta q_c$ . Another aspect is how variable fines content affects the CPT tip and sleeve measurements (i.e. soil “classification”), and what effects this has on the cyclic resistance. An index test measurement includes the effects of all the competing physical phenomena that occur as the measurement is acquired. Physical responses may be working in a constructive or destructive manner to produce the final measurement. The end product is a combination of all these competing effects over time and space.

The cumulative result is that an increase in friction ratio correlates with an increase in liquefaction resistance. This is what has been observed in data trends and what has been quantified using statistical regression. A comparison of previous deterministic analyses on the effects of “fines” with this study is presented in Figure 6.7. Suzuki et al. (1995) was based on a limited database and fit the threshold curves to the data by hand. Robertson & Wride (1998) (also presented in NCEER (1997) and Youd et al. (2001)) used a larger database and also fit the limiting curves by hand. Robertson & Wride (1998) appears to be highly unconservative with increasing “fines”.

The nature of  $I_c$ , the parameter used by Robertson & Wride (1998) to quantify the effects of “fines”, is based on soil “classification”. That is to say  $I_c$  is based not on the physics of liquefaction but on soil “classification” which is a secondary correlation of tip ( $q_c$ ) and sleeve measurements ( $f_s$ ) to laboratory measured fines content (FC), and is controlled by entirely different physics. The result is an exaggerated estimation of the effect of “fines” on liquefaction resistance. The Robertson and Wride (1998) approach has been found to be lacking in the small zone that is labeled  $K_c = 1.0$ , and Robertson and Wride themselves recommend a null correction for fines in this zone. This area is a region where the  $I_c$  curves don’t adequately capture the liquefaction behavior of a particular group of soils, and exists because  $I_c$  is defined for soil “character” and not soil liquefiability. The  $\Delta q_c$  curves presented in this research capture the  $K_c=1.0$  zone accurately because these curves are based on a soil’s liquefiability. The  $\Delta q_c$  curves are almost wholly dependent on friction ratio when projected into the log-log space of  $R_f$  vs.  $q_{c,1}$ . In application,  $\Delta q_c$  is an additive function whereas  $I_c$  is a multiplicative function, and this difference leads to a dramatic (and unconservative for  $I_c$ ) difference in corrected tip resistance as the friction ratio increases.

Figures 6.8 and 6.9 show the  $\Delta q_c$  contours in relation to Robertson & Wride (1998)  $I_c$  contours and to the liquefaction database. As a soil becomes more plastic it is no longer capable of failing in a “classic” liquefaction manner. The limit of confidence in the model is shown as the lower bound on this figure.

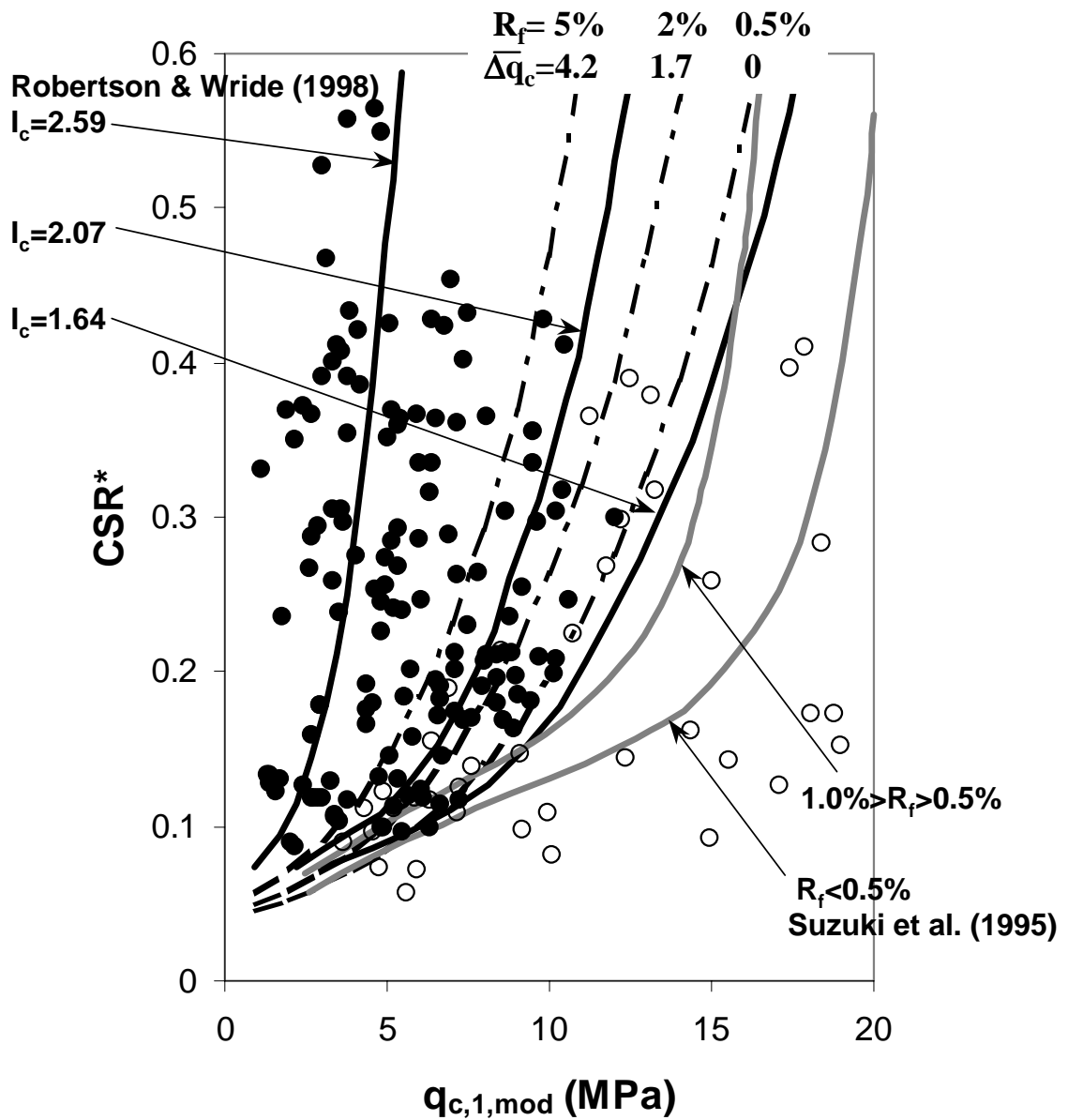


Figure 6.7 Comparison of constant friction ratio triggering curves with previous studies that included the effects of “fines” on liquefiability.

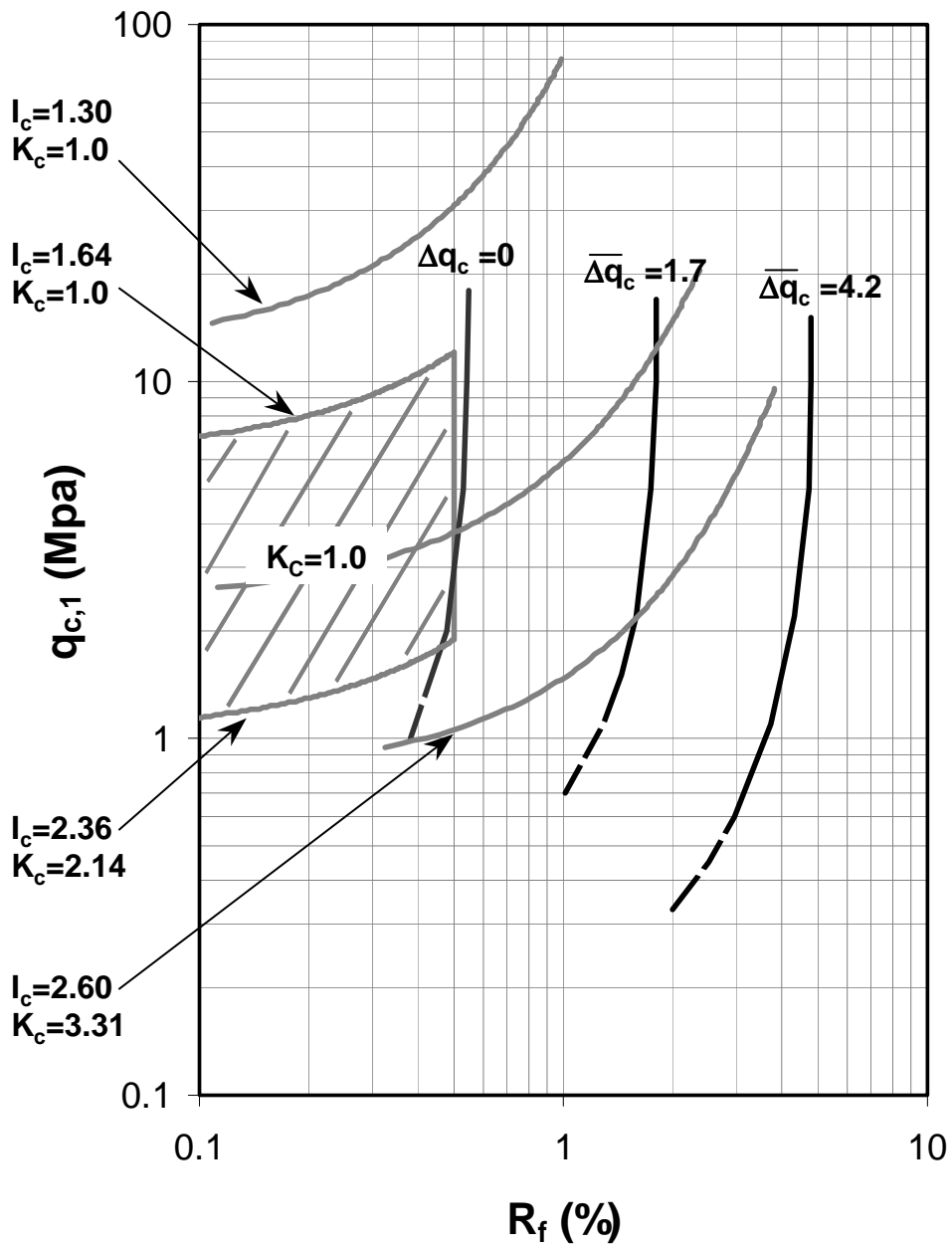


Figure 6.8 Comparison of  $\Delta q_c$  and  $I_c$  curves.

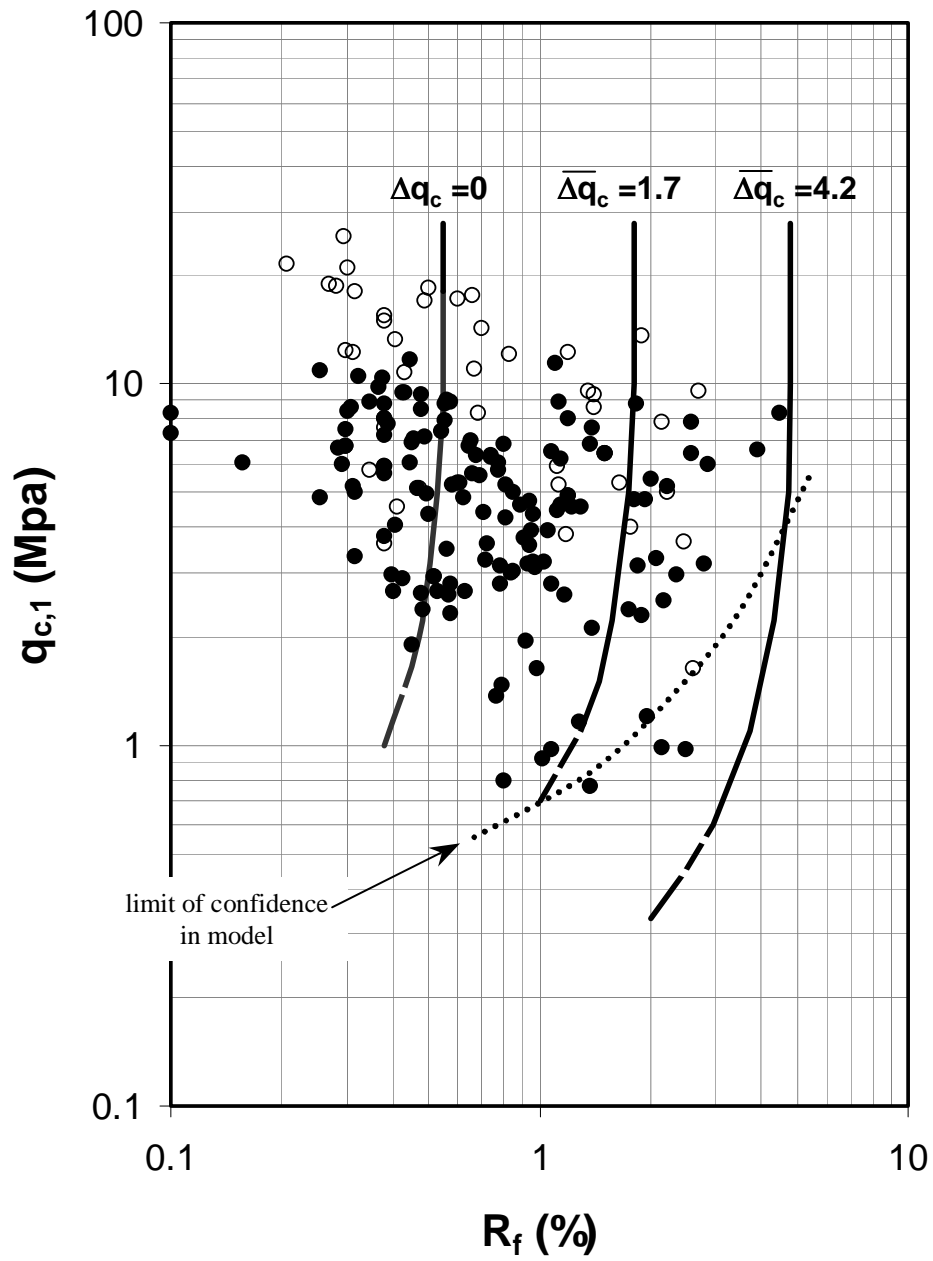


Figure 6.9 Curves of  $\Delta q_c$  shown against the liquefaction database.

## 6.6 Duration Weighting Factor (aka Magnitude Scaling Factor)

All results presented in this study include the correction of “equivalent uniform cyclic stress ratio” (CSR) for duration (or number of equivalent cycles) to CSR\*, representing the equivalent CSR for a duration typical of an “average” event of  $M_w = 7.5$ . This was done by means of a magnitude-correlated duration weighting factor ( $DWF_M$ ) as,

$$CSR^* = \frac{CSR}{DWF_{M_w}} \quad (6.2)$$

This duration weighting factor is somewhat controversial, and has been developed using a variety of different approaches (using cyclic laboratory testing and/or field case history data) by a number of investigators. Figure 6.10 summarizes a number of recommendations, and shows (shaded zone) the recommendations of the NCEER Working Group (Youd et al., 2001). The previous study using SPT data (Cetin, 2000), regressed the  $DWF_M$  from the database which included a number of events covering a wide spectrum of moment magnitudes. The current study using CPT was lacking in a wide enough spectrum to discern accurately the  $DWF_M$  in a similar manner. Based on good agreement of the SPT work with previously published results, the recommended  $DWF_M$  from Cetin et al. 2003 is used. The recommendation can be represented by the equation,

$$DWF_M = 17.84 \cdot M_w^{-1.43} \quad (6.3)$$

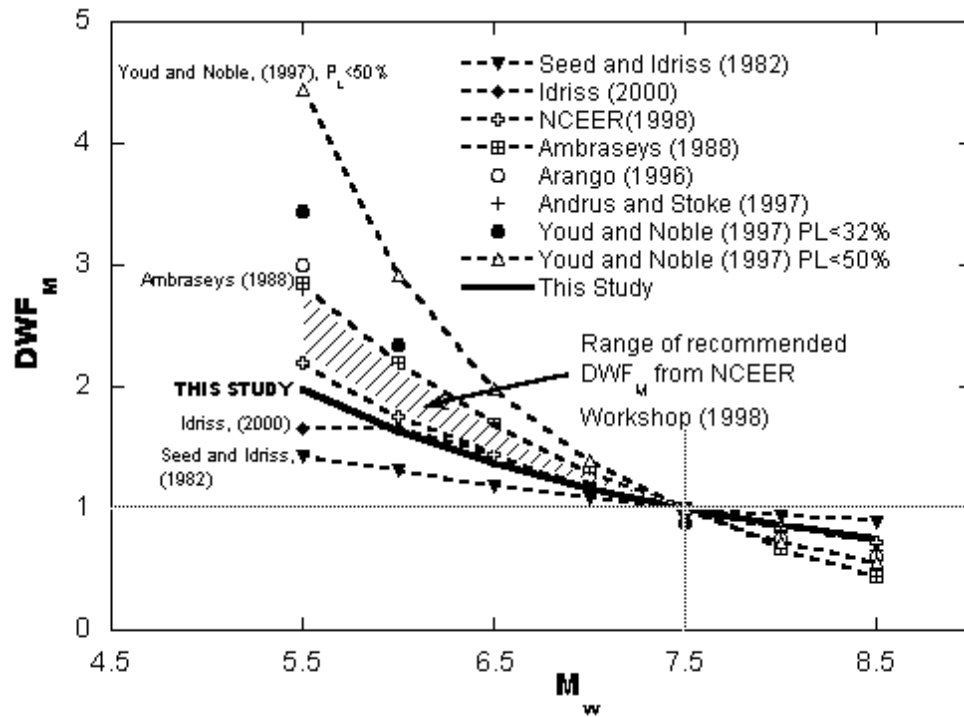


Figure 6.10 Comparison of different  $DWF_M$  studies (from Cetin, 2000).

## 6.7 Final Correlation

The resultant correlations can be represented both probabilistically and deterministically as discussed earlier. Usable probabilistic results are shown in Figure 6.3. The probabilistic contours can be generated using the equation,

$$P_L = \Phi\left(\frac{\hat{g}}{\sigma_\varepsilon}\right) \quad (6.4)$$

where

$P_L$  = the probability of liquefaction in percent

$\Phi$  = standard cumulative normal distribution

$$\hat{g} = q_{c,1}^{1.02} + q_{c,1}(\theta_1 R_f) + (\theta_2 R_f) + c(1 + \theta_3 R_f) - \theta_4 \ln(CSR) - \theta_5 \ln(M_w) - \theta_6 \ln(\sigma_v') - \theta_7$$

$\sigma_\varepsilon$  = standard deviation of model error term

For the given dataset the model parameters and model error term were estimated, using Bayesian updating methods, as the values given in the following table.

**Table 6.2 Model Parameter Estimates**

	$\theta_1$	$\theta_2$	$\theta_3$	$\theta_4$	$\theta_5$	$\theta_6$	$\theta_7$	$\sigma_\epsilon$
Mean	0.110	0.001	0.850	7.177	0.848	0.002	20.923	1.632
Standard Deviation	0.058	0.005	0.086	0.842	0.492	0.007	1.870	0.386
Correlation Matrix								
$\theta_1$	1	-0.255	0.425	0.471	-0.360	0.064	0.464	0.399
$\theta_2$		1	-0.093	-0.205	-0.040	-0.096	-0.254	-0.269
$\theta_3$			1	-0.0267	-0.477	0.205	0.296	0.034
$\theta_4$				1	0.357	0.015	0.579	0.493
$\theta_5$					1	-0.020	-0.354	0.462
$\theta_6$						1	0.219	-0.323
$\theta_7$							1	0.371
$\sigma_\epsilon$								1

For exact parameter estimation (assuming mean values), this then results in the concise equation,

$$P_L = \Phi \left( \frac{\left( q_{c,1}^{1.045} + q_{c,1}(0.110 \cdot R_f) + (0.001 \cdot R_f) + c(1 + 0.850 \cdot R_f) - 7.177 \cdot \right)}{\ln(CSR) - 0.848 \cdot \ln(M_w) - 0.002 \cdot \ln(\sigma_v') - 20.923} \right) \cdot 1.632 \quad (6.5)$$

The cyclic resistance ratio for a given probability of liquefaction can be calculated from,

$$CSR = \exp \left( \frac{\left( q_{c,1}^{1.045} + q_{c,1}(0.110 \cdot R_f) + (0.001 \cdot R_f) + c(1 + 0.850 \cdot R_f) \right)}{-0.848 \cdot \ln(M_w) - 0.002 \cdot \ln(\sigma_v') - 20.923 + 1.632 \cdot \Phi^{-1}(P_L)} \right) \cdot 7.177 \quad (6.6)$$

Usable deterministic results are shown in Figure 6.6. Both the deterministic and probabilistic results should be used in conjunction with the Equations 6.1, 6.2, and 6.3.

## **6.8 Summary**

This chapter has presented accurate and usable tools for liquefaction “triggering” assessment based on the CPT. These results can be used to determine the probability of liquefaction initiation for performance-based design analysis. These results represent the most concerted effort to date to provide an unbiased and robust assessment of the liquefaction threshold and relative distribution of liquefiable materials as measured using the Cone Penetration Test.