SPT - Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Initiation Hazard

by

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A report on research sponsored by
Pacific Gas and Electric Company (PG&E)
Contract No. Z-19-2-133

Pacific Earthquake Engineering Research Report No. PEER-2000/05

August, 2000

Abstract

This report presents the results of studies to develop improved, probabilistically-based correlations for the use of SPT data for evaluation of resistance to “triggering” or initiation of cyclic liquefaction. The relationships presented herein have a number of significant advantages over previous probabilistic and “deterministic” relationships currently available. These include:

1. Previously available field case history data have been re-evaluated, taking advantage of recent developments/insights regarding (a) factors affecting “correction” of SPT data for energy, equipment, procedure, and rod-length effects, and (b) factors affecting evaluation of in-situ equivalent uniform cyclic stress ratio, including source mechanism effects, local site effects, etc.
2. A large number of “new” field case history data were collected and similarly evaluated.
3. Previous, similar efforts have employed overly simplistic and biased assessment of in-situ cyclic shear stress ratio (CSR). In these current studies, CSR was evaluated either by means of (a) direct, case specific site response analyses, or (b) new r_d correlations developed as a part of these studies.
4. New r_d-correlations were developed, providing improved and unbiased “simplified” estimates of in-situ CSR as a function of depth, magnitude, shaking intensity, and site stiffness.
5. A more rigorous and consistent treatment of effective overburden effects (K_σ) was implemented; K_σ corrections were regressed using the full suite of field case history data.

6. With this greatly enhanced database, higher standards were set for acceptability of case history data, and data not meeting these standards were deleted. The result is an enlarged database of high quality.
7. Higher order probabilistic tools, the Bayesian updating method, were used to develop and evaluate correlations. These methods allowed for separate treatment of different sources of aleatory and epistemic uncertainty, and allowed assessment of more contributing variables/parameters than prior studies.

The resulting correlations provide a significantly improved basis for evaluation of liquefaction resistance, and also resolve a number of previously difficult issues including (a) "corrections" for fines content, and (b) magnitude-correlated duration weighting factors (for magnitudes other than $M_W = 7.5$). The new correlations eliminate prior bias, and have greatly reduced uncertainty (or variance) as compared to previous, similar relationships.

Table of Contents

Page

1. INTRODUCTION

The studies reported herein were directed towards the development of improved SPT-based correlations for both probabilistic and deterministic evaluation of potential for “triggering” or initiation of seismically-induced soil liquefaction. The new correlations developed represent a significantly improved basis for evaluation of liquefaction potential, relative to prior correlations currently available.

These studies have a number of advantages over prior related efforts. Current practice in the use of SPT to evaluate seismic liquefaction potential continues to be largely dominated by the correlation proposed by Seed et al. (1984), with a modest adjustment recommended by the NCEER Workshop Working Group (NCEER, 1997), as presented in Figure 1-1. This correlation is intended for use as a “deterministic” procedure, and carries no formal probabilistic basis.

Efforts at development of similar, but formally probabilistically-based, correlations have been published by Liao, et al. (1988, 1998), and more recently by Youd and Noble (1997), and Toprak et al. (1999). Figure 1-2 (a) shows the relationship proposed by Liao et al., expressed as contours of probability of triggering of liquefaction for “clean” sands, with the deterministic relationship of Seed et al. from Figure 1-1 superposed (dashed lines) for reference. The relationships proposed by Youd and Noble and Toprak et al. are, similarly, presented in Figures 1-2 (b) and 1-2 (c).

The deterministic relationship by Seed et al. (1984) has been widely accepted and used in practice, but (1) it is rather dated, and does not make use of an increasing body of field case history data from seismic events that have occurred since 1984, (2) it provides no insight as to probability of liquefaction, (3) it does not employ recent new data and insights regarding equipment, procedure, and rod length effects affecting actual SPT sampling energy and efficiency in interpreting case histories, and (4) it has relatively little field data as a basis for extrapolation of the overall relationship to high cyclic stress ratios (CSR>0.25) This higher range of CSR >0.25 is increasingly important in practice, as higher levels of seismic excitation are increasingly employed as a design basis.

The probabilistic relationship proposed by Liao et al. employs a larger number of case history data points, but this larger number of data points is the result of less severe screening of points for data quality, and so includes a number of low quality data. This relationship was developed using the maximum likelihood estimation method for probabilistic regression (binary regression of logistic models). The way the likelihood function was formulated did not permit separate treatment of aleatory and epistemic sources of uncertainty, and so overstates the overall variance or uncertainty of the proposed correlation. This can lead to large levels of over-conservatism at low levels of probability of liquefaction. An unattractively large, and largely judgmental, correction was made for sampling bias, and this strongly affected the final relationships. An additional shortcoming was that Liao et al. sought, but failed to find, a significant impact of fines content on the regressed relationship between SPT penetration resistance and liquefaction resistance, and so developed reliable curves (Figure 1-2 (a)) only for clean sandy soils (soils with less than 12% fines). In addition, the questionable quality of some of the data employed has led to questioning of the overall correlation.

The relationship proposed by Youd and Noble employs a number of field case history data points from earthquakes which have occurred since the earlier relationships were developed, and deletes the most questionable of the data used by Liao et al. The basic methodology employed, maximum likelihood estimation, is the same, however, and as a result this correlation continues to overstate the overall uncertainty. The effects of fines content were judgmentally prescribed, a priori, in these relationships, and so were not developed as part of the regression. In addition, the authors of this study have disagreements with other details of the processing and development of this correlation, especially the treatment of magnitude-correlated duration weighting factors, and some elements of the database upon which it is based.

The relationship by Toprak et al. also employs an enlarged and updated field case history database, and deletes the most questionable of the data used by Liao et al. As with the studies of Youd et al., the basic regression tool was binary regression, and the resulting overall uncertainty is again very large. Similarly, fines corrections and magnitude correlated duration weighting factors were prescribed a priori, rather than regressed from the field case history data, further decreasing model "fit" (and increasing variance and uncertainty).

Finally, all four of these previous relationships (the deterministic relationship of Seed et al., as well as the three probabilistic relationships) share two additional, common shortcomings. Inconsistent treatment of K_σ-effects introduces some bias in the assessment of shallow case histories, and these shallow case histories comprise a large portion of the database. All four prior correlations also used the same "simplified" r_d-based assessment as Seed et al. (1984), and so also suffered from biased estimates of in-situ CSR, especially at shallow depths.

Overall, these four prior relationships are all excellent efforts, and represent the best of their types. It is proposed that more can be achieved, however, using more powerful and flexible probabilistic tools, and taking fullest possible advantage of the currently available field case histories and current knowledge affecting the processing and interpretation of these.

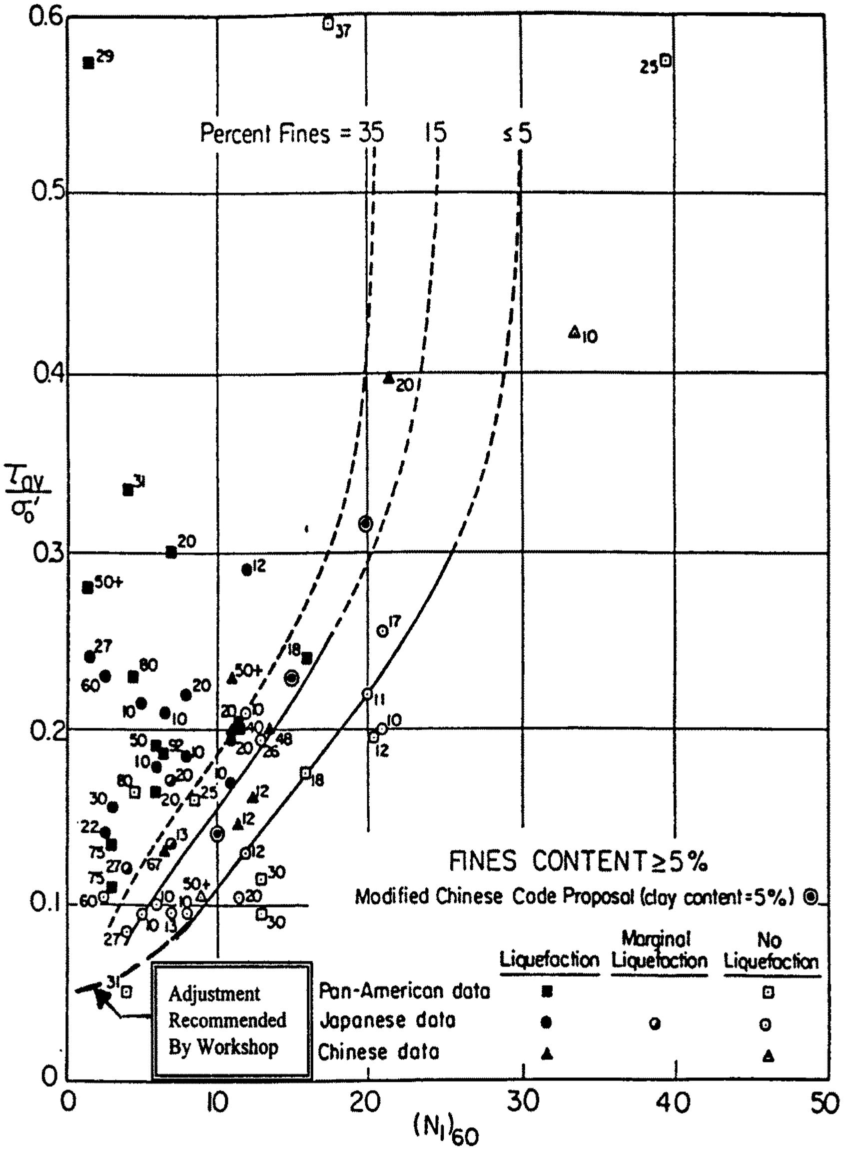
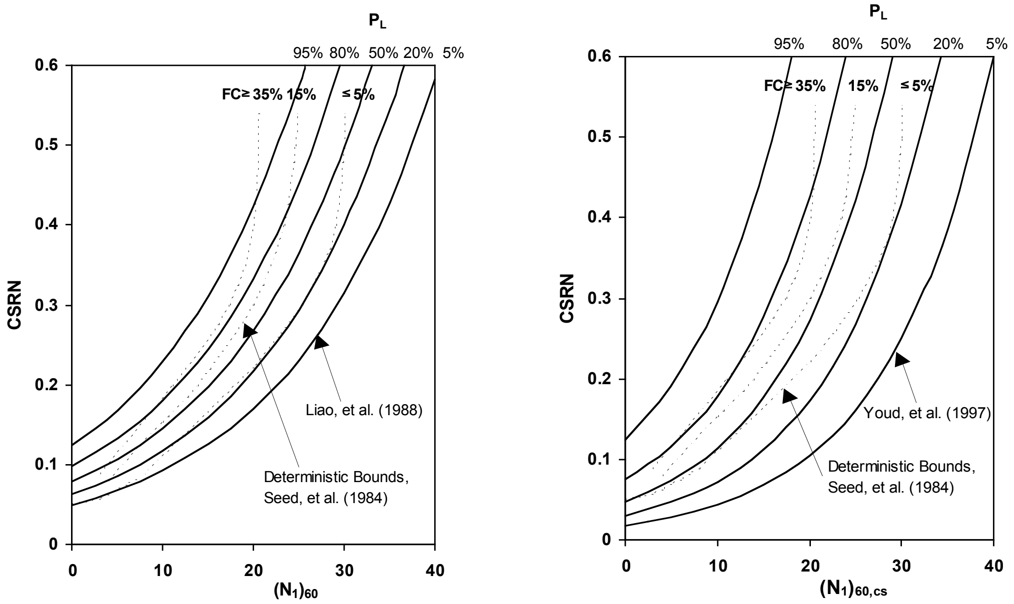


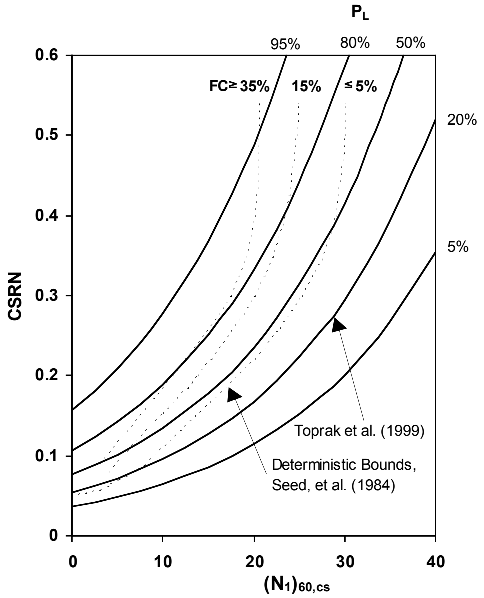
Figure 1-1 : Correlation Between Equivalent Uniform Cyclic Stress Ratio and SPT $N_{1,60}$-Value for Events of Magnitude M ≈ 7.5 for Varying Fines Contents, With Adjustments at Low Cyclic Stress Ratio as Recommended by NCEER Working Group

(Seed, et al., 1984)



(a) Liao, et al. (1988, 1998) Relationships for "Clean" Sandy Soils (with less than 12 % Fines)

(b) Youd, et al. (1997) Relationship Showing Contours for Probability of Liquefaction for Sandy Soils with less than 5 % Fines



(c) Proposed Probability of Liquefaction Contours by Toprak, et al. (1999) for Sandy Soils with less than 5 % Fines

Figure 1-2 : Currently Available Probabilistic SPT-Based Seismic Soil Liquefaction Triggering Correlations

2. CURRENT APPROACH

In these current studies, improvements over previous efforts include the following:

1. A significant number of "new" field case histories have been collected and analyzed, significantly increasing the size of the overall database.
2. Previously available case histories, used in the earlier correlations, have been re-evaluated in the light of improved understanding of significant issues affecting these data, including: (a) procedures for correction of N-values for equipment and procedure (energy) effects, rod length effects, etc., and (b) evaluation of local site effects and directivity and source mechanism effects on shaking intensities at case sites.
3. Site-specific seismic site response analyses were performed for as many case histories as possible, to provide optimum assessment of in-situ CSR within the critical strata. For those cases where suitable strong ground motions records were unavailable (as a basis for development of "input" motions), site response analyses could not be performed. For these cases, new and significantly improved "simplified" correlations for estimation of the shear mass participation factor (r_d) as a function of depth, magnitude, shaking intensity and site stiffness were developed. These also provided significantly improved estimates of in-situ CSR.
4. For all case histories, estimates of variance or uncertainty in both CSR and corrected $N_{1,60}$ were evaluated and incorporated in the analyses. Variance in CSR was modeled as log-normally distributed, and contributing sources of uncertainty included estimation of peak ground acceleration (a_{max}), soil unit

weights, water table depth, and the precise depth limits of the most critical stratum. Variance in N-values was modeled as normally distributed, and contributing sources included variable N-values within a stratum, limited number(s) of N-values within a given stratum, and uncertainties associated with corrections for equipment, procedural and rod length effects, etc.

5. Based on 1, 2, 3 and 4 above, a number of data points from the already quality-screened data set of Seed et al. (1984) were deleted, and the new resulting data set was both significantly enlarged, and also screened to retain only data of demonstrably higher overall quality.
6. Higher order probabilistic methods, the Bayesian updating method (Box and Tiao, 1973), with newly developed enhancements to deal with specific issues raised by this overall problem (Cetin, 2000), were employed. This powerful and flexible method updates the available information (priors) regarding the soil liquefaction model parameters, by using the currently available observations. The implemented Bayesian updating procedure also (a) allowed separate treatment of multiple sources of both aleatory and epistemic uncertainty, (b) permitted internal correlation of data set variables (e.g. internal correlation of loading variables contributing to CSR for data from the same earthquake), (c) resulted in overall correlations that accounted for more of the key variables than had been previously accomplished, and (d) provided greatly reduced overall levels of uncertainty associated with these correlations.
7. In the process, significant new insights (and new corrections/correlations) were developed regarding (a) magnitude-based duration weighting factors, (b)

correction of N-values for fines content effects, and (c) variation of liquefaction resistance as a function of initial effective overburden stress (K_σ-effects). These had been particularly difficult and controversial details in past, similar efforts.

3. CASE HISTORY DATA COLLECTION AND PROCESSING

3.1. General

The 126 case history data points employed by Seed et al. (1984) were re-evaluated in detail. New equipment and procedure corrections were employed, based on those recommended by the NCEER Working Group (NCEER, 1997). One particularly significant change was the use of updated insights regarding rod-length effects on the effective energy transmitted to the SPT sampler at relatively shallow depths.

A second improvement was improved evaluation of peak horizontal ground acceleration at each case history site. Specific details are provided by Cetin (2000). Significant improvements here were principally due to improved understanding and treatment of issues such as (a) directivity effects, (b) effects of site conditions on response, and (c) improved attenuation relationships. In these studies, peak horizontal ground acceleration (a_{max}) is taken as the geometric mean of two recorded orthogonal horizontal components. Whenever possible, earthquake specific attenuation relationships were tuned based on local strong ground motion records, significantly reducing uncertainties. In all cases, both local site effects and rupture mechanism dependent potential directivity effects were also considered.

3.2. Nonlinear Shear Mass Participation Factor (r_d)

A third major improvement was better estimation of in-situ CSR within the critical stratum for each of the field case histories. All previous studies described so far used the "simplified" method of Seed et al. (1971) to estimate CSR at depth (within the critical soil stratum) as

$$CSR = \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_v}{\sigma'_v}\right) \cdot (r_d) \qquad \text{(Eq. 3-1)}$$

where a_{max} = the peak horizontal ground surface acceleration,

g = the acceleration of gravity,

σ_v = total vertical stress,

σ'_v = effective vertical stress, and

r_d = the nonlinear shear mass participation factor.

The original r_d values developed by Seed et al. (1971) are shown in Figure 3-1. These are the values used in the previous studies by Seed et al. (1984), Liao et al. (1988, 1998), Youd et al. (1997), and Toprak et al. (1999).

Recognition that r_d is nonlinearly dependent upon a suite of factors led to studies by Cetin and Seed (2000) to develop improved correlations for estimation of r_d. A suite of site subsurface profiles, mainly taken from well-defined field case histories from the database used in these studies, were subjected to a suite of strong motions of various intensities and characteristics. Table 3-1 provides an overview of the sites modeled, and Table 3-2 provides an overview of the strong ground motions employed. Some of the sites were "truncated" bringing the underlying rock closer to the surface, to provide better balance between shallow, medium and deep sites. The "input" motions of Table 3-2 were developed to provide a balanced suite of motions spanning magnitude, duration, and characteristic ranges of interest, including balanced representation of "near-field" (with and without directivity effects), "mid-field" and "far-field" motions.

Input motions were applied at the base of the profiles, as "rock" motions. In most cases, excepting only those cases where field data showed strongly otherwise, a

Table 3-1: An overview of some of the characteristics of soil sites used to develop r_d correlations

Site No.	Name of the Site	Depth to Bedrock (ft)	V*s,40' (fps)	Tp (sec.)
1	Moss State Beach UC-B1	578	510	1.25
2	Moss State Beach UC-B2	578	580	1.25
3	Woodward Marine UC-B4	572	535	1.21
4	Marine Lab B1	585	560	1.24
5	Marine Lab B2	585	500	1.24
6	MBARI UC-B10	585	530	1.25
7	MBARI-EB1	585	620	1.25
8	MBARI-EB5	585	500	1.25
9	Miller Farm CMF10	585	545	1.25
10	Miller Farm CMF8	585	480	1.25
11	Miller Farm CMF5	585	570	1.25
12	Miller Farm CMF3	585	530	1.25
13	Farris Farm	600	575	1.23
14	Miller Farm	585	550	1.23
15	Treasure Island	350	505	1.34
16	Richmond POR2	110	400	0.25
17	Richmond POR3	110	380	0.24
18	Richmond POR4	110	370	0.24
19	San Francisco Oakland Bay Bridge-1	520	470	1.56
20	San Francisco Oakland Bay Bridge-2	520	510	1.52
21	Alameda Bay Farm Dike	150	630	1.65
22	Port of Oakland 7-2	165	535	1.25
23	Port of Oakland 7-3	165	470	1.49
24	Malden Street	295	465	0.7
25	Wynne Street	295	490	0.69
26	Balboa Street	295	525	0.69
27	Potrero Canyon	80	465	0.52
28	Wildlife Site	890	365	0.26
29	Heber Road A1	910	580	2.63
30	Heber Road A2	910	610	2.55
31	Heber Road A3	910	660	2.62
32	Kornbloom Site	880	495	2.63
33	McKim Ranch	865	570	2.63
34	Radio Tower B1	880	510	2.62
35	Radio Tower B2	880	565	2.62
36	River Park	880	570	2.61
37	Vail Canal	905	560	2.69
38	Richmond Hall	350	360	0.24
39	Moss State Beach UC-B1(Truncated)	183	510	0.53
40	Woodward Marine UC-B4 (Truncated)	242	535	0.63
41	Marine Lab-B1(Truncated)	252	560	0.68
42	MBARI UC-B10 (Truncated)	161	530	0.46
43	Miller Farm (Truncated)	122	550	0.29
44	Miller Farm CMF10 (Truncated)	115	545	0.29
45	Farris Farm (Truncated)	151	575	0.4
46	Alameda Bay Farm Dike (Truncated)	277	630	0.93
47	Heber Road A2 (Truncated)	228	610	0.6
48	Kornbloom (Truncated)	163	495	0.46
49	Radio Tower (Truncated)	151	510	0.42
50	River Park (Truncated)	195	570	0.58

Table 3-2: An overview of some important characteristics of input motions used to develop r_d correlations

No.	Event Type	Event Name	Mw	Scaled PGA	PGA	D (km)	Near Field	Mid Field	Far Field	Total #
1	?	1985 Michoacan-Ocotito	8.1	0.1	0.05	337*			x	
2	Strike Slip	Synthetic Seismograph	8	0.3	0.54	5	x			
3	Reverse	Synthetic Seismograph	8	0.3	0.63	5	x			3
4	?	1978 Miyagioki-Ofunato Bochi	7.4	0.15	0.22	30*			x	
5	Reverse	1978 Tabas-Dayhook	7.4	0.3	0.36	17*	x			
6	Strike Slip	1992 Landers-Lucerne	7.3	0.4	0.76	1.1	x			
7	Strike Slip	1992 Landers-Silent Valley	7.3	0.09	0.045	51.3			x	
8	?	1979 Alaska-Munday Creek	7.3?	0.1	0.05	72			x	5
9	?	1994 Euroka-Cape Mendocino	7.2	0.05	0.03	126*			x	
10	Strike Slip	1999 Hector Mines-LA City Terrace	7.1	0.08	0.04	184*			x	
11	?	1971 Adak Alaska-Naval Base	7.1	0.15	0.15	66.2*		x		
12	Reverse	1992 Cape Mendocino-Cape Mendocino	7	0.55	1.25	3.8*	x			
13	Strike Slip	1989 Loma Prieta-Gilroy # 1	7	0.3	0.44	10	x			
14	Strike Slip	1989 Loma Prieta-Lick Lab	7	0.3	0.42	18	x			
15	Strike Slip	1989 Loma Prieta- Piedmont Jr. High	7	0.15	0.075	73			x	
16	Strike Slip	1995 Kobe-Chihaya	6.9	0.15	0.11	48.7			x	
17	Strike Slip	1995 Kobe-Kobe University	6.9	0.3	0.31	0.2	x			
18	Reverse	1985 Nahanni-Site1	6.8	0.55	1.04	6	x			
19	Reverse	1985 Nahanni-Site3	6.8	0.15	0.2	16		x		
20	Reverse	1976 Gazli-Karakyr	6.8	0.35	0.66	3	x			12
21	Strike Slip	1987 Superstition Hills-Superstition Mtn	6.7	0.3	0.78	4.3	x			
22	Reverse	1994 Northridge-Lake Hughes # 9	6.7	0.15	0.18	28.9			x	
23	Reverse	1994 Northridge-Vasquez Rocks	6.7	0.15	0.14	24			x	
24	Reverse	1971 San Fernando-Cedar Springs	6.6	0.05	0.03	86.6			x	
25	Reverse	1971 San Fernando-Carbon Canyon	6.6	0.12	0.07	66.4			x	
26	Reverse	1971 San Fernando-Lake Hughes#4	6.6	0.25	0.17	19.6		x		
27	Reverse	1983 Coalinga-Parkfield Cholame 3E	6.6	0.08	0.05	38.4			x	
28	Strike Slip	1979 Imperial Valley-Cerro Prieto	6.5	0.25	0.163	23.5		x		
29	Strike Slip	1979 Imperial Valley-Superstition Mt Cmr	6.5	0.23	0.146	26		x		9
30	Strike Slip	1986 Chalfant Valley-Paradise Lodge	6.2	0.25	0.163	23*		x		
31	Strike Slip	1986 Chalfant Valley-Tinemaha	6.2	0.06	0.037	40.6			x	
32	Strike Slip	1984 Morgan Hill-Gilroy # 1	6.2	0.13	0.082	16.2			x	
33	Strike Slip	1984 Morgan Hill-USCS Lick Observatory	6.2	0.09	0.054	44.1			x	
34	Reverse	1986 N. Palm Springs-Silent Valley	6	0.13	0.125	25.8		x		
35	Reverse	1986 N. Palm Springs-Murieta Hot Springs	6	0.09	0.051	63.3			x	
36	Reverse	1987 Whittier Narrows-Mnt. Wilson	6	0.25	0.15	28*		x		
37	Strike Slip	1980 Victoria-Cerro Prieto	5.9	0.4	0.604	34.8*	x			
38	Dip :80	1981 Westmorland-Camera (Sup)	5.9	0.1	0.09	23.9		x		
39	Reverse	1983 Coalinga-Oil Fields Fire Station	5.8	0.25	0.2	10.9	x			
40	Reverse	1983 Coalinga-Skunk Hollow	5.8	0.25	0.3	12.2	x			
41	Reverse	1983 Coalinga-Oil Transmitter Hill	5.8	0.4	0.95	9.2	x			
42	Strike Slip	1979 Cayote Lake-Gilroy Array # 1	5.7	0.12	0.116	9.1		x		13
							15	10	17	42

* Epicentral distance

"weathered" rock transition was modeled overlying a half-space of more intact "rock" (typically with V_s ("rock") ≈ 3000 to 4000 ft/sec.) Analyses were performed using the equivalent linear method (SHAKE) to approximate nonlinear response. Previous analyses by Golesorkhi (1989) have shown that these equivalent linear analyses, carefully performed, produce results very similar (and without statistical bias) to the results of well-performed fully nonlinear analyses for purposes of assessment of r_d.

A total of 2,153 analyses were performed, and the results are presented en masse in Figure 3-2. The heavier lines show the mean and ± one standard deviation values of the results. Also shown for comparison are the earlier recommendations of Seed and Idriss (1971). As shown in Figure 3-2 (a), these earlier values are biased, especially at depths of on the order of 10 to 40 feet. Figure 3-2 (b) shows the distribution of depths of the critical soil strata from the field case histories eventually used in these current studies to develop liquefaction triggering correlations. As shown in this figure, the field cases are strongly concentrated in a range of depths of between 5 to 40 feet, and the previous bias in estimation of r_d is pronounced over much of this range.

Accordingly, a new empirical correlation was developed for estimation of r_d based on the 2,153 site response analyses performed. The proposed new correlation for estimation of r_d as a function of depth, magnitude, intensity of shaking, and site stiffness is

d < 65 ft

$$r_d(d, M_w, a_{max}, V^*_{s,40'}) = \frac{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (-d + 0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]}{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]} \pm \sigma_{\varepsilon_{r_d}} \qquad \text{(Eq. 3-2)}$$

d ≥ 65 ft

$$r_d(d, M_w, a_{max}, V^*_{s,40'}) = \frac{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (-65 + 0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]}{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]} - 0.0014 \cdot (d - 65) \pm \sigma_{\varepsilon_{r_d}}$$

d < 40 ft **d ≥ 40 ft**

$$\sigma_{\varepsilon_{r_d}}(d) = d^{0.850} \cdot 0.0072 \qquad \sigma_{\varepsilon_{r_d}}(d) = 40^{0.850} \cdot 0.0072 \qquad \text{(Eq. 3-3)}$$

where d = depth in feet,

M_w = Moment magnitude of the earthquake,

a_{max} =Peak ground acceleration in g's,

$V_{s,40ft}$ = Weighted average of shear wave velocity in the upper 40 ft in ft/sec. (= 40 ft /Travel time(sec.)), and

$\sigma_{\varepsilon_{r_d}}$ = Standard deviation of r_d.

Figures 3-3 (a) through (l) show the results of the 2,153 site response analyses, separated into "bins" by magnitude, shaking intensity, and site stiffness ($V_{s,40\text{ ft.}}$). Also shown in each figure is the prediction of Equation 3-2, centralized to the mean parameters of each "bin". The relationship of Figure 3-2 provides a significantly improved basis for estimation of in-situ CSR relative to prior, simplified proposed bases.

It is noted, however, that in-situ CSR (and r_d) can "jump" or transition irregularly within a soil profile, especially near sharp transitions between "soft" and "stiff" strata. Accordingly, the best means of estimation of in-situ CSR within any given stratum is to directly calculate CSR by means of appropriate seismic site response analysis, when this is feasible.

In assessing the field case histories, it was feasible to perform site-specific site response analyses when : (1) sufficient subsurface characterization data was available, and (2) an event-specific and azimuthly appropriate strong motion record was available from which the necessary "input" motion could be developed. For 53 of the case histories, case specific site response analyses were performed (Cetin, 2000; Cetin et al., 2000). For the remaining 148 cases, CSR was evaluated using Equation 3-1 and the new (improved) r_d correlation of Equation 3-2.

3.3. Conventions Used in Evaluating Field Case Histories

This section presents a concise summary of some of the key elements of the conventions and procedures employed in evaluation of the field case histories. A more comprehensive description is provided by Cetin (2000).

In these studies, peak ground acceleration estimates (a_{max}) were developed using all available information. Values of a_{max} are taken as the geometric mean of the two orthogonal horizontal components of motion. Source mechanism, near-field effects, and local site response effects were all accounted for as fully as possible. In most cases, applicable attenuation relationships were locally calibrated for event-specific and azimuth-specific variations using nearby strong ground motion records. Adjustments for site effects were made either based on judgements and experience, on event-specific data, or based on performance of full site response analyses. Variance in a_{max} was considered to be log-normally distributed. Uncertainty (or variance) in a_{max} is directly reflective of the level and quality of data and information available for each case history.

In-situ cyclic stress ratio (CSR) is taken as the “equivalent uniform CSR” equal to 65 % of the single peak CSR as

$$\mathrm{CSR}_{\mathrm{eq}} = (0.65) \cdot \mathrm{CSR}_{\mathrm{peak}} \qquad \text{(Eq. 3-4)}$$

In-situ $\mathrm{CSR}_{\mathrm{eq}}$ was evaluated directly, based on performance of full seismic site response analyses (using SHAKE 90; Idriss et al., 1992), for cases where (a) sufficient sub-surface data was available, and (b) where suitable “input” motions could be developed from nearby strong ground motion records. For cases wherein full seismic site response analyses were not performed, $\mathrm{CSR}_{\mathrm{eq}}$ was evaluated using the estimated $a_{\max}$ and Equation 3-1, with r_d-values estimated using Equation 3-2.

Factors contributing to overall variance in estimation of $\mathrm{CSR}_{\mathrm{eq}}$ were summed within a reliability framework, and the main contributions to this variance were (1) uncertainty in $a_{\max}$, and (b) uncertainty in shear mass participation (or r_d). Additional variables which generally contributed slightly to overall variance in estimates of $\mathrm{CSR}_{\mathrm{eq}}$ were (a) the limits of the critical soil stratum, (b) uncertainty in soil unit weights, and (c) uncertainty regarding the location of the phreatic surface (or “water table depths”).

At each case history site, the critical stratum was identified as the stratum most susceptible to triggering of liquefaction. When possible, collected surface boil materials were also considered, but problems associated with mixing and segregation during transport, and recognition that liquefaction of underlying strata can result in transport of overlying soils to the surface through boils, limited the usefulness of some of this data.

The $N_{1,60}$-values employed were “truncated mean values” within the critical stratum. Measured N-values (from one or more values) within a critical stratum were corrected for overburden, energy, equipment, and procedural effects to $N_{1,60}$ values, and were then plotted vs. elevation. Occasional high values, not apparently representative of the general characteristics of the stratum, were considered "non-representative" and were deleted in a number of the cases. Similarly, though less often, very low $N_{1,60}$ values (very much lower than the apparent main body of the stratum, and often associated with locally high fines content) were similarly deleted. The remaining, corrected $N_{1,60}$ values were then used to evaluate both the mean of $N_{1,60}$ within the stratum, and the variance in $N_{1,60}$. For cases wherein the critical stratum had only one single useful $N_{1,60}$-value, coefficicent of variation ($C.O.V._{N_{1,60}}$) was taken as 20 %; a value typical of the larger variances among the cases with multiple $N_{1,60}$ values within the critical stratum (reflecting the increased uncertainty due to lack of data when only a single value was available).

All N-values are corrected for overburden effects (to the hypothetical value, N_1, that "would" have been measured if the effective overburden stress at the depth of the SPT had been 1 atmosphere ≈ 2,000 lb/ft^2) as

$$N_1 = N \cdot C_N \qquad \text{(Eq. 3-5)}$$

where C_N is taken (based on Liao and Whitman, 1986) as

$$C_N = \left(\frac{1}{\sigma'_v} \right) \qquad \text{(Eq. 3-6)}$$

where σ'_v is the actual effective overburden stress at the depth of the SPT in atmospheres.

The resulting N_1 values are then further corrected for energy, equipment, and procedural effects to <u>fully</u> standardized $N_{1,60}$ values as

$$N_{1,60} = N_1 \cdot C_R \cdot C_S \cdot C_B \cdot C_E \qquad \text{(Eq. 3-7)}$$

where C_R = a correction for "short" rod length,

C_S = a correction for non-standardized sampler configuration,

C_B = a correction for borehole diamater, and

C_E = a correction for hammer energy efficiency.

The corrections for C_R, C_S, C_B and C_E employed correspond largely to those recommended by the NCEER Working Group (NCEER, 1997). The correction for "short" rod length between the driving hammer and the penetrating sampler was taken as nonlinear "curve" rather than the incremental values of the NCEER Workshop recommendations but the two agree at all NCEER mid-increments of length. Except for cases where rod "stick-up" (protrusion) above the top of the borehole was recorded, rod protrusion of ~ 4 ft was assumed for donut hammers and the USGS safety hammers, and rod protrusion of ~ 7 ft was assumed for all other safety hammers.

C_S was applied in cases wherein a "nonstandard" (though very common) SPT sampler was used in which the sampler had an internal space for sample liner rings, but the rings were not used. This results in an "indented" interior liner annulus of enlarged diameter, and reduces friction between the sample and the interior of the sampler, resulting in reduced overall penetration resistance. The reduction in penetration resistance is on the order of ~ 10 % in loose soils (N_1<10 blows/ft), and ~ 30 % in very dense soils (N_1>30 blows/ft), so C_S varied from 1.1 to 1.3 over this range.

Borehole diameter corrections (C_B) were as recommended in the NCEER Workshop Proceedings.

Corrections for hammer energy (C_E), which were often significant, were as recommended by the NCEER Working Group except in those cases where better hammer/system-specific information was available. Cases where better information was available included cases where either direct energy measurements were made during driving of the SPT sampler, or where the hammer and the raising/dropping system (and the operator, when appropriate) had been calibrated by means of direct driving energy measurements.

3.4. New Data

Additional new case history data were next collected, mainly (but not entirely) from events post-dating 1984, and these cases were similarly processed. Figure 3-4 shows the new data employed in these studies. In all cases, both old and new, data processing included assessment of variance or uncertainty in both CSR and corrected N-values.

3.5. Data Rating System and Data Quality Assessment

A rating system was established to evaluate the quality of each data point. Data were rated as falling into one of four classes (from highest to lowest quality) as follows:

Class A:

1. A minimum of 3 or more N-values in the critical stratum, and
2. Equipment and procedural details affecting SPT data well-defined, and
3. Coefficient of variation, $C.O.V._{CSR} \leq 0.20$

Class B:

1. Equipment and procedural details affecting SPT data well-defined, and
2. $0.2 < C.O.V._{CSR} \leq 0.35$,

   or satisfies Class A but less than 3 N-values in the critical stratum.

Class C:

1. Equipment and procedural details affecting SPT data well-defined, and
2. $0.35 < C.O.V._{CSR} \leq 0.5$

Class D:

1. Equipment and procedural details affecting SPT data not well-defined, or
2. Seismicity, and/or site effects not well-defined ($C.O.V._{CSR} > 0.5$), but some reasonable basis for at least approximate estimation of CSR available, or
3. Poor site performance data/documentation, or
4. Original boring logs or other important data not accessible, etc.

Case histories where no basis for equipment/procedure corrections of SPT were available, where very poor seismicity data was available for estimation of CSR, or where other important issues were undefined, and data from sites not qualifying as "level ground", etc., were considered to be of lesser quality even than Class D, and were deleted from all further consideration here (Class "E").

The previous studies of Seed et al. (1984) had employed a total of 126 data points, falling into these classes as shown in Tables 3-3 and 3-4. Liao et al. (1988, 1998) had employed a larger number of data, but much of the increase was through the use of data of Class D quality, or lower.

The new data collected and processed for these current studies was of generally higher overall quality, as indicated by Tables 3-3 and 3-4. Based on the availability of a sufficient quantity of relatively high-quality data, it was decided to eliminate all data of Class D or lower, and to employ only data of Class C or better for these current studies. The result was availability of 201 data of Class C or better, after deletion of 36 "Class D" data points from the earlier database of Seed et al. (1984). Several additional "special" data sets were also examined, and some use was made of additional data as described below.

Figure 3-5 shows the data points deleted on this quality screening basis from the data set of Seed et al. (1984). In both Figures 3-5 and 3-6, CSR values have been corrected for Magnitude-correlated duration weighting factors (DWF_M) based on the final correlations developed herein, and the N-values have been similarly corrected for fines effects (to $(N_1)_{60,cs}$-values), again based on the final correlations developed. Tables 3-5 and 3-6 present a summary of the data points from the Seed et al. (1984) database, and the new cases, respectively, used in these studies. Table 3-7 lists data points deleted from the earlier studies of Seed et al.(1984).

Table 3-3 : Field Case History Distribution by Performance as Used in These Studies

Database	Liquefied	Marginal Liquefaction	Non-liquefied
Seed et al. (1984) Modified	47	2	41
Seed et al. (1984) Deleted	(20)	(4)	(12)
New Database	42	-	25
Kobe Alluvium	20	1	23
Kobe Masado Fill	(25)	-	(36)
Youd's Small Mag.	(1)	-	(43)
Data Currently Used	109	3	89
		Total	201

Table 3.4 : Field Case History Data Distribution by Quality Classifications as Used in These Studies

Database	Class A	Class B	Class C	(Class D)
Seed et al. (1984) Non-liquefied	6	34	1	-
Seed et al. (1984) Liquefied	7	38	2	-
Seed et al. (1984) Marginally Liq.	1	1	-	-
Seed et al. (1984) Deleted	-	-	-	(36)
New Database Non-liquefied	11	13	1	-
New Database Liquefied	20	21	1	-
Kobe Alluvium Non-liquefied	4	19	-	
Kobe Alluvium Liquefied	12	8	-	
Kobe Alluvium Marginally Liq.	1	-	-	-
Data Currently Used	62	134	5	-
			Total=201	(Deleted)

Two additional data sets were examined. The first of these was a "small magnitude" data set developed by Youd (1999). These data could not all be tracked back to their source documents (though most were), and generally did not consistently meet the criteria for Class C or better. These data are summarized in Table 3-8. Although these data were less well documented, they were potentially valuable due to the relative paucity of small magnitude (M_w<6.2) data. Accordingly, the overall development of correlations was performed both (a) without this data set of Table 3-8, and with this data, but with the data of Table 6 down-weighted by a weighting factor of 0.5, for purposes of development of magnitude-correlated duration weighting factors (DWF_M) correlations only. The results were found to differ only slightly, and, based on difficulties with some of these data, it was decided not to include these data of Table 3-8 in the final overall correlations presented herein.

A second additional data set evaluated was a proprietary data set from alluvium sites just inboard of the well-known coastal fills at Kobe, Japan. These data were particularly valuable, as the stiffer underlying soil conditions inboard of the coastal fills were able to sustain higher ground accelarations, so that these data provide good coverage of the high CSR range (CSR> 0.3) for which data was previously scarce. Table 3-9 presents the processed data from this set, and Figure 3-6 shows plots of these data. Additional documentation of these data is provided by Cetin et al. (2000).

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1944 Tohnankai M=8.0	Ienaga	Yes	B	8.0 - 20.0	14.0	8.0 ± 1.0	1360.0 ± 208.9	985.6 ± 112.0	0.20 ± 0.060
1944 Tohnankai M=8.0	Komei	Yes	B	6.4 - 16.4	11.4	6.4 ± 1.0	1108.1 ± 173.8	797.8 ± 98.0	0.20 ± 0.060
1944 Tohnankai M=8.0	Meiko	Yes	C	1.6 - 11.5	6.5	1.6 ± 1.0	645.9 ± 166.1	340.1 ± 86.9	0.20 ± 0.060
1948 Fukui M=7.3	Shonenji Temple	Yes	B	3.9 - 18.0	11.0	3.9 ± 1.0	1110.4 ± 249.0	672.8 ± 117.5	0.40 ± 0.120
1948 Fukui M=7.3	Takaya 45	Yes	B	12.3 - 40.0	26.2	12.3 ± 1.0	2761.3 ± 542.8	1897.0 ± 270.4	0.35 ± 0.105
1964 Niigata M=7.5	Cc17-1	Yes	B	16.4 - 36.1	26.2	3.0 ± 1.0	2725.9 ± 372.2	1275.3 ± 205.1	0.16 ± 0.024
1964 Niigata M=7.5	Old Town -1	No	B	16.4 - 32.8	24.6	6.0 ± 1.0	2832.8 ± 337.9	1671.7 ± 180.9	0.18 ± 0.027
1964 Niigata M=7.5	Old Town -2	No	B	32.8 - 42.7	37.7	6.0 ± 1.0	4407.6 ± 236.3	2427.6 ± 165.6	0.18 ± 0.027
1964 Niigata M=7.5	Rail Road-1	Yes	B	16.4 - 32.8	24.6	3.0 ± 1.0	2553.7 ± 315.7	1205.4 ± 182.9	0.16 ± 0.024
1964 Niigata M=7.5	Rail Road-2	No/Yes	B	29.5 - 36.1	32.8	3.0 ± 1.0	3578.9 ± 216.5	1718.9 ± 194.3	0.16 ± 0.024
1964 Niigata M=7.5	River Site	Yes	B	13.1 - 42.7	27.9	2.0 ± 1.0	2908.5 ± 527.3	1291.1 ± 240.0	0.16 ± 0.024
1964 Niigata M=7.5	Road Site	No	B	13.1 - 29.5	21.3	8.2 ± 1.0	2222.8 ± 315.1	1403.9 ± 166.7	0.18 ± 0.027
1964 Niigata M=7.5	Showa Br 2	Yes	A	4.5 - 20.0	12.3	0.0 ± 0.0	1286.3 ± 275.6	521.9 ± 120.5	0.16 ± 0.024
1964 Niigata M=7.5	Showa Br 4	No	B	16.4 - 23.0	19.7	4.0 ± 1.0	2262.2 ± 149.5	1283.5 ± 99.4	0.18 ± 0.027
1968 Tokachioki M=7.9	Hachinohe - 2	No	A	10.0 - 26.0	18.0	7.0 ± 1.0	2180.0 ± 337.7	1493.6 ± 182.9	0.23 ± 0.025
1968 Tokachioki M=7.9	Hachinohe - 4	No	A	3.0 - 13.0	8.0	3.0 ± 1.0	875.0 ± 195.4	563.0 ± 105.6	0.23 ± 0.025
1968 Tokachioki M=7.9	Hachinohe-6	Yes	A	6.6 - 20.0	13.3	2.0 ± 1.0	1376.5 ± 251.8	671.4 ± 141.8	0.23 ± 0.025
1968 Tokachioki M=7.9	Nanaehama1-2-3	Yes	B	3.0 - 16.4	9.7	3.0 ± 1.0	955.2 ± 227.8	537.0 ± 110.9	0.20 ± 0.040
1971 San Fernando Mw=6.6	Juvenile Hall	Yes	A	14.4 - 20.7	17.6	14.0 ± 2.0	1703.0 ± 125.1	1481.3 ± 127.6	0.45 ± 0.045
1971 San Fernando Mw=6.6	Van Norman	Yes	A	17.0 - 24.0	20.5	17.0 ± 2.0	1982.5 ± 142.2	1764.1 ± 135.2	0.45 ± 0.045
1975 Haicheng Ms=7.3	Panjin Ch. F. P.	Yes	B	11.5 - 41.0	26.2	5.0 ± 1.0	2706.0 ± 524.2	1379.4 ± 233.1	0.13 ± 0.026
1975 Haicheng Ms=7.3	Shuang Tai Zi R.	Yes	B	19.7 - 36.1	27.9	5.0 ± 1.0	2878.3 ± 302.2	1449.3 ± 158.4	0.10 ± 0.020
1975 Haicheng Ms=7.3	Ying Kou G. F. P.	Yes	B	16.4 - 29.5	23.0	5.0 ± 1.0	2451.4 ± 264.9	1329.6 ± 158.5	0.20 ± 0.040
1975 Haicheng Ms=7.3	Ying Kou P. P.	Yes	B	14.8 - 34.4	24.6	5.0 ± 1.0	2533.8 ± 354.0	1309.5 ± 169.8	0.20 ± 0.040
1976 Guatemala M=7.5	Amatitlan B-1	Yes	B	10.0 - 50.0	30.0	5.0 ± 1.0	2550.0 ± 605.5	990.0 ± 201.6	0.14 ± 0.015
1976 Guatemala M=7.5	Amatitlan B-2	No/Yes	A	10.0 - 20.0	15.0	8.0 ± 1.0	1110.0 ± 155.2	673.2 ± 62.2	0.14 ± 0.015
1976 Guatemala M=7.5	Amatitlan B-3&4	No	B	20.0 - 45.0	32.5	11.0 ± 2.0	2595.0 ± 385.8	1253.4 ± 148.6	0.14 ± 0.015
1976 Tangshan Ms=7.8	Coastal Region	Yes	B	9.8 - 19.7	14.8	4.0 ± 1.0	1510.2 ± 178.5	838.7 ± 98.7	0.13 ± 0.026
1976 Tangshan Ms=7.8	Le Ting L8-14	Yes	B	11.5 - 19.7	15.6	3.5 ± 1.0	1739.7 ± 165.7	985.6 ± 99.7	0.20 ± 0.040
1976 Tangshan Ms=7.8	Qing Jia Ying	Yes	B	14.8 - 21.3	18.0	3.0 ± 1.0	2030.8 ± 140.8	1089.1 ± 96.6	0.35 ± 0.070

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Ienaga	470	0.83 ± 0.068	0.15 ± 0.048	8	0.15 ± 0.050	25.0± 3.0	0.90	1	1	1.17	1.42	2.2 ± 0.8	Kishida (1969)
Komei	560	0.93 ± 0.057	0.17 ± 0.055	8	0.40 ± 0.100	13.0± 1.0	0.87	1	1	1.17	1.58	9.4 ± 2.9	Kishida (1969)
Meiko	380	0.89 ± 0.036	0.22 ± 0.079	8	0.20 ± 0.050	27.0± 3.0	0.80	1	1	1.17	2.00	3.6 ± 1.6	Kishida (1969)
Shonenji Temple	600	0.95 ± 0.055	0.41 ± 0.133	7.3	0.40 ± 0.030	0.0± 0.0	0.86	1	1	1.17	1.72	6.6 ± 2.2	Kishida (1969)
Takaya 45	620	0.79 ± 0.115	0.26 ± 0.089	7.3	0.50 ± 0.100	4.0± 1.0	1.00	1	1	1.30	1.03	21.5 ± 3.5	Kishida (1969)
Cc17-1	510	0.65 ± 0.116	0.15 ± 0.035	7.5	0.20 ± 0.035	8.0± 2.0	1.00	1	1	1.09	1.25	12.0 ± 3.1	Kishida (1966)
Old Town -1	480	0.75 ± 0.110	0.15 ± 0.032	7.5	0.20 ± 0.035	8.0± 2.0	0.99	1	1	1.21	1.09	22.7 ± 0.7	Kishida (1966)
Old Town -2	560	0.55 ± 0.158	0.12 ± 0.038	7.5	0.20 ± 0.035	8.0± 2.0	1.00	1	1	1.21	0.91	27.1 ± 3.3	Koizumi (1964)
Rail Road-1	560	0.78 ± 0.110	0.17 ± 0.038	7.5	0.20 ± 0.035	8.0± 2.0	0.99	1	1	1.09	1.29	13.0 ± 1.6	Koizumi (1964)
Rail Road-2	580	0.65 ± 0.140	0.14 ± 0.038	7.5	0.20 ± 0.035	2.0± 2.0	1.00	1	1	1.09	1.08	18.8 ± 2.5	Koizumi (1964)
River Site	580	0.60 ± 0.122	0.14 ± 0.037	7.5	0.43 ± 0.040	0.0± 0.0	1.00	1	1	1.09	1.24	11.1 ± 4.3	Ishihara (1979)
Road Site	490	0.78 ± 0.097	0.14 ± 0.030	7.5	0.45 ± 0.040	0.0± 0.0	0.96	1	1	1.09	1.19	15.1 ± 3.9	Ishihara (1979)
Showa Br 2	540	0.86 ± 0.061	0.22 ± 0.039	7.5	0.40 ± 0.040	10.0± 3.0	0.88	1	1	1.09	1.96	7.5 ± 0.6	Ishihara (1979)
Showa Br 4	480	0.87 ± 0.091	0.18 ± 0.034	7.5	0.30 ± 0.030	0.0± 0.0	0.95	1	1	1.21	1.25	43.0 ± 3.4	Ishihara (1979)
Hachinohe - 2	660	0.93 ± 0.084	0.20 ± 0.031	7.9	0.25 ± 0.025	5.0± 2.0	0.94	1	1	1.21	1.16	37.4 ± 2.8	Ohsaki (1970)
Hachinohe - 4	580	0.96 ± 0.042	0.22 ± 0.037	7.9	0.25 ± 0.025	5.0± 2.0	0.82	1	1	1.21	1.88	26.0 ± 2.6	Ohsaki (1970)
Hachinohe-6	530	0.89 ± 0.065	0.27 ± 0.047	7.9	0.25 ± 0.025	5.0± 2.0	0.89	1	1	1.09	1.73	7.6 ± 0.9	Ohsaki (1970)
Nanaehama1-2-3	560	0.95 ± 0.050	0.22 ± 0.055	7.9	0.12 ± 0.020	20.0± 3.0	0.84	1	1	1.17	1.93	10.4 ± 1.4	Kishida (1970)
Juvenile Hall	540	0.81 ± 0.082	0.27 ± 0.046	6.6	0.05 ± 0.010	55.0± 5.0	0.90	1	1	1.13	1.16	4.1 ± 1.0	Bennett (1989)
Van Norman	620	0.86 ± 0.094	0.28 ± 0.047	6.6	0.06 ± 0.010	50.0± 5.0	0.93	1	1	1.13	1.06	8.2 ± 2.8	Bennett (1989)
Panjin Ch. F. P.	610	0.79 ± 0.116	0.13 ± 0.034	7.3	0.06 ± 0.010	67.0± 7.0	1.00	1	1	0.83	1.20	8.2 ± 1.2	Shengcong et al. (1983)
Shuang Tai Zi R.	610	0.77 ± 0.122	0.10 ± 0.026	7.3	0.07 ± 0.015	5.0± 2.0	1.00	1	1	1.00	1.17	11.1 ± 1.8	Shengcong et al. (1983)
Ying Kou G. F. P.	610	0.83 ± 0.103	0.20 ± 0.048	7.3	0.08 ± 0.015	48.0± 5.0	0.98	1	1	1.00	1.23	14.9 ± 1.1	Shengcong et al. (1983)
Ying Kou P. P.	560	0.74 ± 0.110	0.19 ± 0.048	7.3	0.10 ± 0.050	5.0± 2.0	0.99	1	1	1.00	1.24	12.5 ± 4.0	Shengcong et al. (1983)
Amatitlan B-1	400	0.46 ± 0.117	0.10 ± 0.030	7.5	0.80 ± 0.150	3.0± 1.0	1.00	1	1	0.75	1.42	4.6 ± 1.5	Seed, et al.(1979)
Amatitlan B-2	420	0.75 ± 0.065	0.11 ± 0.019	7.5	0.80 ± 0.150	3.0± 1.0	0.88	1	1	0.75	1.72	8.5 ± 1.1	Seed, et al. (1979)
Amatitlan B-3&4	440	0.47 ± 0.125	0.09 ± 0.026	7.5	0.80 ± 0.150	3.0± 1.0	1.00	1	1	0.75	1.26	14.1 ± 1.8	Seed, et al. (1979)
Coastal Region	590	0.92 ± 0.064	0.14 ± 0.032	8	0.14 ± 0.030	12.0± 3.0	0.90	1	1	1.00	1.54	13.2 ± 3.2	Shengcong et al. (1983)
Le Ting L8-14	650	0.94 ± 0.067	0.22 ± 0.048	8	0.10 ± 0.030	12.0± 3.0	0.91	1	1	1.00	1.42	12.8 ± 2.6	Shengcong et al. (1983)
Qing Jia Ying	640	0.92 ± 0.076	0.39 ± 0.087	8	0.14 ± 0.030	20.0± 3.0	0.94	1	1	1.00	1.36	23.2 ± 2.6	Shengcong et al. (1983)

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1976 Tangshan Ms=7.8	Tangshan City	No	B	11.5 - 18.0	14.8	9.8 ± 1.0	1574.8 ± 139.9	1267.7 ± 87.8	0.50 ± 0.100
1976 Tangshan Ms=7.8	Yao Yuan Village	Yes	B	11.5 - 16.4	13.9	3.3 ± 1.0	1501.0 ± 101.2	835.6 ± 79.1	0.20 ± 0.040
1977 Argentina M=7.4	San Juan B-1	Yes	B	26.0 - 28.0	27.0	15.0 ± 1.0	2745.0 ± 86.4	1996.2 ± 91.7	0.20 ± 0.015
1977 Argentina M=7.4	San Juan B-3	Yes	B	33.5 - 43.0	38.3	22.0 ± 1.0	3796.3 ± 199.3	2782.3 ± 138.8	0.20 ± 0.015
1977 Argentina M=7.4	San Juan B-4	No	B	4.0 - 12.0	8.0	4.0 ± 1.0	820.0 ± 149.2	570.4 ± 82.4	0.20 ± 0.015
1977 Argentina M=7.4	San Juan B-5	No	B	7.0 - 12.0	9.5	7.0 ± 1.0	952.5 ± 102.3	796.5 ± 67.8	0.20 ± 0.015
1977 Argentina M=7.4	San Juan B-6	Yes	B	12.0 - 18.0	15.0	6.0 ± 1.0	1530.0 ± 119.9	968.4 ± 77.0	0.20 ± 0.015
1978 Miyagiken-Oki M=6.7	Arahama	No	B	6.6 - 26.2	16.4	3.0 ± 1.0	1774.5 ± 365.2	938.0 ± 173.6	0.10 ± 0.020
1978 Miyagiken-Oki M=6.7	Hiyori-18	No	B	8.2 - 13.1	10.7	8.0 ± 1.0	1092.9 ± 97.6	926.7 ± 74.5	0.14 ± 0.028
1978 Miyagiken-Oki M=6.7	Ishinomaki-2	No	B	4.6 - 19.7	12.1	4.6 ± 1.0	1228.7 ± 266.6	757.8 ± 124.4	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Kitawabuchi-2	No	B	9.8 - 13.1	11.5	9.8 ± 0.5	1115.5 ± 72.9	1013.1 ± 53.7	0.14 ± 0.028
1978 Miyagiken-Oki M=6.7	Nakajima-18	No	B	8.0 - 20.0	14.0	8.0 ± 1.0	1490.0 ± 235.5	1115.6 ± 125.0	0.14 ± 0.028
1978 Miyagiken-Oki M=6.7	Nakamura 4	Yes	B	9.8 - 16.4	13.1	1.6 ± 1.0	1361.5 ± 124.3	645.0 ± 84.1	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Nakamura 5	No	B	9.0 - 13.1	11.1	4.3 ± 1.0	1118.8 ± 79.6	694.7 ± 68.1	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Oiiri-1	No	B	14.0 - 25.0	19.5	14.0 ± 2.0	1907.5 ± 227.9	1564.3 ± 177.7	0.14 ± 0.024
1978 Miyagiken-Oki M=6.7	Shiomi-6	No	A	9.8 - 19.7	14.8	8.0 ± 1.0	1544.0 ± 188.0	1122.0 ± 107.3	0.14 ± 0.024
1978 Miyagiken-Oki M=6.7	Yuriage Br-1	No	B	9.8 - 13.1	11.5	5.6 ± 1.0	1146.5 ± 67.0	780.0 ± 65.9	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Yuriage Br-2	No	B	6.0 - 10.0	8.0	4.3 ± 1.0	797.3 ± 74.3	564.3 ± 63.8	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Yuriage Br-3	No	B	6.6 - 13.1	9.8	0.9 ± 0.5	1024.9 ± 120.5	464.0 ± 64.5	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Yuriagekami-1	No	B	5.9 - 18.0	12.0	5.9 ± 1.0	1198.3 ± 215.4	819.6 ± 106.4	0.12 ± 0.024
1978 Miyagiken-Oki M=6.7	Yuriagekami-2	No	B	6.6 - 18.0	12.3	2.8 ± 1.0	1263.9 ± 205.1	670.2 ± 104.7	0.12 ± 0.024
1978 Miyagiken-Oki M=7.4	Nakajima-18	Yes	B	8.0 - 20.0	14.0	8.0 ± 1.0	1490.0 ± 235.5	1115.6 ± 125.0	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Arahama	Yes	B	6.6 - 26.2	16.4	3.0 ± 1.0	1774.5 ± 365.2	938.0 ± 173.6	0.20 ± 0.040
1978 Miyagiken-Oki M=7.4	Hiyori-18	Yes	B	8.2 - 13.1	10.7	8.0 ± 1.0	1092.9 ± 97.6	926.7 ± 74.5	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Ishinomaki-2	Yes	B	4.6 - 19.7	12.1	4.6 ± 1.0	1228.7 ± 266.6	757.8 ± 124.4	0.20 ± 0.040
1978 Miyagiken-Oki M=7.4	Ishinomaki-4	No	B	4.6 - 23.0	13.8	4.6 ± 1.0	2786.0 ± 339.5	2212.6 ± 160.2	0.20 ± 0.040
1978 Miyagiken-Oki M=7.4	Kitawabuchi-2	Yes	B	9.8 - 13.1	11.5	9.8 ± 0.5	1115.5 ± 72.9	1013.1 ± 53.7	0.28 ± 0.056
1978 Miyagiken-Oki M=7.4	Kitawabuchi-3	No	B	10.0 - 18.0	14.0	10.0 ± 3.0	1392.5 ± 160.1	1141.5 ± 161.7	0.28 ± 0.056
1978 Miyagiken-Oki M=7.4	Nakajima-2	No	B	10.0 - 20.0	15.0	8.0 ± 1.0	1605.0 ± 199.4	1168.2 ± 112.8	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Nakamura 1	No	B	6.6 - 13.1	9.8	3.0 ± 1.0	1038.4 ± 124.9	608.5 ± 76.5	0.32 ± 0.064
1978 Miyagiken-Oki M=7.4	Nakamura 4	Yes	B	9.8 - 16.4	13.1	1.6 ± 1.0	1361.5 ± 124.3	645.0 ± 84.1	0.32 ± 0.064
1978 Miyagiken-Oki M=7.4	Nakamura 5	Yes	B	9.0 - 13.1	11.1	4.3 ± 1.0	1118.8 ± 79.6	694.7 ± 68.1	0.32 ± 0.064
1978 Miyagiken-Oki M=7.4	Oiiri-1	Yes	B	14.0 - 25.0	19.5	14.0 ± 2.0	1907.5 ± 227.9	1564.3 ± 177.7	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Shiomi-6	Yes	B	9.8 - 19.7	14.8	8.0 ± 1.0	1544.0 ± 188.0	1122.0 ± 107.3	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriage Br-1	Yes	B	9.8 - 13.1	11.5	5.6 ± 1.0	1146.5 ± 67.0	780.0 ± 65.9	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriage Br-2	Yes	B	6.0 - 10.0	8.0	4.3 ± 1.0	797.3 ± 74.3	564.3 ± 63.8	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriage Br-3	Yes	B	6.6 - 13.1	9.8	0.9 ± 0.5	1024.9 ± 120.5	464.0 ± 64.5	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriage Br-5	No	B	19.7 - 29.5	24.6	4.3 ± 1.0	2744.4 ± 226.2	1475.1 ± 156.3	0.24 ± 0.048

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Tangshan City	675	0.96 ± 0.064	0.39 ± 0.084	8	0.20 ± 0.024	10.0± 2.0	0.90	1	1	1.00	1.26	33.7 ± 5.8	Shengcong et al. (1983)
Yao Yuan Village	575	0.92 ± 0.061	0.21 ± 0.048	8	0.15 ± 0.050	5.0± 3.0	0.90	1	1	1.00	1.55	11.9 ± 5.3	Shengcong et al. (1983)
San Juan B-1	610	0.78 ± 0.107	0.14 ± 0.022	7.4	0.14 ± 0.050	20.0± 3.0	0.98	1	1	0.75	1.00	6.7 ± 1.5	Idriss, et al. (1979)
San Juan B-3	580	0.56 ± 0.144	0.10 ± 0.027	7.4	0.14 ± 0.050	20.0± 3.0	1.00	1	1	0.75	0.85	7.3 ± 1.0	Idriss, et al. (1979)
San Juan B-4	590	0.97 ± 0.038	0.18 ± 0.027	7.4	0.29 ± 0.025	4.0± 1.5	0.77	1	1	0.75	1.87	14.8 ± 0.6	Idriss, et al. (1979)
San Juan B-5	670	0.98 ± 0.044	0.15 ± 0.019	7.4	0.24 ± 0.025	3.0± 1.0	0.80	1	1	0.75	1.58	14.5 ± 0.1	Idriss, et al. (1979)
San Juan B-6	630	0.94 ± 0.065	0.19 ± 0.023	7.4	0.10 ± 0.025	50.0± 5.0	0.87	1	1	0.75	1.44	5.7 ± 0.2	Idriss, et al. (1979)
Arahama	610	0.91 ± 0.070	0.11 ± 0.025	6.7	0.45 ± 0.080	0.0± 0.0	0.92	1	1	1.09	1.46	14.1 ± 2.7	Tohno et al. (1981)
Hiyori-18	640	0.96 ± 0.048	0.10 ± 0.023	6.7	0.15 ± 0.030	20.0± 3.0	0.86	1	1	1.09	1.47	12.5 ± 2.5	Tsuchida et al. (1979, 1980)
Ishinomaki-2	520	0.89 ± 0.054	0.11 ± 0.026	6.7	0.15 ± 0.030	10.0± 2.0	0.88	1	1	1.09	1.62	6.2 ± 0.5	Ishihara et al. (1980)
Kitawabuchi-2	460	0.85 ± 0.052	0.08 ± 0.018	6.7	0.53 ± 0.100	5.0± 2.0	0.87	1	1	1.00	1.41	13.5 ± 2.5	Iwasaki (1978)
Nakajima-18	590	0.92 ± 0.061	0.11 ± 0.025	6.7	0.35 ± 0.050	3.0± 1.0	0.90	1	1	1.09	1.34	12.6 ± 5.3	Tsuchida et al. (1979, 1980)
Nakamura 4	700	0.97 ± 0.058	0.16 ± 0.037	6.7	0.70 ± 0.150	5.0± 1.0	0.89	1	1	1.00	1.76	8.7 ± 0.7	Iwasaki (1978)
Nakamura 5	620	0.96 ± 0.050	0.12 ± 0.027	6.7	0.28 ± 0.030	4.0± 1.0	0.86	1	1	1.00	1.70	10.3 ± 2.0	Iwasaki (1978)
Oiiri-1	490	0.73 ± 0.081	0.08 ± 0.018	6.7	0.34 ± 0.100	5.0± 3.0	0.95	1	1	1.00	1.13	9.8 ± 1.8	Iwasaki (1978)
Shiomi-6	600	0.92 ± 0.064	0.11 ± 0.023	6.7	0.25 ± 0.050	10.0± 2.0	0.90	1	1	1.09	1.34	9.7 ± 2.3	Tsuchida et al. (1979, 1980)
Yuriage Br-1	600	0.94 ± 0.051	0.11 ± 0.024	6.7	0.40 ± 0.100	5.0± 1.0	0.87	1	1	1.00	1.60	4.1 ± 1.8	Iwasaki (1978)
Yuriage Br-2	660	0.98 ± 0.038	0.11 ± 0.025	6.7	1.60 ± 0.200	7.0± 1.0	0.82	1	1	1.12	1.88	19.7 ± 2.8	Iwasaki (1978)
Yuriage Br-3	620	0.96 ± 0.045	0.17 ± 0.036	6.7	1.20 ± 0.200	12.0± 2.0	0.85	1	1	1.00	2.00	12.0 ± 2.1	Iwasaki (1978)
Yuriagekami-1	560	0.92 ± 0.053	0.10 ± 0.024	6.7	0.04 ± 0.010	60.0± 5.0	0.77	1	1	1.00	1.56	2.8 ± 1.2	Iwasaki (1978)
Yuriagekami-2	620	0.95 ± 0.055	0.14 ± 0.032	6.7	0.40 ± 0.100	0.0± 0.0	0.88	1	1	1.00	1.73	13.3 ± 5.2	Iwasaki (1978)
Nakajima-18	590	0.92 ± 0.061	0.19 ± 0.043	7.4	0.35 ± 0.050	3.0± 1.0	0.90	1	1	1.09	1.34	12.6 ± 5.3	Tsuchida et al. (1979, 1980)
Arahama	610	0.91 ± 0.070	0.22 ± 0.051	7.4	0.45 ± 0.080	0.0± 0.0	0.92	1	1	1.09	1.46	13.1 ± 3.6	Tohno et al. (1981)
Hiyori-18	640	0.97 ± 0.048	0.18 ± 0.039	7.4	0.15 ± 0.030	20.0± 3.0	0.86	1	1	1.09	1.47	12.5 ± 2.7	Tsuchida et al. (1979, 1980)
Ishinomaki-2	520	0.89 ± 0.054	0.19 ± 0.044	7.4	0.15 ± 0.030	10.0± 2.0	0.88	1	1	1.09	1.62	6.0 ± 0.7	Ishihara et al. (1980)
Ishinomaki-4	650	0.95 ± 0.060	0.16 ± 0.034	7.4	0.18 ± 0.020	10.0± 2.0	0.89	1	1	1.21	0.95	25.2 ± 2.4	Ishihara et al. (1980)
Kitawabuchi-2	460	0.85 ± 0.052	0.17 ± 0.036	7.4	0.53 ± 0.100	5.0± 2.0	0.87	1	1	1.00	1.41	13.5 ± 2.9	Iwasaki (1978)
Kitawabuchi-3	670	0.96 ± 0.061	0.21 ± 0.057	7.4	0.41 ± 0.080	0.0± 0.0	0.90	1	1	1.21	1.32	18.9 ± 7.3	Iwasaki (1978)
Nakajima-2	620	0.93 ± 0.065	0.20 ± 0.044	7.4	0.12 ± 0.030	26.0± 5.0	0.91	1	1	1.09	1.31	15.4 ± 3.1	Tsuchida et al. (1979, 1980)
Nakamura 1	680	0.98 ± 0.045	0.35 ± 0.079	7.4	0.28 ± 0.040	4.0± 1.0	0.85	1	1	1.12	1.81	26.8 ± 7.2	Iwasaki (1978)
Nakamura 4	700	0.97 ± 0.058	0.43 ± 0.098	7.4	0.70 ± 0.150	5.0± 1.0	0.89	1	1	1.00	1.76	8.7 ± 0.7	Iwasaki (1978)
Nakamura 5	620	0.96 ± 0.050	0.32 ± 0.072	7.4	0.28 ± 0.030	7.0± 2.0	0.86	1	1	1.00	1.70	10.3 ± 2.0	Iwasaki (1978)
Oiiri-1	490	0.74 ± 0.081	0.14 ± 0.035	7.4	0.34 ± 0.100	5.0± 3.0	0.95	1	1	1.00	1.13	9.8 ± 2.2	Iwasaki (1978)
Shiomi-6	600	0.92 ± 0.064	0.20 ± 0.044	7.4	0.25 ± 0.050	10.0± 2.0	0.90	1	1	1.09	1.34	9.7 ± 2.3	Tsuchida et al. (1979, 1980)
Yuriage Br-1	600	0.95 ± 0.051	0.22 ± 0.048	7.4	0.40 ± 0.100	5.0± 1.0	0.87	1	1	1.00	1.60	4.1 ± 1.8	Iwasaki (1978)
Yuriage Br-2	660	0.98 ± 0.038	0.22 ± 0.050	7.4	1.60 ± 0.200	7.0± 1.0	0.82	1	1	1.12	1.88	19.7 ± 2.8	Iwasaki (1978)
Yuriage Br-3	620	0.96 ± 0.045	0.33 ± 0.073	7.4	1.20 ± 0.200	12.0± 2.0	0.85	1	1	1.00	2.00	12.0 ± 2.1	Iwasaki (1978)
Yuriage Br-5	660	0.86 ± 0.099	0.25 ± 0.059	7.4	0.35 ± 0.080	17.0± 3.0	0.99	1	1	1.12	1.16	26.3 ± 8.6	Iwasaki (1978)

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1978 Miyagiken-Oki M=7.4	Yuriagekami-1	Yes	B	5.9 - 18.0	12.0	5.9 ± 1.0	1198.3 ± 215.4	819.6 ± 106.4	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriagekami-2	Yes	B	6.6 - 18.0	12.3	2.8 ± 1.0	1263.9 ± 205.1	670.2 ± 104.7	0.24 ± 0.048
1978 Miyagiken-Oki M=7.4	Yuriagekami-3	No	B	14.8 - 24.6	19.7	7.1 ± 1.0	2122.7 ± 198.3	1334.5 ± 112.2	0.24 ± 0.048
1979 Imperial Valley ML=6.6	Radio Tower B2	No	B	6.6 - 9.8	8.2	6.6 ± 1.0	746.4 ± 58.8	644.0 ± 65.9	0.16 ± 0.019
1979 Imperial Valley ML=6.6	Heber Road A1	No	B	5.9 - 16.4	11.2	5.9 ± 3.0	1246.7 ± 233.4	919.2 ± 160.0	0.47 ± 0.050
1979 Imperial Valley ML=6.6	Heber Road A2	Yes	B	6.0 - 15.1	10.6	5.9 ± 3.0	974.1 ± 147.3	683.4 ± 181.6	0.47 ± 0.050
1979 Imperial Valley ML=6.6	Heber Road A3	No	B	5.9 - 16.1	11.0	5.9 ± 3.0	1095.0 ± 183.2	777.7 ± 175.8	0.47 ± 0.050
1979 Imperial Valley ML=6.6	Kornbloom B	No	A	8.5 - 17.0	12.8	9.0 ± 1.0	1248.8 ± 154.1	1014.8 ± 88.9	0.13 ± 0.010
1979 Imperial Valley ML=6.6	McKim Ranch A	Yes	A	5.0 - 13.0	9.0	5.0 ± 1.0	875.0 ± 135.9	625.4 ± 80.4	0.51 ± 0.050
1979 Imperial Valley ML=6.6	Radio Tower B1	Yes	B	9.8 - 18.0	13.9	6.6 ± 1.0	1291.8 ± 135.8	831.2 ± 82.7	0.18 ± 0.019
1979 Imperial Valley ML=6.6	River Park A	Yes	C	1.0 - 5.9	3.5	1.0 ± 0.5	323.0 ± 78.4	170.0 ± 40.6	0.16 ± 0.045
1979 Imperial Valley ML=6.6	Wildlife B	No	B	9.0 - 22.0	15.5	3.0 ± 1.0	1520.0 ± 239.1	740.0 ± 139.7	0.17 ± 0.045
1980 Mid-Chiba M=6.1	Owi-1	No	A	13.1 - 23.0	18.0	3.0 ± 1.0	1879.7 ± 179.0	940.9 ± 102.7	0.10 ± 0.001
1980 Mid-Chiba M=6.1	Owi-2	No	C	42.7 - 52.5	47.6	3.0 ± 1.0	4980.1 ± 218.9	2198.8 ± 162.4	0.10 ± 0.001
1981 WestMorland ML=5.6	Kornbloom B	Yes	A	8.5 - 17.0	12.8	9.0 ± 1.0	1248.8 ± 154.1	1014.8 ± 88.9	0.19 ± 0.025
1981 Westmorland ML=5.6	Radio Tower B1	Yes	B	9.8 - 18.0	13.9	6.6 ± 1.0	1291.8 ± 134.7	831.2 ± 80.9	0.17 ± 0.020
1981 Westmorland ML=5.6	Radio Tower B2	No	B	6.6 - 9.8	8.2	6.6 ± 1.0	746.4 ± 56.2	644.0 ± 63.6	0.16 ± 0.020
1981 Westmorland ML=5.6	River Park A	No	B	1.0 - 5.9	3.5	1.0 ± 0.5	323.0 ± 78.4	170.0 ± 40.6	0.17 ± 0.020
1981 WestMorland ML=5.6	River Park C	No	A	11.0 - 17.0	14.0	1.0 ± 0.5	1520.0 ± 122.1	708.8 ± 73.7	0.17 ± 0.020
1981 WestMorland ML=5.6	Wildlife B	Yes	A	9.0 - 22.0	15.5	3.0 ± 1.0	1520.0 ± 222.9	740.0 ± 109.7	0.23 ± 0.020
1981Westmorland ML=5.6	McKim Ranch A	No	B	5.0 - 13.0	9.0	5.0 ± 1.0	875.0 ± 135.9	625.4 ± 80.4	0.09 ± 0.023

Table 3-5 : Field Case History Data from Seed et al. (1984) of Classes A, B and C as Re-Evaluated for These Studies

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Yuriagekami-1	560	0.92 ± 0.053	0.21 ± 0.049	7.4	0.04 ± 0.010	60.0± 5.0	0.87	1	1	1.00	1.56	2.8 ± 1.2	Iwasaki (1978)
Yuriagekami-2	620	0.95 ± 0.055	0.28 ± 0.064	7.4	0.40 ± 0.100	0.0± 0.0	0.88	1	1	1.00	1.73	13.3 ± 5.2	Iwasaki (1978)
Yuriagekami-3	660	0.91 ± 0.082	0.23 ± 0.051	7.4	0.60 ± 0.015	0.0± 0.0	0.95	1	1	1.12	1.22	27.3 ± 2.5	Iwasaki (1978)
Radio Tower B2	*	0.99 ± 0.020	0.12 ± 0.019	6.5	0.10 ± 0.020	30.0± 5.0	0.77	1	1	1.13	1.76	17.0 ± 2.8	Bennett et al.(1984)
Heber Road A1	*	0.82 ± 0.010	0.33 ± 0.074	6.5	0.11 ± 0.010	25.0± 4.0	0.82	1	1	1.13	1.48	45.2 ± 3.6	Youd et al. (1983)
Heber Road A2	*	0.78 ± 0.020	0.35 ± 0.101	6.5	0.11 ± 0.010	29.0± 4.5	0.74	1	1	1.13	1.71	3.8 ± 2.4	Youd et al. (1983)
Heber Road A3	*	0.75 ± 0.025	0.33 ± 0.085	6.5	0.10 ± 0.010	37.0± 5.0	0.82	1	1	1.13	1.60	19.5 ± 6.1	Youd et al (1983)
Kornbloom B	*	0.83 ± 0.030	0.09 ± 0.010	6.5	0.05 ± 0.020	92.0± 10.0	0.85	1	1	1.13	1.40	7.2 ± 3.5	Bennett et al. (1984)
McKim Ranch A	590	0.95 ± 0.042	0.44 ± 0.072	6.4	0.11 ± 0.003	31.0± 3.0	0.79	1	1	1.13	1.79	8.5 ± 4.2	Bennett et al. (1984
Radio Tower B1	*	0.97 ± 0.030	0.16 ± 0.025	6.5	0.05 ± 0.015	75.0± 10.0	0.86	1	1	1.13	1.55	6.8 ± 5.2	Bennett et al. (1984)
River Park A	*	0.99 ± 0.015	0.17 ± 0.067	6.5	0.04 ± 0.010	80.0± 10.0	0.66	1	1	1.13	2.00	4.0 ± 3.4	Youd et al. (1982)
Wildlife B	*	0.67 ± 0.035	0.13 ± 0.039	6.5	0.09 ± 0.005	40.0± 3.0	0.88	1	1	1.13	1.64	12.8 ± 5.7	Bennett et al. (1984)
Owi-1	490	0.75 ± 0.076	0.09 ± 0.011	6.1	0.18 ± 0.020	13.0± 1.0	0.86	1	1	1.09	1.46	6.3 ± 0.6	Ishihara (1981)
Owi-2	490	0.33 ± 0.149	0.05 ± 0.021	6.1	0.17 ± 0.020	27.0± 1.0	1.00	1	1	1.09	0.95	3.7 ± 0.6	Ishihara (1981)
Kornbloom B	*	0.83 ± 0.012	0.14 ± 0.020	5.9	0.05 ± 0.020	92.0± 10.0	0.85	1	1	1.13	1.40	7.2 ± 3.5	Bennett et al. (1984)
Radio Tower B1	*	0.89 ± 0.012	0.14 ± 0.023	5.9	0.05 ± 0.015	75.0± 10.0	0.80	1	1	1.13	1.55	6.8 ± 5.2	Bennett et al. (1984)
Radio Tower B2	*	0.98 ± 0.010	0.12 ± 0.019	5.9	0.10 ± 0.020	30.0± 5.0	0.77	1	1	1.13	1.76	17.0 ± 2.8	Bennett et al.(1984)
River Park A	*	0.99 ± 0.003	0.19 ± 0.043	5.9	0.04 ± 0.010	80.0± 10.0	0.66	1	1	1.13	2.00	4.0 ± 3.4	Youd et al. (1983)
River Park C	*	0.97 ± 0.010	0.23 ± 0.030	5.9	0.15 ± 0.008	18.0± 3.0	0.86	1	1	1.13	1.68	20.2 ± 7.7	Youd et al. (1983)
Wildlife B	*	0.89 ± 0.013	0.24 ± 0.030	5.9	0.09 ± 0.005	40.0± 3.0	0.88	1	1	1.13	1.64	12.8 ± 5.7	Bennett et al. (1984)
McKim Ranch A	*	0.93 ± 0.010	0.08 ± 0.022	5.9	0.11 ± 0.003	31.0± 3.0	0.79	1	1	1.13	1.79	8.5 ± 4.2	Bennett et al. (1984)

Table 3-6 : New Field Case History Data of Classes A, B and C as Developed for These Studies

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1964 Niigata M=7.5	Arayamotomachi	Yes	B	6.6 - 14.8	10.7	3.3 ± 1.0	1103.2 ± 147.2	642.6 ± 87.9	0.09 ± 0.018
1964 Niigata M=7.5	Cc17-2	Yes	B	11.5 - 23.0	17.2	3.0 ± 1.0	1778.6 ± 219.3	891.0 ± 130.4	0.16 ± 0.024
1968 Tokachi-Oki M=7.9	Aomori Station	Yes	A	13.1 - 24.6	18.9	0.0 ± 1.0	1980.8 ± 214.9	803.6 ± 122.8	0.21 ± 0.030
1976 Tangshan Ms=7.8	Luan Nan-L1	No	B	4.9 - 18.0	11.5	3.6 ± 1.0	1287.7 ± 265.9	796.4 ± 135.9	0.22 ± 0.044
1976 Tangshan Ms=7.8	Luan Nan-L2	Yes	B	4.9 - 18.0	11.5	3.6 ± 1.0	1169.6 ± 232.5	678.3 ± 112.4	0.22 ± 0.044
1983 Nihonkai-Chubu M=7.1	Arayamotomachi	No	B	3.3 - 24.6	13.9	3.3 ± 1.0	1447.7 ± 375.9	782.3 ± 168.0	0.15 ± 0.030
1983 Nihonkai-Chubu M=7.1	Arayamotomachi Coarse Sand	No	B	26.2 - 34.4	30.3	3.3 ± 1.0	3305.4 ± 186.0	1616.5 ± 137.4	0.15 ± 0.030
1983 Nihonkai-Chubu M=7.1	Takeda Elementary Sch.	Yes	B	8.2 - 21.3	14.8	1.1 ± 1.0	1544.5 ± 236.1	694.8 ± 122.3	0.12 ± 0.022
1983 Nihonkai-Chubu M=7.7	Aomori Station	Yes	B	13.1 - 24.6	18.9	0.0 ± 1.0	1980.8 ± 214.9	803.6 ± 122.8	0.12 ± 0.018
1983 Nihonkai-Chubu M=7.7	Arayamotomachi	Yes	B	3.3 - 24.6	13.9	3.3 ± 1.0	1447.7 ± 375.9	782.3 ± 168.0	0.20 ± 0.040
1983 Nihonkai-Chubu M=7.7	Gaiko Wharf B-2	Yes	B	8.2 - 41.0	24.6	1.3 ± 1.0	2570.9 ± 581.8	1115.3 ± 256.4	0.23 ± 0.035
1983 Nihonkai-Chubu M=7.7	Noshiro Section N-7	Yes	B	6.6 - 16.4	11.5	5.7 ± 1.0	1148.3 ± 175.6	790.0 ± 93.2	0.25 ± 0.055
1983 Nihonkai-Chubu M=7.7	Takeda Elementary Sch.	Yes	A	8.2 - 21.3	14.8	1.1 ± 1.0	1544.5 ± 236.1	694.8 ± 122.3	0.28 ± 0.040
1987 Elmore Ranch Mw=6.2	Radio Tower B1	No	B	9.8 - 18.0	13.9	6.6 ± 1.0	1291.8 ± 134.7	831.2 ± 80.9	0.09 ± 0.025
1987 Elmore Ranch Mw=6.2	Wildlife B	No	A	9.0 - 22.0	15.5	3.0 ± 1.0	1520.0 ± 222.9	740.0 ± 109.7	0.00 ± 0.005
1987 Superstition Hills Mw=6.6	Radio Tower B1	No	B	9.8 - 18.0	13.9	6.6 ± 1.0	1291.8 ± 134.7	831.2 ± 80.9	0.20 ± 0.040
1987 Superstition Hills Mw=6.6	Wildlife B	Yes	A	9.0 - 22.0	15.5	3.0 ± 1.0	1520.0 ± 222.9	740.0 ± 109.7	0.18 ± 0.005
1987 Superstition Hills Mw=6.7	Heber Road A1	No	B	5.9 - 16.4	11.2	5.9 ± 3.0	1246.7 ± 233.4	919.2 ± 160.0	0.16 ± 0.020
1987 Superstition Hills Mw=6.7	Heber Road A2	No	B	6.0 - 15.1	10.6	5.9 ± 3.0	974.1 ± 156.2	683.4 ± 188.9	0.15 ± 0.020
1987 Superstition Hills Mw=6.7	Heber Road A3	No	B	5.9 - 16.1	11.0	5.9 ± 3.0	1095.0 ± 183.2	777.7 ± 175.8	0.13 ± 0.020
1987 Superstition Hills Mw=6.7	Kornbloom B	No	A	8.5 - 17.0	12.8	9.0 ± 1.0	1248.8 ± 154.1	1014.8 ± 88.9	0.17 ± 0.020
1987 Superstition Hills Mw=6.7	McKim Ranch A	No	A	5.0 - 13.0	9.0	5.0 ± 1.0	875.0 ± 135.9	625.4 ± 80.4	0.16 ± 0.020
1987 Superstition Hills Mw=6.7	Radio Tower B2	No	B	6.6 - 9.8	8.2	6.6 ± 1.0	746.4 ± 66.7	644.0 ± 73.0	0.18 ± 0.020
1987 Superstition Hills Mw=6.7	River Park A	No	C	1.0 - 5.9	3.5	1.0 ± 1.0	323.0 ± 78.5	170.0 ± 64.2	0.19 ± 0.020
1987 Superstition Hills Mw=6.7	River Park C	No	A	11.0 - 17.0	14.0	1.0 ± 0.5	1520.0 ± 122.1	708.8 ± 73.7	0.19 ± 0.020
1989 Loma Prieta Mw=7	Alameda BF Dike	No	B	19.7 - 23.0	21.3	9.8 ± 3.0	2616.5 ± 92.5	1899.9 ± 185.7	0.24 ± 0.024
1989 Loma Prieta Mw=7	Farris Farm	Yes	B	16.4 - 23.0	19.7	14.8 ± 3.0	1796.3 ± 162.8	1489.2 ± 215.5	0.37 ± 0.050
1989 Loma Prieta Mw=7	Hall Avenue	No	A	11.5 - 18.9	15.2	11.5 ± 2.0	1421.0 ± 141.1	1190.7 ± 118.6	0.14 ± 0.013
1989 Loma Prieta Mw=7	Marine Laboratory UC-B1	Yes	B	7.9 - 18.0	13.0	7.9 ± 3.0	1282.0 ± 184.3	964.7 ± 177.0	0.24 ± 0.025
1989 Loma Prieta Mw=7	MBARI NO:3 EB-1	No	B	6.6 - 9.8	8.2	6.6 ± 1.0	820.2 ± 75.2	717.8 ± 55.9	0.24 ± 0.025
1989 Loma Prieta Mw=7	MBARI NO:3 EB-5	No	A	5.9 - 21.0	13.5	5.9 ± 1.0	1428.8 ± 292.5	957.9 ± 144.1	0.27 ± 0.025
1989 Loma Prieta Mw=7	Sandholdt UC-B10	Yes	B	5.9 - 12.0	9.0	5.5 ± 1.0	885.0 ± 110.2	669.6 ± 72.8	0.26 ± 0.025
1989 Loma Prieta Mw=7	Miller Farm	Yes	B	13.1 - 26.2	19.7	13.1 ± 1.0	1804.5 ± 216.0	1395.0 ± 108.7	0.42 ± 0.050
1989 Loma Prieta Mw=7	Miller Farm CMF10	Yes	B	23.0 - 32.8	27.9	9.8 ± 1.0	2600.1 ± 176.3	1474.1 ± 113.6	0.41 ± 0.050
1989 Loma Prieta Mw=7	Miller Farm CMF3	Yes	A	18.9 - 24.6	21.7	18.7 ± 3.0	2016.9 ± 142.9	1827.5 ± 154.9	0.46 ± 0.050
1989 Loma Prieta Mw=7	Miller Farm CMF5	Yes	B	18.0 - 27.9	23.0	15.4 ± 1.0	2409.8 ± 201.3	1938.9 ± 120.0	0.41 ± 0.050
1989 Loma Prieta Mw=7	Miller Farm CMF8	Yes	B	16.4 - 26.2	21.3	16.1 ± 1.0	2052.2 ± 177.5	1724.6 ± 108.1	0.46 ± 0.050
1989 Loma Prieta Mw=7	State Beach UC-B1	Yes	A	5.9 - 12.0	9.0	5.9 ± 1.0	865.7 ± 105.1	675.6 ± 73.9	0.29 ± 0.025
1989 Loma Prieta Mw=7	State Beach UC-B2	Yes	A	9.0 - 22.0	15.5	9.0 ± 1.0	1582.5 ± 231.8	1176.9 ± 117.4	0.24 ± 0.025
1989 Loma Prieta Mw=7	POO7-2	Yes	A	18.0 - 22.3	20.2	9.8 ± 2.0	2320.4 ± 99.7	1675.5 ± 142.2	0.22 ± 0.010

Table 3-6 : New Field Case History Data of Classes A, B and C as Developed for These Studies

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Arayamotomachi	490	0.90 ± 0.054	0.09 ± 0.021	7.5	0.15 ± 0.070	5.0± 2.0	0.86	1	1	1.22	1.76	4.8 ± 2.6	Yasuda and Tohno (1988)
Cc17-2	480	0.78 ± 0.081	0.16 ± 0.032	7.5	0.20 ± 0.035	8.0± 2.0	0.93	1	1	1.09	1.50	12.0 ± 2.1	Kishida (1966)
Aomori Station	520	0.80 ± 0.087	0.27 ± 0.054	7.8	0.25 ± 0.020	3.0± 1.0	0.94	1	1	1.22	1.58	16.3 ± 1.6	Yasuda and Tohno (1988)
Luan Nan-L1	640	0.96 ± 0.052	0.22 ± 0.050	8	0.17 ± 0.060	5.0± 3.0	0.87	1	1	1.00	1.58	26.5 ± 3.6	Shengcong et al. (1983)
Luan Nan-L2	640	0.96 ± 0.052	0.24 ± 0.055	8	0.17 ± 0.060	3.0± 2.0	0.87	1	1	1.00	1.72	8.8 ± 0.9	Shengcong et al. (1983)
Arayamotomachi	490	0.84 ± 0.061	0.15 ± 0.036	7.1	0.15 ± 0.070	15.0± 4.0	0.90	1	1	1.22	1.60	8.9 ± 4.9	Yasuda and Tohno (1988)
Arayamotomachi Coarse Sand	550	0.63 ± 0.118	0.13 ± 0.035	7.1	0.42 ± 0.100	0.0± 1.0	1.00	1	1	1.22	1.11	17.7 ± 4.5	Yasuda and Tohno (1988)
Takeda Elementary Sch.	470	0.80 ± 0.064	0.14 ± 0.031	7.1	0.24 ± 0.020	0.0± 1.0	0.90	1	1	1.22	1.70	14.6 ± 1.6	Yasuda and Tohno (1988)
Aomori Station	520	0.80 ± 0.079	0.15 ± 0.030	7.7	0.25 ± 0.020	3.0± 1.0	0.94	1	1	1.22	1.58	16.3 ± 1.6	Yasuda and Tohno (1988)
Arayamotomachi	490	0.85 ± 0.061	0.20 ± 0.048	7.7	0.15 ± 0.070	15.0± 4.0	0.90	1	1	1.22	1.60	8.9 ± 4.9	Yasuda and Tohno (1988)
Gaiko Wharf B-2	550	0.74 ± 0.099	0.25 ± 0.054	7.7	0.25 ± 0.020	1.0± 1.0	0.99	1	1	1.22	1.34	12.3 ± 2.9	Hamada (1992)
Noshiro Section N-7	560	0.93 ± 0.052	0.22 ± 0.054	7.7	0.25 ± 0.020	1.0± 1.0	0.87	1	1	1.22	1.59	16.4 ± 3.6	Hamada (1992)
Takeda Elementary Sch.	470	0.81 ± 0.064	0.32 ± 0.062	7.7	0.24 ± 0.020	0.0± 1.0	0.90	1	1	1.22	1.70	14.6 ± 1.6	Yasuda and Tohno (1988)
Radio Tower B1	*	0.97 ± 0.032	0.09 ± 0.026	6.2	0.05 ± 0.015	75.0± 10.0	0.86	1	1	1.13	1.55	6.8 ± 5.2	Bennett et al. (1984)
Wildlife B	*	0.75 ± 0.035	0.10 ± 0.011	6.2	0.09 ± 0.000	40.0± 3.0	0.88	1	1	0.00	1.64	12.8 ± 5.7	Bennett et al. (1984)
Radio Tower B1	*	0.94 ± 0.032	0.18 ± 0.042	6.6	0.05 ± 0.015	75.0± 10.0	0.86	1	1	1.13	1.55	6.8 ± 5.2	Bennett et al. (1984)
Wildlife B	*	0.84 ± 0.035	0.20 ± 0.021	6.6	0.09 ± 0.005	40.0± 3.0	0.88	1	1	1.13	1.64	12.8 ± 5.7	Bennett et al. (1984)
Heber Road A1	*	0.82 ± 0.022	0.12 ± 0.026	6.7	0.11 ± 0.010	25.0± 4.0	0.82	1	1	1.13	1.48	44.0 ± 3.6	Youd et al. (1983)
Heber Road A2	*	0.78 ± 0.024	0.12 ± 0.034	6.7	0.11 ± 0.010	29.0± 4.5	0.81	1	1	1.13	1.71	3.8 ± 2.4	Youd et al. (1983)
Heber Road A3	*	0.75 ± 0.025	0.11 ± 0.026	6.7	0.10 ± 0.010	37.0± 5.0	0.82	1	1	1.13	1.60	19.5 ± 6.1	Youd et al (1983)
Kornbloom B	*	0.83 ± 0.030	0.13 ± 0.017	6.7	0.05 ± 0.020	92.0± 10.0	0.85	1	1	1.13	1.40	7.2 ± 3.5	Bennett et al. (1984)
McKim Ranch A	*	0.95 ± 0.025	0.14 ± 0.024	6.7	0.11 ± 0.003	31.0± 3.0	0.79	1	1	1.13	1.79	8.5 ± 4.2	Bennett et al. (1984
Radio Tower B2	*	0.99 ± 0.020	0.13 ± 0.021	6.7	0.10 ± 0.020	30.0± 5.0	0.77	1	1	1.13	1.76	17.0 ± 2.8	Bennett et al.(1984)
River Park A	*	0.99 ± 0.010	0.19 ± 0.088	6.7	0.04 ± 0.010	80.0± 10.0	0.66	1	1	1.13	2.00	4.0 ± 3.4	Youd et al. (1983)
River Park C	*	0.97 ± 0.025	0.24 ± 0.031	6.7	0.15 ± 0.008	18.0± 3.0	0.86	1	1	1.13	1.68	20.2 ± 7.7	Youd et al. (1983)
Alameda BF Dike	760	0.95 ± 0.087	0.20 ± 0.034	7	0.28 ± 0.020	7.0± 2.0	0.94	1.3	1	0.92	1.03	42.6 ± 1.8	Mitchell et al. (1994)
Farris Farm	*	0.90 ± 0.020	0.28 ± 0.049	7	0.20 ± 0.020	8.0± 2.0	0.92	1	1	1.13	1.16	10.9 ± 2.5	Holzer et al. (1994)
Hall Avenue	*	0.72 ± 0.013	0.08 ± 0.011	7	0.09 ± 0.010	30.0± 7.0	0.88	1.1	1	0.92	1.30	5.3 ± 3.7	Mitchell et al. (1994)
Marine Laboratory UC-B1	*	0.99 ± 0.011	0.20 ± 0.046	7	0.80 ± 0.050	3.0± 1.0	0.85	1	1	1.00	1.44	12.5 ± 0.9	Boulager et al. (1997)
MBARI NO:3 EB-1	*	0.99 ± 0.007	0.18 ± 0.024	7	0.60 ± 0.100	1.0± 2.0	0.69	1	1	1.00	1.67	23.9 ± 3.5	Boulanger et al (1997)
MBARI NO:3 EB-5	*	0.99 ± 0.007	0.24 ± 0.033	7	0.60 ± 0.100	1.0± 2.0	0.86	1	1	1.00	1.44	18.7 ± 3.5	Boulanger et al. (1997)
Sandholdt UC-B10	*	0.99 ± 0.008	0.23 ± 0.032	7	0.80 ± 0.100	2.0± 2.0	0.79	1	1	1.25	1.73	16.1 ± 1.0	Boulanger et al. (1997)
Miller Farm	*	0.84 ± 0.017	0.32 ± 0.043	7	0.16 ± 0.020	22.0± 3.0	0.92	1	1	1.13	1.20	10.0 ± 4.4	Holzer et al. (1994)
Miller Farm CMF10	*	0.88 ± 0.024	0.37 ± 0.056	7	0.15 ± 0.020	20.0± 3.0	0.99	1	1	1.13	1.16	24.0 ± 3.5	Bennett and Tinsley (1995)
Miller Farm CMF3	*	0.83 ± 0.019	0.26 ± 0.041	7	0.12 ± 0.010	27.0± 5.0	0.94	1	1	1.13	1.05	11.6 ± 4.1	Bennett and Tinsley (1995)
Miller Farm CMF5	*	0.90 ± 0.016	0.29 ± 0.039	7	0.19 ± 0.020	13.0± 2.0	0.95	1	1	1.13	1.02	21.9 ± 3.5	Bennett and Tinsley (1995)
Miller Farm CMF8	*	0.73 ± 0.013	0.25 ± 0.032	7	0.20 ± 0.030	15.0± 2.0	0.94	1	1	1.13	1.08	10.3 ± 1.0	Bennett and Tinsley (1995)
State Beach UC-B1	*	0.95 ± 0.010	0.24 ± 0.032	7	0.26 ± 0.100	2.0± 2.0	0.79	1	1	1.25	1.72	8.5 ± 1.6	Boulanger et al. (1997)
State Beach UC-B2	*	0.99 ± 0.013	0.21 ± 0.028	7	0.40 ± 0.100	1.0± 2.0	0.88	1	1	1.25	1.30	19.0 ± 2.5	Boulanger et al. (1997)
POO7-2	*	0.95 ± 0.018	0.17 ± 0.014	7	0.30 ± 0.030	3.0± 1.0	0.93	1.1	1	0.92	1.09	13.0 ± 3.1	Mitchell et al. (1994)

Table 3-6 : New Field Case History Data of Classes A, B and C as Developed for These Studies

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1989 Loma Prieta Mw=7	POO7-3	Yes	B	19.7 - 23.0	21.3	9.8 ± 1.0	2452.4 ± 87.3	1735.9 ± 91.5	0.22 ± 0.010
1989 Loma Prieta Mw=7	POR-2&3&4	Yes	A	13.1 - 19.0	16.1	11.5 ± 1.0	1388.1 ± 101.2	1102.4 ± 80.4	0.15 ± 0.013
1989 Loma Prieta Mw=7	SFOBB-1&2	Yes	A	18.0 - 23.0	20.5	9.8 ± 1.0	2460.6 ± 118.0	1795.3 ± 101.8	0.27 ± 0.010
1989 Loma Prieta Mw=7	WoodMarine UC-B4	Yes	B	3.3 - 8.2	5.7	3.3 ± 1.0	557.7 ± 83.8	404.2 ± 67.2	0.25 ± 0.025
1989 Loma Prieta Mw=7	Marine Laboratory UC-B2	Yes	A	10.0 - 13.0	11.5	8.2 ± 1.0	1125.5 ± 64.1	919.7 ± 66.7	0.26 ± 0.025
1989 Loma Prieta Mw=7	Treasure Island	Yes	A	4.9 - 29.5	17.2	4.9 ± 2.0	1784.0 ± 434.0	1016.2 ± 215.7	0.18 ± 0.010
1990 Luzon Mw=7.6	Cereenan St. B-12	No	A	7.9 - 24.6	16.2	7.5 ± 1.0	1792.2 ± 324.1	1249.6 ± 162.4	0.25 ± 0.025
1990 Luzon Mw=7.6	Perez Blv. B-11	Yes	A	13.1 - 34.4	23.8	7.5 ± 1.0	2659.9 ± 415.1	1646.6 ± 206.9	0.25 ± 0.025
1993 Kushiro-Oki Mw=8	Kushiro Port Seismo St.	Yes	B	62.3 - 72.2	67.3	5.2 ± 1.0	8018.4 ± 317.5	4149.1 ± 271.4	0.40 ± 0.040
1993 Kushiro-Oki Mw=8	Kushiro Port Site A	Yes	A	13.1 - 21.3	17.2	6.6 ± 1.0	1861.9 ± 158.6	1196.5 ± 100.2	0.40 ± 0.040
1993 Kushiro-Oki Mw=8	Kushiro Port Site D	No	B	24.6 - 45.9	35.3	5.2 ± 1.0	4179.8 ± 443.7	2306.6 ± 244.0	0.40 ± 0.040
1994 Northridge Mw=6.7	Balboa Blv. Unit C	Yes	A	27.1 - 32.0	29.5	23.6 ± 2.0	3336.6 ± 144.6	2968.1 ± 145.3	0.69 ± 0.060
1994 Northridge Mw=6.7	Malden Street Unit D	Yes	A	27.1 - 33.6	30.3	12.8 ± 1.0	3601.5 ± 162.7	2506.3 ± 120.3	0.51 ± 0.060
1994 Northridge Mw=6.7	Potrero Canyon C1	Yes	A	19.7 - 23.0	21.3	10.8 ± 1.0	2503.3 ± 92.4	1848.2 ± 84.0	0.40 ± 0.040
1994 Northridge Mw=6.7	Wynne Ave. Unit C1	Yes	A	18.9 - 22.1	20.5	14.1 ± 1.0	2351.5 ± 93.5	1952.3 ± 85.2	0.54 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Ashiyama A (Marine Sand)	No	A	22.6 - 29.5	26.1	11.5 ± 1.0	2957.7 ± 157.3	2046.7 ± 110.2	0.40 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Ashiyama A (Mountain Sand 1)	No	A	11.5 - 22.6	17.1	11.5 ± 1.0	1847.1 ± 220.0	1499.1 ± 122.1	0.40 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Ashiyama C-D-E (Marine Sand)	Yes	B	24.6 - 32.8	28.7	11.5 ± 1.0	3186.5 ± 178.0	2111.7 ± 121.5	0.40 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Ashiyama C-D-E (Mountain Sand 2)	Yes	C	40.0 - 49.2	44.6	11.5 ± 1.0	5016.4 ± 225.3	2948.7 ± 170.0	0.40 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Port Island Borehole Array Station	Yes	A	7.9 - 43.0	25.4	7.9 ± 1.0	3060.2 ± 735.5	1964.9 ± 377.2	0.34 ± 0.010
1995 Hyogoken-Nambu ML=7.2	Port Island Improved Site (Ikegaya)	No	A	16.4 - 39.4	27.9	16.4 ± 1.0	3239.8 ± 485.3	2523.3 ± 257.1	0.40 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Port Island Improved Site (Tanahashi)	No	B	16.4 - 49.2	32.8	16.4 ± 1.0	3855.0 ± 689.9	2831.4 ± 357.8	0.40 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Port Island Improved Site (Watanabe)	No	A	16.4 - 45.9	31.2	16.4 ± 1.0	3649.9 ± 621.6	2728.7 ± 324.0	0.40 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Port Island Site I	Yes	B	19.7 - 45.9	32.8	9.8 ± 1.0	3838.6 ± 534.5	2405.5 ± 276.1	0.34 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Rokko Island Building D	Yes	A	13.1 - 36.1	24.6	13.1 ± 1.0	2878.9 ± 483.7	2162.4 ± 254.0	0.40 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Rokko Island Site G	Yes	B	13.1 - 62.3	37.7	13.1 ± 1.0	4396.3 ± 990.6	2860.9 ± 488.3	0.34 ± 0.040
1995 Hyogoken-Nambu ML=7.2	Torishima Dike	Yes	A	9.8 - 21.3	15.6	0.0 ± 1.0	1714.2 ± 219.8	741.8 ± 122.2	0.25 ± 0.040

Table 3-6 : New Field Case History Data of Classes A, B and C as Developed for These Studies

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
POO7-3	*	0.83 ± 0.018	0.16 ± 0.011	7	0.32 ± 0.020	5.0± 1.0	0.94	1.1	1	0.92	1.07	13.2 ± 4.1	Mitchell et al. (1994)
POR-2&3&4	*	0.71 ± 0.017	0.09 ± 0.010	7	0.09 ± 0.010	50.0± 5.0	0.89	1.1	1	0.92	1.35	3.8 ± 1.2	Mitchell et al. (1994)
SFOBB-1&2	*	0.77 ± 0.013	0.19 ± 0.010	7	0.28 ± 0.010	8.0± 3.0	0.93	1.2	1	0.92	1.06	8.1 ± 2.2	Mitchell et al. (1994)
WoodMarine UC-B4	*	0.99 ± 0.005	0.20 ± 0.043	7	0.10 ± 0.050	35.0± 5.0	0.72	1	1	1.00	2.00	9.7 ± 0.3	Boulanger et al. (1997)
Marine Laboratory UC-B2	*	0.99 ± 0.008	0.20 ± 0.024	7	0.50 ± 0.050	3.0± 1.0	0.83	1	1	1.00	1.47	15.9 ± 3.5	Boulanger et al. (1997)
Treasure Island	*	0.88 ± 0.012	0.16 ± 0.027	7	0.17 ± 0.030	20.0± 4.0	0.90	1.1	1	1.13	1.40	7.6 ± 4.6	De Alba et al., Youd and Shakal (1994)
Cereenan St. B-12	610	0.91 ± 0.069	0.21 ± 0.032	7.6	0.20 ± 0.020	19.0± 2.0	0.92	1	1	0.65	1.27	26.2 ± 5.3	Wakamatsu (1992)
Perez Blv. B-11	610	0.82 ± 0.096	0.22 ± 0.035	7.6	0.20 ± 0.020	19.0± 2.0	0.98	1	1	0.65	1.10	14.0 ± 2.8	Wakamatsu (1992)
Kushiro Port Seismo St.	670	0.47 ± 0.149	0.23 ± 0.079	8	0.15 ± 0.070	10.0± 3.0	1.00	1	1	1.22	0.69	7.2 ± 1.9	Iai et al. (1994)
Kushiro Port Site A	670	0.94 ± 0.073	0.38 ± 0.053	8	0.34 ± 0.070	2.0± 1.0	0.93	1	1	1.22	1.29	17.1 ± 4.2	Iai et al. (1994)
Kushiro Port Site D	715	0.79 ± 0.134	0.37 ± 0.075	8	0.34 ± 0.070	0.0± 1.0	1.00	1	1	1.22	0.93	30.3 ± 3.6	Iai et al. (1994)
Balboa Blv. Unit C	*	0.71 ± 0.005	0.36 ± 0.035	6.7	0.11 ± 0.020	43.0± 13.0	1.00	1	1	1.13	0.82	18.5 ± 4.0	Bennett et al.(1998)
Malden Street Unit D	*	0.70 ± 0.006	0.34 ± 0.040	6.7	0.25 ± 0.100	25.0± 5.0	1.00	1	1	1.13	0.89	24.4 ± 2.7	Bennett et al. (1998)
Potrero Canyon C1	525	0.72 ± 0.087	0.25 ± 0.041	6.7	0.10 ± 0.020	37.0± 5.0	0.94	1	1	1.13	1.04	10.5 ± 0.7	Bennett et al. (1998)
Wynne Ave. Unit C1	*	0.86 ± 0.040	0.35 ± 0.034	6.7	0.15 ± 0.100	38.0± 23.0	0.93	1	1	1.13	1.01	11.0 ± 1.6	Bennett et al. (1998)
Ashiyama A (Marine Sand)	650	0.82 ± 0.104	0.31 ± 0.056	6.9	0.19 ± 0.025	2.0± 1.0	1.00	1	1	1.22	0.99	31.3 ± 5.9	Shibata et al. (1996)
Ashiyama A (Mountain Sand 1)	610	0.89 ± 0.072	0.29 ± 0.047	6.9	0.13 ± 0.025	18.0± 4.0	0.93	1	1	1.22	1.16	21.6 ± 7.1	Shibata et al. (1996)
Ashiyama C-D-E (Marine Sand)	560	0.64 ± 0.113	0.25 ± 0.055	6.9	0.19 ± 0.025	2.0± 1.0	1.00	1	1	1.22	0.97	12.9 ± 3.1	Shibata et al. (1996)
Ashiyama C-D-E (Mountain Sand 2)	560	0.41 ± 0.149	0.18 ± 0.070	6.9	0.13 ± 0.025	18.0± 4.0	1.00	1	1	1.22	0.82	5.8 ± 2.8	Shibata et al. (1996)
Port Island Borehole Array Station	560	0.71 ± 0.101	0.24 ± 0.039	6.9	0.40 ± 0.200	20.0± 5.0	0.99	1	1	1.22	1.01	6.9 ± 1.7	Shibata et al. (1996)
Port Island Improved Site (Ikegaya)	660	0.80 ± 0.110	0.27 ± 0.048	6.9	0.40 ± 0.200	20.0± 5.0	1.00	1	1	1.22	0.89	21.9 ± 4.1	Yasuda et al. (1996)
Port Island Improved Site (Tanahashi)	660	0.73 ± 0.126	0.26 ± 0.054	6.9	0.40 ± 0.200	20.0± 5.0	1.00	1	1	1.22	0.84	18.6 ± 3.3	Yasuda et al. (1996)
Port Island Improved Site (Watanabe)	730	0.84 ± 0.121	0.29 ± 0.054	6.9	0.40 ± 0.200	20.0± 5.0	1.00	1	1	1.22	0.86	32.2 ± 7.0	Yasuda et al. (1996)
Port Island Site I	620	0.67 ± 0.126	0.24 ± 0.053	6.9	0.40 ± 0.200	20.0± 5.0	1.00	1	1	1.22	0.91	10.8 ± 1.8	Tokimatsu et al. (1996)
Rokko Island Building D	700	0.89 ± 0.099	0.31 ± 0.055	6.9	0.80 ± 0.300	25.0± 5.0	0.99	1	1	1.22	0.96	17.1 ± 6.9	Tokimatsu et al. (1996)
Rokko Island Site G	620	0.59 ± 0.142	0.20 ± 0.055	6.9	0.40 ± 0.200	20.0± 5.0	1.00	1	1	1.22	0.84	12.2 ± 3.5	Tokimatsu et al. (1996)
Torishima Dike	560	0.87 ± 0.067	0.33 ± 0.065	6.9	0.20 ± 0.100	20.0± 7.0	0.91	1	1	1.22	1.64	15.5 ± 3.5	Matsuo (1996)

Table 3-7 : Field Case History Data Deleted form the Data Set of Seed, et al. (1984) as Not Conforming to Class C or Better

Earthquake	Site	Liquefied?	FC (%)	$(N_1)_{60}$	CSRN	Explanation
1933 Long Beach M=6.3	Pier A	No	25	8	0.165	Original boring log is not given in the source document
1933 Long Beach M=6.3	Reservation Point	No	2	8.5	0.125	Source document could not be accessed.
1957 San Francisco M=5.3	Lake Merced	Yes	3	5.5	0.085	Data point is above water table at the time of the earthquake. The side is sloped more than 30 degrees
1967 Venezuela M=6.3	Caraballeda	Yes	?	3.5	0.07	Source document could not be accessed; The critical depth is 3' where SPT values may not be realiable
1891 Mino-Owari M=7.9	Ogaki	Yes	0	25.5	0.375	Not clear if the eruption is due to liquefaction or artesian conditions; artesian conditions complicated the CSR estimations; PGA is estimated from Kawasumi Intensity scale, poor PGA info.
1891 Mino-Owari M=7.9	Ginan	Yes	5	12.5	0.33	" "
1891 Mino-Owari M=7.9	Unuma	Yes	3	25	0.33	" "
1891 Mino-Owari M=7.9	Ogase	Yes	4	17	0.29	" "
1944 Tohnankai M=8.0	Ginan	Yes	5	12.5	0.33	" "
1923 Kanto M=7.9	Arakawa 7	Yes	10	11	0.17	Poor Seismic info. PGA is difficult to estimate. No reliable PGA information.
1923 Kanto M=7.9	Arakawa 12	Yes	22	2.5	0.14	" "
1923 Kanto M=7.9	Arakawa 21	Yes	1	20.5	0.24	" "
1923 Kanto M=7.9	Arakawa 30	Yes	5	16.5	0.23	" "
1923 Kanto M=7.9	Arakawa 49	Yes/No	20	7	0.17	" "
1948 Fukui M=7.3	Takaya 2	No	2	40.5	0.385	Due to the liquefaction of the upper layer, the "nonliquefied" layer might not have been shaken as severely as the method assumes.
1948 Fukui M=7.3	Agricultural Union.	No	0	29	0.45	" "
1964 Niigata M=7.3	General Ohsaki	Yes/No	2	12	0.18	Not a real case history data, adopted from Dr. Koizimu's "critical" N-value plot vs. depth plot after 1964 Niigata Earthquake
1978 Miyagiken-Oki M=6.7	Oiiri 2	No	4	9	0.115	Oiiri 2 Site was not mentioned in the referred document.
1978 Miyagiken-Oki M=7.4	Oiiri 2	Yes	4	9	0.22	Oiiri 2 Site was not mentioned in the referred document.
1979 Miyagiken-Oki M=7.4	Shiomi 2	No	10	12	0.21	Due to the liquefaction of the upper layer, the "nonliquefied" layer might not have been shaken as severely as the method assumes.
1980 Miyagiken-Oki M=7.4	Hiyori 5	No	5	26.5	0.22	" "
1978 Miyagiken-Oki M=7.4	Sendaikou 1	No	11	20	0.22	Data is summarized on chart. Original boring logs are not available.
1978 Miyagiken-Oki M=7.4	Sendaikou 4	No	12	20.5	0.195	" "
1979 Imperial Valley M=6.6	River Park C	Yes	18	16	0.24	Soil layer above "layer C" has also liquefied. Difficult to estimate CSR
1980 Mid-Chiba M=6.1	Owi-1	Yes/No	13	7	0.135	Cyclic TX-Test results on frozen samples were used to estimate the level of shaking that will cause 5 % double amplitude strain level; poor CSR basis.
1980 Mid-Chiba M=6.1	Owi-2	Yes/No	27	4	0.12	" "
1975 Haicheng M=7.3	Shuangtaihe E. B.	No	Fine Sand	11	0.095	Obtained the source reference. However the data is summarized in table; no specific boring log info was available.
1975 Haicheng M=7.3	Shenglitang	No	Sand	11.5	0.09	" "
1975 Haicheng M=7.3	Ligohe Ch. F. P.	Yes	Sand	6.5	0.1	" "
1975 Haicheng M=7.3	Nanheyan Irr. S.	Yes	Sand	6.5	0.095	" "
1975 Haicheng M=7.3	Shuiyuan Comm	Yes	Sand	8	0.195	" "
1975 Haicheng M=7.3	Yingkou Gate	Yes	Sand	8	0.19	" "
1976 Tangshan M=7.6	Weigezhuang	Yes	Fine Sand	13.5	0.17	Obtained the source reference. However the data is summarized in table; no specific boring log info was available.
1976 Tangshan M=7.6	Lujiatuo Mine	Yes	Fine Sand	4.5	0.405	" "
1976 Tangshan M=7.6	Ma Feng	No	1	11.5	0.06	" "
1976 Tangshan M=7.6	Wang Zhuang	Yes	2	12.5	0.21	" "

Table 3-8 : Special “Small Magnitude” Data Base (Youd, 1999)

1957 Daly City, California $M_W = 5.3$

ID #	Site	L	D	D_{GW}	s_0	s'_0	r_d	D_{50}	FC	N	C_n	N_1	SPT	$(N_1)_{60}$	$(N_1)_{60CS}$	A_{max}	CSR
31	Lake Merced	1	3.0	2.4	0.52	0.46	0.981	0.34	3	4	1.47	5.90	0.75	4.42	4.40	0.19	0.137
32	3500 Scott Street	0	3.4	2.6	0.67	0.55	0.978	0.12	2	4	1.35	5.39	1.00	5.39	5.35	0.2	0.155
33	2250 Bay Street	0	3.0	2.3	0.51	0.42	0.981	0.12	1	7	1.54	10.80	1.00	10.80	10.70	0.2	0.155
34	1529 Beach Street	0	4.4	3.2	0.81	0.68	0.972	0.12	4	2	1.21	2.43	1.00	2.43	2.42	0.2	0.151
35	3647 Webster Street	0	4.3	2.7	0.8	0.64	0.973	0.12	3	8	1.25	10.00	1.00	10.00	9.95	0.2	0.158
36	2100 Northpoint B1	0	3.4	2.4	0.6	0.5	0.978	0.12	13	4	1.41	5.66	1.00	5.66	7.75	0.2	0.153
37	2100 Northpoint B2	0	3.7	2.4	0.66	0.54	0.976	0.12	9	1	1.36	1.36	1.00	1.36	1.94	0.2	0.155
38	160 Mallorca	0	3.2	3.0	0.6	0.58	0.979	0.14	10	1	1.31	1.31	1.00	1.31	2.21	0.2	0.132
39	3490 Scott Street	0	3.0	2.4	0.55	0.5	0.981	0.09	28	6	1.41	8.49	1.00	8.49	14.22	0.2	0.140
40	1801 Beach Street	0	3.5	2.3	0.69	0.56	0.978	0.09	14	0.5	1.34	0.67	1.00	0.67	2.90	0.2	0.157
41	1725/33/39 Northpoint	0	4.0	3.0	0.75	0.66	0.975	0.09	29	2	1.23	2.46	1.00	2.46	7.46	0.2	0.144
42	341 Avila Street	0	5.8	2.7	1.08	0.77	0.962	0.12	8	7	1.14	7.98	1.00	7.98	8.38	0.2	0.175
43	22 Cervantes Blvd B1	0	4.4	2.3	0.77	0.55	0.972	0.09	12	5	1.35	6.74	1.00	6.74	8.51	0.2	0.177
44	3675 Fillmore Street	0	3.2	2.1	0.58	0.47	0.979	0.12	9	3	1.46	4.38	1.00	4.38	5.01	0.2	0.157
45	101 Cervantes Blvd B1	0	3.0	2.4	0.55	0.5	0.981	0.09	14	7	1.41	9.90	1.00	9.90	12.52	0.2	0.140
46	101 Cervantes Blvd B2	0	4.7	2.4	0.94	0.71	0.970	0.09	16	3	1.19	3.56	1.00	3.56	6.52	0.2	0.167
47	1600 Beach Street	0	3.0	2.7	0.5	0.48	0.981	0.16	10	6	1.44	8.66	1.00	8.66	9.72	0.2	0.133
48	3820 Scott Street	0	3.0	2.4	0.57	0.51	0.981	0.12	4	3	1.40	4.20	1.00	4.20	4.19	0.2	0.142
49	1529 Beach Street B1	0	4.6	3.7	0.8	0.71	0.971	0.12	4	3	1.19	3.56	1.00	3.56	3.55	0.2	0.142
50	290 Alhambra Street	0	3.0	2.3	0.53	0.43	0.981	0.12	4	6	1.52	9.15	1.00	9.15	9.13	0.2	0.157
51	2 Alhambra Street	0	4.3	2.3	0.79	0.59	0.973	0.09	14	5	1.30	6.51	1.00	6.51	8.99	0.2	0.169
52	400 Avila Street B1	0	3.2	2.4	0.58	0.5	0.979	0.12	13	0.5	1.41	0.71	1.00	0.71	2.62	0.2	0.148
53	400 Avila Street B3	0	8.8	2.4	1.6	0.95	0.928	0.09	25	0.5	1.03	0.51	1.00	0.51	4.86	0.2	0.203
	1987 Whittier Narrows, California $M_W = 5.9$																
305	Bridge 1707	0	9.1	7.9	1.81	1.67	0.923	0.12	5	6	0.77	4.64	1.00	4.64	4.65	0.29	0.189
306	Bridge 1710	0	3.0	3.0	0.6	0.6	0.981	0.09	5	2	1.29	2.58	1.00	2.58	2.59	0.29	0.185
307	Bridge 1711	0	4.3	2.1	0.86	0.64	0.973	0.09	20	8	1.25	10.00	1.00	10.00	14.41	0.29	0.246
308	Bridge 1722	0	7.6	2.4	1.54	1.01	0.945	0.10	15	8	1.00	7.96	1.00	7.96	10.84	0.29	0.272
309	Bridge 1732 B1	0	3.0	2.1	0.61	0.51	0.981	0.09	20	5	1.40	7.00	1.00	7.00	11.17	0.29	0.221
310	Bridge 1733	0	4.6	3.4	0.92	0.8	0.971	0.09	20	5	1.12	5.59	1.00	5.59	9.65	0.29	0.210
311	Bridge 1432	0	3.2	0.6	0.65	0.39	0.979	0.09	20	6	1.60	9.61	1.00	9.61	13.99	0.29	0.308
312	Bridge 1431	0	3.2	0.6	0.65	0.39	0.979	0.09	20	7	1.60	11.21	1.00	11.21	15.71	0.29	0.308
313	Bridge 1706	0	9.1	7.9	1.81	1.69	0.923	0.09	12	14	0.77	10.77	1.00	10.77	12.66	0.29	0.186
314	Bridge 1753	0	9.1	3.0	1.85	1.23	0.923	0.05	32	8	0.90	7.21	1.00	7.21	13.28	0.29	0.262
315	Bridge 832	0	7.6	4.0	1.4	1.03	0.945	0.12	5	11	0.99	10.84	1.00	10.84	10.85	0.46	0.384
316	Bridge 833	0	6.1	3.7	1.11	0.86	0.960	0.05	10	8	1.08	8.63	1.00	8.63	9.68	0.46	0.370
317	Bridge 836	0	5.9	2.1	1.12	0.73	0.962	0.12	5	10	1.17	11.70	1.00	11.70	11.72	0.46	0.441
318	Bridge 837	0	9.1	7.3	1.62	1.43	0.923	0.12	5	41	0.84	34.29	1.00	34.29	34.33	0.46	0.313
319	Bridge 828	0	5.2	4.7	0.9	0.86	0.967	0.12	5	10	1.08	10.78	1.00	10.78	10.80	0.46	0.302
320	Bridge 1742 B2	0	6.7	3.4	1.24	0.89	0.955	0.06	34	6	1.06	6.36	1.00	6.36	12.49	0.29	0.251
321	Bridge 1433 B1	0	3.0	2.0	0.55	0.44	0.981	0.09	20	10	1.51	15.08	1.00	15.08	19.89	0.29	0.231
	1972 Managua $M_W = 6.2$																
171	Teatro N.	0	4.5	3.5	0.85	0.75	0.971		10	12	1.15	13.86	1.00	13.86	15.03	0.45	0.322
	1978 Jun 20 Thessaloniki $M_W = 6.5$																
245	Harbour 6	0	5.8	1.5	1.1	0.67	0.962		35	9	1.22	11.00	1.10	12.09	19.46	0.24	0.246
	1986 Jul Lotung $M_W = 6.2$																
301	Lotung CPT#1	0	5.0	0.5	0.92	0.46	0.968	0.05	35	5	1.47	7.37	1.00	7.37	13.80	0.18	0.227
302	Lotung CPT#2	0	3.0	0.5	0.55	0.29	0.981	0.05	35	3	1.86	5.57	1.00	5.57	11.65	0.18	0.218

Table 3-9 : Field Case History Data from Proprietary Alluvial Sites Near Kobe, Japan

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 1	No	B	16.4 - 23.0	19.7	7.7 ± 1.0	2186.7 ± 138.4	1439.4 ± 96.4	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 2	No	B	16.4 - 39.4	27.9	9.5 ± 1.0	3112.2 ± 448.0	1963.7 ± 223.9	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 3	No	B	11.5 - 24.6	18.0	8.2 ± 1.0	1993.1 ± 256.9	1378.9 ± 136.4	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 4	No	B	9.8 - 21.3	15.6	6.7 ± 1.0	1602.7 ± 205.9	1049.9 ± 109.2	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 5	Yes	B	21.3 - 36.1	28.7	9.9 ± 1.0	3251.8 ± 295.5	2078.7 ± 165.1	0.35 ± 0.045
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 6	Yes	A	14.1 - 24.0	19.0	7.5 ± 1.0	2150.6 ± 196.6	1434.1 ± 117.3	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 7	Yes	A	14.1 - 27.2	20.7	10.4 ± 1.0	2325.1 ± 258.3	1682.3 ± 141.2	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 8	Yes	A	13.1 - 19.7	16.4	9.7 ± 1.0	1674.0 ± 124.2	1254.4 ± 87.7	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 9	Yes	A	10.8 - 17.4	14.1	9.1 ± 1.0	1531.5 ± 132.8	1218.3 ± 88.2	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 10	No	B	19.7 - 29.5	24.6	14.6 ± 1.0	2633.5 ± 193.9	2011.2 ± 120.0	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 11	Yes	B	12.3 - 32.0	22.1	4.8 ± 1.0	2301.5 ± 352.0	1216.5 ± 167.4	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 12	No	A	14.1 - 20.7	17.4	10.5 ± 1.0	1773.3 ± 125.4	1343.4 ± 89.4	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 13	Yes	A	16.4 - 26.2	21.3	7.5 ± 1.0	2201.4 ± 183.4	1341.6 ± 110.1	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 14	No	A	14.1 - 17.4	15.7	10.2 ± 1.0	1602.7 ± 74.0	1254.7 ± 77.4	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 15	Yes	A	15.3 - 22.6	18.9	12.0 ± 1.0	1929.5 ± 140.7	1494.5 ± 95.5	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 16	No/Yes	A	13.1 - 16.4	14.8	8.0 ± 1.0	1510.0 ± 71.3	1090.3 ± 74.8	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 17	Yes	A	9.8 - 19.7	14.8	2.5 ± 1.0	1537.9 ± 179.5	770.2 ± 103.4	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 18	No	B	29.5 - 39.4	34.4	25.1 ± 1.0	3836.1 ± 217.0	3252.7 ± 149.1	0.70 ± 0.105
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 19	No	B	23.0 - 26.2	24.6	20.0 ± 1.0	2629.6 ± 103.9	2343.0 ± 101.6	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 20	No	B	13.1 - 26.2	19.7	6.6 ± 1.0	2198.2 ± 258.5	1379.3 ± 139.4	0.55 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 21	No	B	9.8 - 13.1	11.5	5.4 ± 1.0	1266.4 ± 71.5	887.7 ± 68.1	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 22	No	B	13.1 - 26.2	19.7	7.9 ± 1.0	2185.0 ± 258.1	1448.0 ± 138.6	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 23	No	A	13.1 - 19.7	16.4	9.8 ± 1.0	1788.1 ± 134.7	1378.6 ± 91.1	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 24	Yes	B	9.8 - 13.1	11.5	7.7 ± 1.0	1243.4 ± 72.3	1008.0 ± 68.9	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 25	No	B	9.8 - 13.1	11.5	7.1 ± 1.0	1250.0 ± 71.9	973.6 ± 68.4	0.70 ± 0.105
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 26	No	B	9.8 - 13.1	11.5	3.0 ± 1.0	1248.4 ± 70.3	716.1 ± 72.6	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 27	No	B	6.6 - 9.8	8.2	3.4 ± 1.0	844.0 ± 62.2	547.1 ± 66.3	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 28	Yes	B	13.1 - 16.4	14.8	5.7 ± 1.0	1521.5 ± 71.8	958.5 ± 75.3	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 29	Yes	A	9.8 - 14.8	12.3	6.6 ± 1.0	1287.7 ± 97.2	929.5 ± 74.1	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 30	No	B	23.0 - 32.8	27.9	4.9 ± 1.0	2903.5 ± 196.3	1470.5 ± 130.4	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 31	No	A	9.8 - 16.4	13.1	3.9 ± 1.0	1404.2 ± 127.2	831.0 ± 84.0	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 32	No	B	6.6 - 16.4	11.5	4.6 ± 1.0	1125.3 ± 167.4	695.4 ± 90.5	0.50 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 33	No	B	23.0 - 29.5	26.2	6.6 ± 1.0	2723.1 ± 141.8	1494.8 ± 111.1	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 34	Yes	B	13.1 - 32.8	23.0	5.9 ± 1.0	2381.9 ± 352.0	1317.3 ± 167.5	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 35	Yes	A	9.8 - 19.7	14.8	6.7 ± 1.0	1516.6 ± 177.3	1015.0 ± 99.7	0.50 ± 0.075
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 36	No	B	9.8 - 13.1	11.5	3.1 ± 1.0	1190.3 ± 67.8	666.2 ± 71.5	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 37	Yes	A	6.6 - 19.7	13.1	13.1 ± 1.0	1312.3 ± 235.6	1312.3 ± 121.4	0.35 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 38	Yes	B	19.7 - 32.8	26.2	9.8 ± 1.0	2706.7 ± 242.1	1683.1 ± 133.5	0.50 ± 0.075

Table 3-9 : Field Case History Data from Proprietary Alluvial Sites Near Kobe, Japan

Site	$V^*_{s,40'}$ (fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Kobe Alluvial Site No 1	700	0.93 ± 0.082	0.37 ± 0.066	6.9	NA	4.0± 1.5	0.95	1	1	1.22	1.18	57.7 ± 3.2	Note 1
Kobe Alluvial Site No 2	680	0.83 ± 0.110	0.34 ± 0.071	6.9	NA	15.0± 5.0	1.00	1	1	1.22	1.01	42.7 ± 9.6	Note 1
Kobe Alluvial Site No 3	650	0.91 ± 0.076	0.34 ± 0.063	6.9	NA	4.0± 1.0	0.94	1	1	1.22	1.20	54.2 ± 7.2	Note 1
Kobe Alluvial Site No 4	600	0.90 ± 0.067	0.36 ± 0.066	6.9	NA	4.0± 1.0	0.91	1	1	1.22	1.38	43.5 ± 5.3	Note 1
Kobe Alluvial Site No 5	600	0.71 ± 0.113	0.25 ± 0.053	6.9	NA	2.0± 1.0	1.00	1	1	1.22	0.98	6.9 ± 1.6	Note 1
Kobe Alluvial Site No 6	580	0.84 ± 0.079	0.33 ± 0.061	6.9	NA	25.0± 3.0	0.95	1	1	1.22	1.18	22.7 ± 3.9	Note 1
Kobe Alluvial Site No 7	580	0.81 ± 0.085	0.29 ± 0.056	6.9	NA	0.0± 0.0	0.96	1	1	1.22	1.09	27.3 ± 1.7	Note 1
Kobe Alluvial Site No 8	600	0.89 ± 0.070	0.39 ± 0.069	6.9	NA	0.0± 0.0	0.92	1	1	1.22	1.26	24.5 ± 2.9	Note 1
Kobe Alluvial Site No 9	570	0.89 ± 0.061	0.37 ± 0.064	6.9	NA	3.0± 1.0	0.90	1	1	1.22	1.28	12.1 ± 5.3	Note 1
Kobe Alluvial Site No 10	590	0.75 ± 0.099	0.38 ± 0.078	6.9	NA	9.0± 1.0	0.99	1	1	1.22	1.00	27.7 ± 4.2	Note 1
Kobe Alluvial Site No 11	520	0.70 ± 0.090	0.43 ± 0.090	6.9	NA	5.0± 1.0	0.97	1	1	1.22	1.28	8.3 ± 2.3	Note 1
Kobe Alluvial Site No 12	550	0.83 ± 0.073	0.36 ± 0.065	6.9	NA	13.0± 3.0	0.92	1	1	1.22	1.22	26.7 ± 1.3	Note 1
Kobe Alluvial Site No 13	590	0.81 ± 0.087	0.43 ± 0.083	6.9	NA	18.0± 3.0	0.96	1	1	1.22	1.22	13.3 ± 1.5	Note 1
Kobe Alluvial Site No 14	540	0.84 ± 0.068	0.35 ± 0.062	6.9	NA	18.0± 3.0	0.91	1	1	1.22	1.26	22.5 ± 2.3	Note 1
Kobe Alluvial Site No 15	520	0.76 ± 0.079	0.32 ± 0.061	6.9	NA	5.0± 2.0	0.94	1	1	1.22	1.16	19.9 ± 4.4	Note 1
Kobe Alluvial Site No 16	630	0.93 ± 0.064	0.50 ± 0.088	6.9	NA	5.0± 1.0	0.90	1	1	1.22	1.35	26.1 ± 1.5	Note 1
Kobe Alluvial Site No 17	630	0.93 ± 0.064	0.60 ± 0.112	6.9	NA	5.0± 1.0	0.90	1	1	1.22	1.61	23.2 ± 7.9	Note 1
Kobe Alluvial Site No 18	630	0.62 ± 0.131	0.33 ± 0.087	6.9	NA	0.0± 0.0	1.00	1	1	1.22	0.78	38.6 ± 4.1	Note 1
Kobe Alluvial Site No 19	680	0.86 ± 0.099	0.38 ± 0.072	6.9	NA	10.0± 1.0	0.99	1	1	1.22	0.92	21.7 ± 1.0	Note 1
Kobe Alluvial Site No 20	700	0.93 ± 0.082	0.53 ± 0.102	6.9	NA	0.0± 0.0	0.95	1	1	1.22	1.20	64.3 ± 2.0	Note 1
Kobe Alluvial Site No 21	650	0.96 ± 0.052	0.53 ± 0.093	6.9	NA	0.0± 0.0	0.87	1	1	1.22	1.50	36.4 ± 3.2	Note 1
Kobe Alluvial Site No 22	620	0.86 ± 0.082	0.51 ± 0.095	6.9	NA	6.0± 2.0	0.88	1	1	1.22	1.18	40.8 ± 12.2	Note 1
Kobe Alluvial Site No 23	600	0.89 ± 0.070	0.45 ± 0.080	6.9	NA	8.0± 2.0	0.92	1	1	1.22	1.20	24.3 ± 1.0	Note 1
Kobe Alluvial Site No 24	640	0.96 ± 0.052	0.38 ± 0.066	6.9	NA	0.0± 0.0	0.87	1	1	1.22	1.41	25.3 ± 1.4	Note 1
Kobe Alluvial Site No 25	660	0.96 ± 0.052	0.56 ± 0.097	6.9	NA	4.0± 1.0	0.76	1	1	1.22	1.43	39.4 ± 1.2	Note 1
Kobe Alluvial Site No 26	690	0.97 ± 0.052	0.66 ± 0.120	6.9	NA	0.0± 0.0	0.87	1	1	1.22	1.67	43.1 ± 6.8	Note 1
Kobe Alluvial Site No 27	690	0.98 ± 0.039	0.59 ± 0.114	6.9	NA	10.0± 2.0	0.82	1	1	1.22	1.91	52.2 ± 5.7	Note 1
Kobe Alluvial Site No 28	630	0.93 ± 0.064	0.38 ± 0.068	6.9	NA	10.0± 2.0	0.90	1	1	1.22	1.44	26.3 ± 4.0	Note 1
Kobe Alluvial Site No 29	610	0.94 ± 0.055	0.34 ± 0.059	6.9	NA	0.0± 0.0	0.88	1	1	1.22	1.47	18.8 ± 3.4	Note 1
Kobe Alluvial Site No 30	620	0.73 ± 0.110	0.57 ± 0.123	6.9	NA	10.0± 1.0	1.00	1	1	1.22	1.17	43.4 ± 6.6	Note 1
Kobe Alluvial Site No 31	640	0.94 ± 0.058	0.62 ± 0.111	6.9	NA	0.0± 0.0	0.89	1	1	1.22	1.55	59.8 ± 6.3	Note 1
Kobe Alluvial Site No 32	600	0.94 ± 0.052	0.49 ± 0.107	6.9	NA	6.0± 2.0	0.87	1	1	1.22	1.70	32.2 ± 3.5	Note 1
Kobe Alluvial Site No 33	600	0.74 ± 0.104	0.44 ± 0.093	6.9	NA	50.0± 5.0	1.00	1	1	1.22	1.16	30.3 ± 2.1	Note 1
Kobe Alluvial Site No 34	550	0.73 ± 0.093	0.35 ± 0.071	6.9	NA	9.0± 1.0	0.98	1	1	1.22	1.23	25.8 ± 3.7	Note 1
Kobe Alluvial Site No 35	540	0.86 ± 0.064	0.42 ± 0.077	6.9	NA	8.0± 2.0	0.90	1	1	1.22	1.40	19.0 ± 2.6	Note 1
Kobe Alluvial Site No 36	580	0.93 ± 0.052	0.65 ± 0.120	6.9	NA	3.0± 1.0	0.87	1	1	1.22	1.73	36.6 ± 1.5	Note 1
Kobe Alluvial Site No 37	580	0.92 ± 0.058	0.21 ± 0.040	6.9	NA	0.0± 0.0	0.89	1	1	1.22	1.23	22.3 ± 3.1	Note 1
Kobe Alluvial Site No 38	590	0.73 ± 0.104	0.38 ± 0.081	6.9	NA	5.0± 1.0	1.00	1	1	1.22	1.09	20.1 ± 2.8	Note 1

Note 1: Proprietary data set; see Cetin et al., 2000

Table 3-9 : Field Case History Data from Proprietary Alluvial Sites Near Kobe, Japan

Earthquake	Site	Liquefied?	Data Class	Crit.Depth Range (ft)	Critical Depth (ft)	Depth to GWT (ft)	σ_o (psf)	σ'_o (psf)	a_{max} (g)
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 39	No	B	13.1 - 16.4	14.8	8.5 ± 1.0	1612.5 ± 76.4	1223.6 ± 73.2	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 40	No	B	9.8 - 13.1	11.5	9.2 ± 1.0	1274.6 ± 73.6	1131.3 ± 74.5	0.60 ± 0.090
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 41	Yes	A	7.4 - 19.7	13.5	6.6 ± 1.0	1455.9 ± 228.8	1020.8 ± 119.5	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 42	Yes	A	13.1 - 19.7	16.4	3.8 ± 1.0	1621.6 ± 121.5	833.4 ± 88.1	0.40 ± 0.060
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 43	Yes	B	13.6 - 16.9	15.3	7.1 ± 1.0	1566.6 ± 72.1	1054.8 ± 75.6	0.35 ± 0.050
1995 Hyogoken-Nambu ML=7.2	Kobe Alluvial Site No 44	Yes	B	9.8 - 16.4	13.1	5.1 ± 1.0	1286.9 ± 115.9	785.3 ± 80.2	0.40 ± 0.060

Table 3-9 : Field Case History Data from Proprietary Alluvial Sites Near Kobe, Japan

Site	$V^*_{s,40'}$(fps)	r_d	CSR	Equivalent Mag. (Mw)	D_{50}	% Fines	C_R	C_S	C_B	C_E	C_N	$(N_1)_{60}$	References
Kobe Alluvial Site No 39	700	0.96 ± 0.064	0.49 ± 0.085	6.9	NA	0.0± 0.0	0.90	1	1	1.22	1.28	66.1 ± 4.4	Note 1
Kobe Alluvial Site No 40	680	0.97 ± 0.052	0.43 ± 0.072	6.9	NA	0.0± 0.0	0.87	1	1	1.22	1.33	43.6 ± 10.8	Note 1
Kobe Alluvial Site No 41	620	0.93 ± 0.059	0.35 ± 0.064	6.9	NA	0.0± 0.0	0.89	1	1	1.22	1.40	14.7 ± 2.9	Note 1
Kobe Alluvial Site No 42	520	0.81 ± 0.070	0.41 ± 0.078	6.9	NA	10.0± 1.0	0.92	1	1	1.22	1.55	12.2 ± 0.5	Note 1
Kobe Alluvial Site No 43	600	0.91 ± 0.066	0.31 ± 0.053	6.9	NA	20.0± 2.0	0.91	1	1	1.22	1.38	15.2 ± 0.3	Note 1
Kobe Alluvial Site No 44	520	0.87 ± 0.058	0.37 ± 0.068	6.9	NA	5.0± 1.0	0.89	1	1	1.22	1.60	8.0 ± 2.0	Note 1

Note 1: Proprietary data set; see Cetin et al., 2000

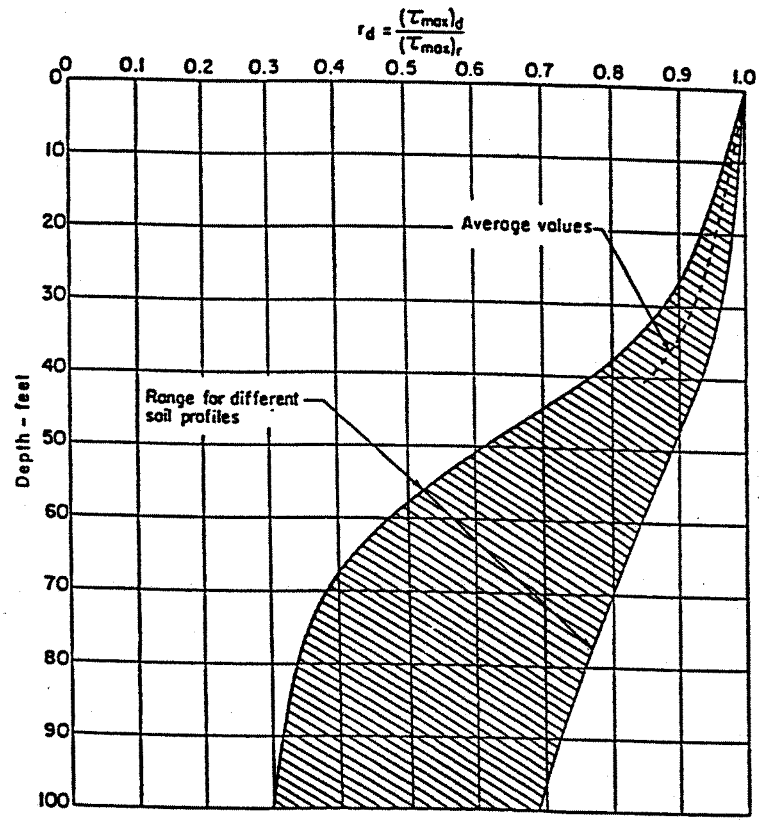
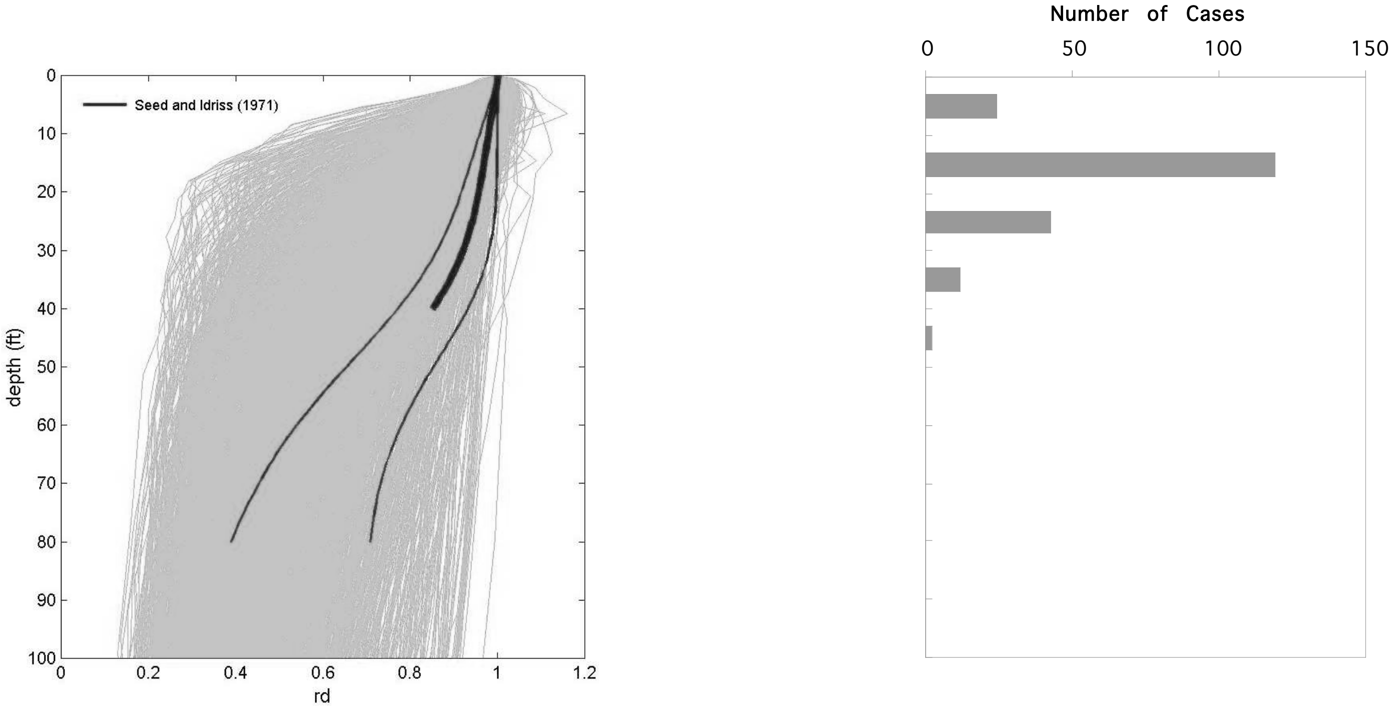


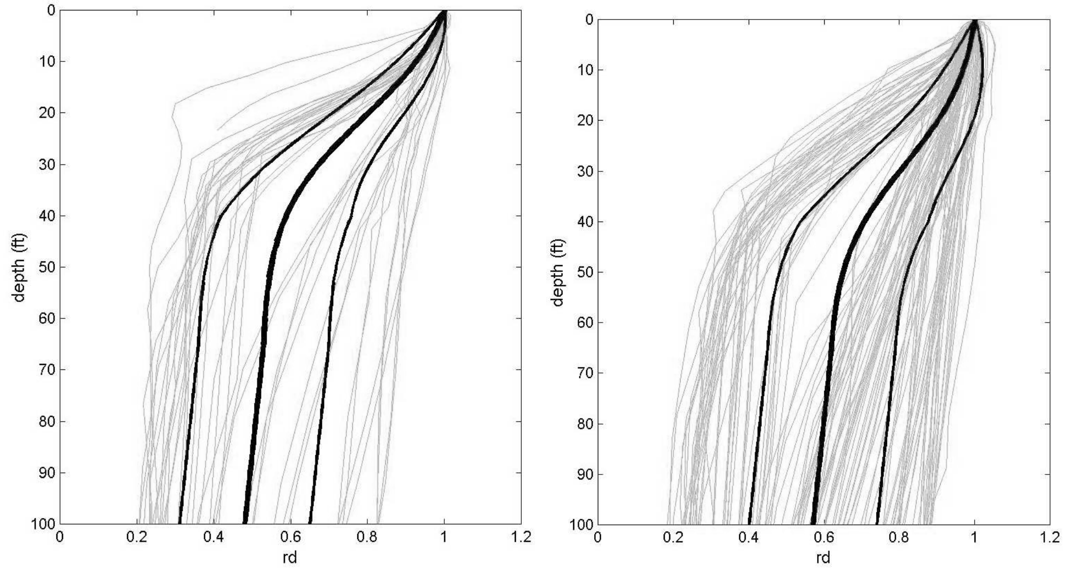
Figure 3-1 : Early Recommendations for the Nonlinear Shear Mass Participation Factor (r_d) of Seed and Idriss (1971)



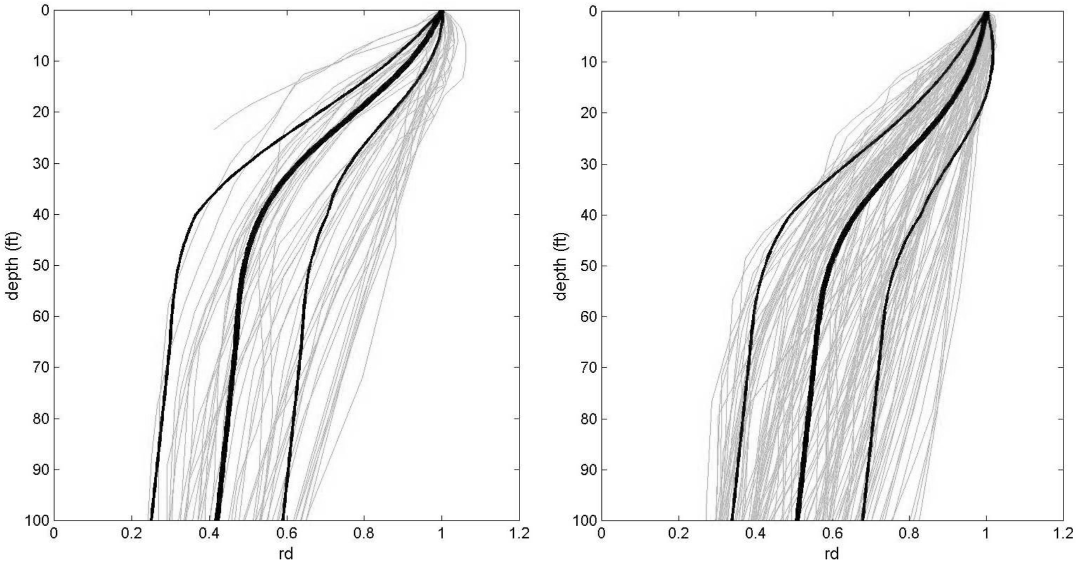
(a) Results of Analyses

(b) Depths of Critical Strata in Field Case Histories

Figure 3-2 : Results of 2,153 Site Response Analyses for Evaluation of the Nonlinear Shear Mass Participation Factor (r_d)

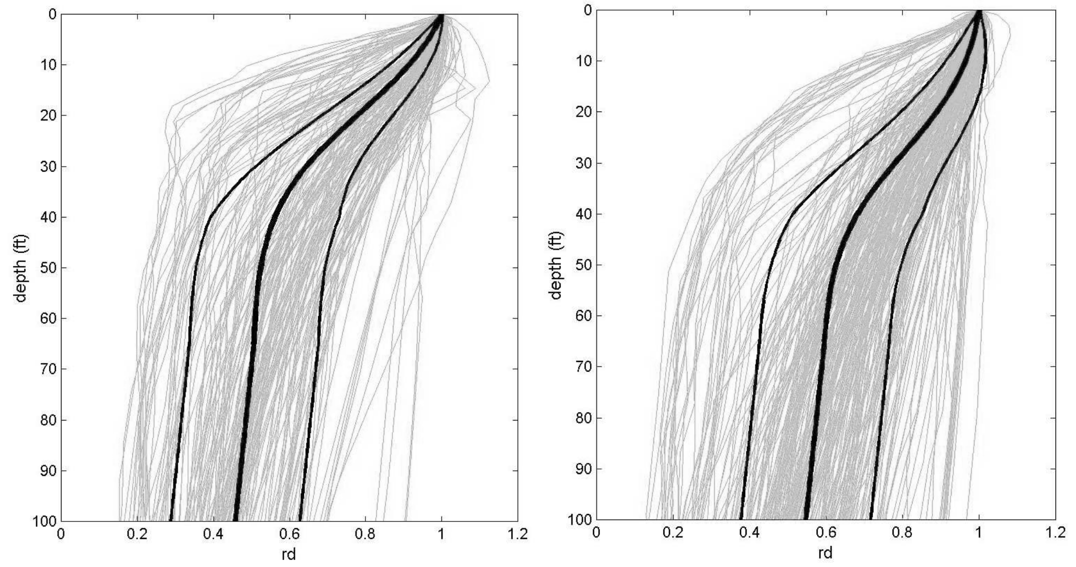


(a) $M_w \geq 6.8$, $a_{max} \leq 0.12g$, $V_{s,40\text{ ft.}} \leq 525$ fps (b) $M_w \geq 6.8$, $a_{max} \leq 0.12g$, $V_{s,40\text{ ft.}} > 525$ fps

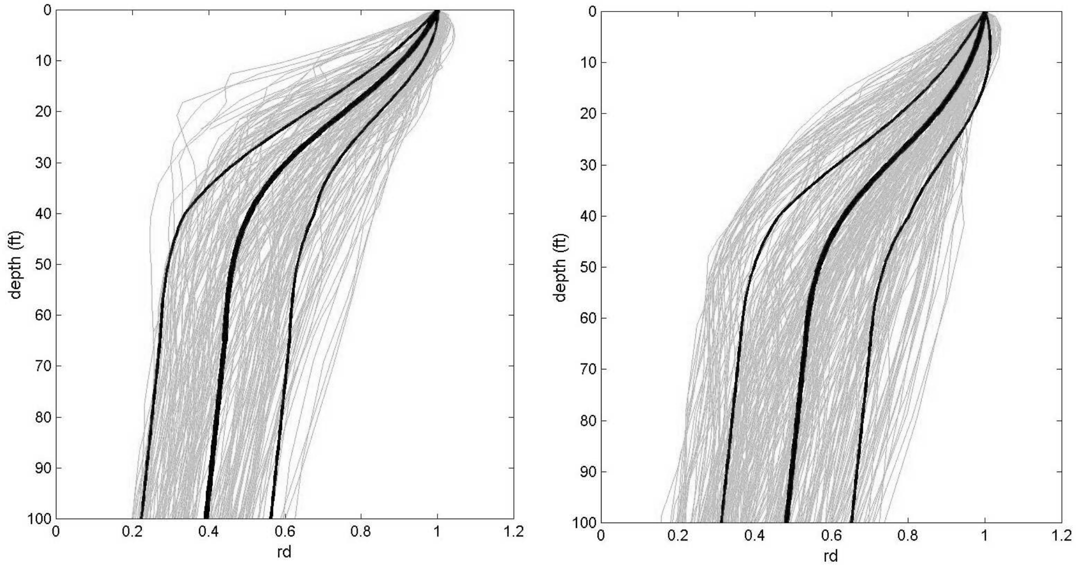


(c) $M_w < 6.8$, $a_{max} \leq 0.12g$, $V_{s,40\text{ ft.}} \leq 525$ fps (d) $M_w < 6.8$, $a_{max} \leq 0.12g$, $V_{s,40\text{ ft.}} > 525$ fps

Figure 3-3: R_d results for various bins superimposed with the predictions based on bin mean values of V_s, M_w, and a_{max} .

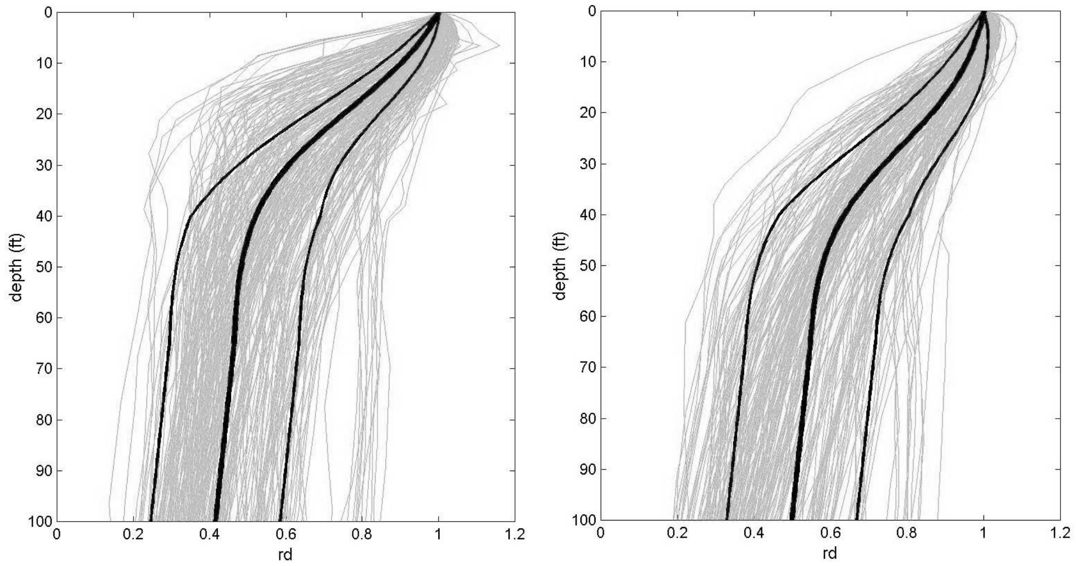


(e) $M_w \geq 6.8$, $0.12 < a_{max} \leq 0.23g$, $V_{s,40\ ft.} \leq 525$ fps (f) $M_w \geq 6.8$, $0.12 < a_{max} \leq 0.23g$, $V_{s,40\ ft.} > 525$ fps



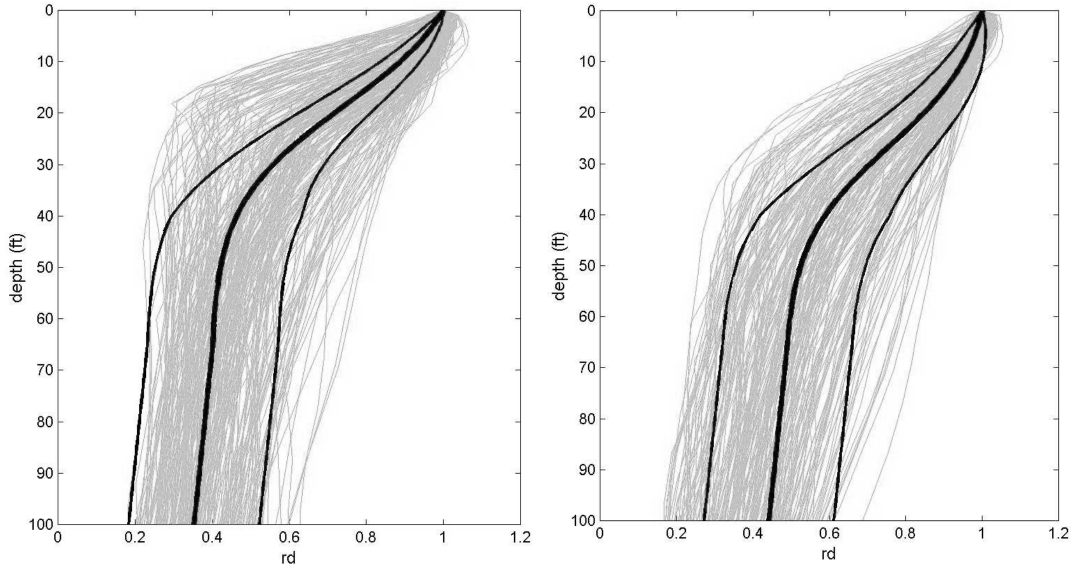
(g) $M_w < 6.8$, $0.12 < a_{max} \leq 0.23g$, $V_{s,40\ ft.} \leq 525$ fps (h) $M_w < 6.8$, $0.12 < a_{max} \leq 0.23g$, $V_{.s,40\ ft.} > 525$ fps

Figure 3-3: R_d results for various bins superimposed with the predictions based on bin mean values of V_s, M_w, and a_{max}



(i) $M_w \geq 6.8$, $0.23 < a_{max}$, $V_{s,40\,ft.} \leq 525$ fps

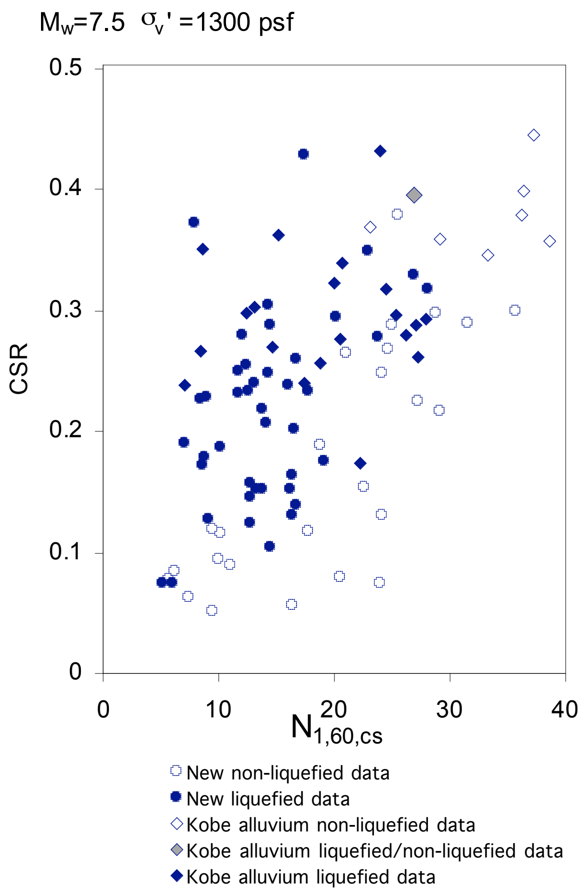
(j) $M_w \geq 6.8$, $0.23 < a_{max}$, $V_{s,40\,ft.} > 525$ fps



(k) $M_w < 6.8$, $0.23 < a_{max}$, $V_{s,40\,ft.} \leq 525$ fps

(l) $M_w < 6.8$, $0.23 < a_{max}$, $V_{s,40\,ft.} > 525$ fps

Figure 3-3: R_d results for various bins superimposed with the predictions based on bin mean values of V_s, M_w, and a_{max}



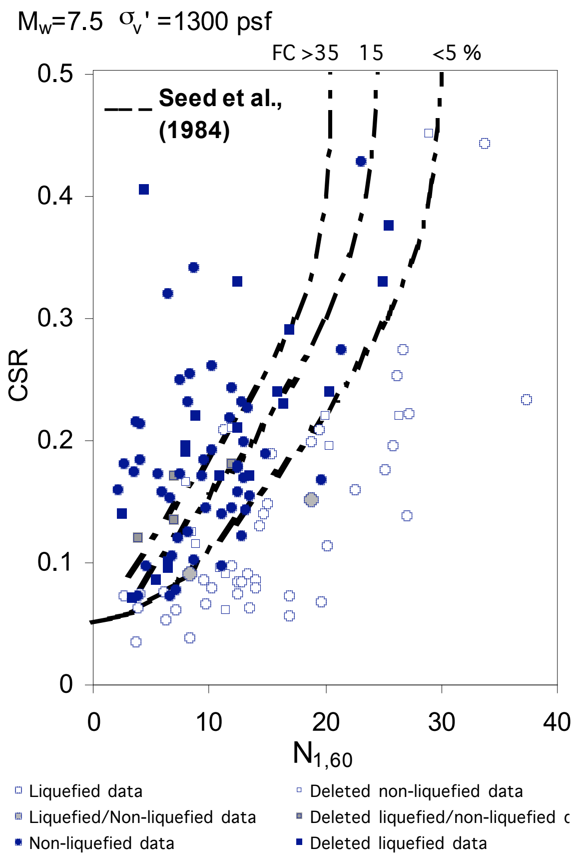


Figure 3-4: New Case History Data Used in These Studies

Figure 3-5: Data Base of Seed, et al. (1984) Showing Data Points Deleted

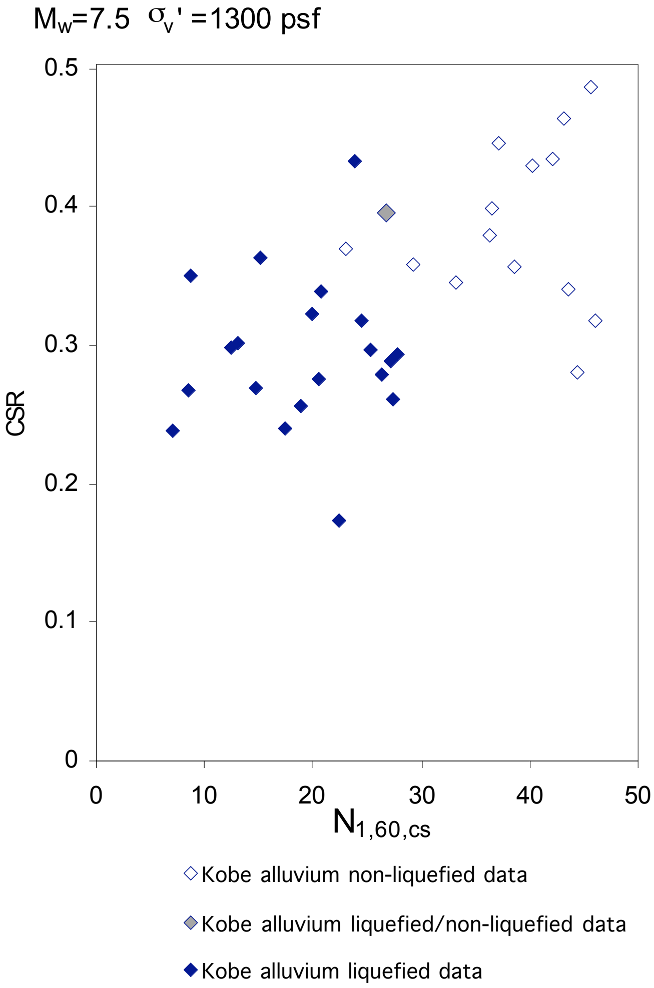


Figure 3-6 : Proprietary Field Case History Data from the 1995 Hyogoken-Nambu ("Kobe") Earthquake

4. DEVELOPMENT OF CORRELATIONS

4.1. General :

Using the data as assessed and presented in Chapter 3, correlations were developed to assess the likelihood of initiation (or "triggering") of liquefaction. The methodology employed was the Bayesian updating method, and the specific formulations and approaches employed are described in detail by Cetin (2000), and Cetin et al., (2000).

Within the Bayesian updating analyses, which were performed using a modified version of the program BUMP (Geyskins et al., 1993), all data were modeled not as "points", but rather as distributions, with variances in both CSR and $N_{1,60}$. The Bayesian updating method serves much the same purpose as a "regression" analysis, but is better able to facilitate separate accounting for different contributing sources of variance or uncertainty. These regression-type analyses were simultaneously applied to a number of contributing variables, and the results are illustrated in Figures 4-1 through 4-9, and are expressed in Equations 4.1 through 4.6.

Figure 4-1 shows the proposed probabilistic relationship between duration-corrected equivalent uniform cyclic stress ratio (CSR_{EQ}), and fines-corrected penetration resistances ($N_{1,60,cs}$), for an effective overburden stress of $\sigma'_v = 0.65\,\text{atm.}$ (1,300 lb/ft^2). The contours shown (solid lines) are for probabilities of liquefaction of P_L=5%, 20%, 50%, 80%, and 95%. All "data points" shown represent median values, also corrected for duration and fines. These are superposed (dashed lines) with the relationship proposed by Seed et al.(1984) for reference.

As shown in this figure, the "clean sand" (Fines Content $\leq$ 5%) line of Seed et al. (1984) corresponds roughly to P_L=50%. It was Seed's intent that this boundary should represent approximately a 10 to 15% probability of liquefaction, and these earlier efforts did not fully achieve this at shallow depths ($\sigma'_v = 1{,}300\,\mathrm{lb/ft^2}$), based on the data available at that time. It is proposed that the new boundary curve for P_L=20% represents a suitable new (updated) basis for "deterministic" analyses, much as the prior relationship of Seed et al. (1984) had done. This proposed new "deterministic" correlation is presented in Figure 4-2, again for $\sigma'_v = 1{,}300\,\mathrm{lb/ft^2}$, but this time with the N-value axis <u>not</u> corrected for fines content effects, so that the (P_L=20%) boundary curves are, instead, offset to account for varying fines content. In this figure, the earlier correlation proposed by Seed et al. (1984) is also shown, with dashed lines, for comparison. The principal differences between these two "deterministic" relationships are (1) a slight improvement in the "belly" region (at $N_{1,60,CS}$ = 8 to 20), (2) improvement at high CSR (CSR>0.3), a region within which data were previously scarce, and (3) updating of the correction for "fines".

Also shown in Figure 4-2(a) is the boundary curve proposed by Yoshimi et al. (1994), based on high quality cyclic simple shear testing of frozen samples of alluvial sandy soils. The line of Yoshimi et al. is arguably unconservatively biased at very low densities (low N-values) as these loose samples densified during laboratory thawing and reconsolidation. Their testing provides potentially valuable insight, however, at high N-values where reconsolidation densification was not significant. In this range, the new proposed correlation provides better agreement with the test data than does the earlier relationship proposed by Seed et al. (1984).

Both the probabilistic and recommended deterministic (based on P_L=20%) relationships of Figures 4-2 and 4-3 are based on correction of "equivalent uniform cyclic stress ratio" (CSR_{EQ}) for duration (or number of equivalent cycles) to CSRN, 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

$$CSRN = CSR_{EQ} / DWF_M \qquad \text{(Eq. 4-1)}$$

This duration weighting factor has been somewhat controversial, and has been developed by a variety of different approaches (using cyclic laboratory testing and/or field case history data) by a number of investigators. Figure 4-3 summarizes a number of recommendations, and shows (shaded zone) the recommendations of the NCEER Working Group (NCEER, 1997). In these current studies, this important and controversial factor could be derived as a part of the Bayesian Updating analyses. Moreover, the factor (DWF_M) could also be investigated for possible dependence on density (correlation with $N_{1,60}$). Figures 4-3 and 4-4 show the resulting values of DWF_M, as a function of varying corrected $N_{1,60}$-values. As shown in this figure, the dependence on density, or $N_{1,60}$-values, was found to be relatively minor.

The duration weighting factors shown in Figures 4-3 and 4-4 fall slightly below those recommended by the NCEER Working group, and slightly below (but close to) recent recommendations of Idriss (2000). Idriss' recommendations are based on a judgmental combination of interpretation of high-quality cyclic laboratory test data and empirical assessment of "equivalent" numbers of cycles from strong motion time histories. The close agreement of this very different (and principally laboratory data based) approach, and the careful probabilistic assessments of these current studies, are strongly mutually supportive. In any case, the current results are very strongly based.

In these current studies, the energy- and procedure- and overburden-corrected N-values ($N_{1,60}$) are further corrected for fines content as

$$N_{1,60,CS} = N_{1,60} \cdot C_{FINES} \qquad \text{(Eq. 4-2)}$$

where the fines correction was "regressed" as a part of the Bayesian updating analyses. The fines correction was equal to zero for fines contents of $FC \leq 5\%$, and reached a maximum (limiting) value for $FC \geq 35\%$. As illustrated in Figure 4-2, the maximum fines correction resulted in an increase of N-values of about +6.5 blows/ft., at high N (and high CSR). As illustrated in this figure, this maximum fines correction is somewhat smaller than the earlier maximum correction of +10 blows/ft. proposed by Seed et al. (1984).

The relationship for C_{FINES} is

$$C_{FINES} = (1 + 0.004 \cdot FC) + 0.05 \cdot \left(\frac{FC}{N_{1,60}} \right), \quad \text{lim: FC} \leq 35 \text{ and FC} \geq 5 \qquad \text{(Eq. 4-3)}$$

where FC = percent fines content (by dry weight). The relationship of Figure 4-1 shows all data plotted as corrected to the "equivalent clean sand" basis ($N_{1,60,CS}$).

An additional factor not directly resolved in prior studies based on field case histories is the increased susceptibility of soils to cyclic liquefaction, at the same CSR, with increases in effective overburden stress. This is in addition to the normalization of N-values for overburden effects as per Equations 3-5 and 3-6.

The additional effect of reduction of normalized liquefaction resistance with increased effective initial effective overburden stress (σ'_v) has been demonstrated by means of laboratory testing, but remains poorly understood and poorly-defined. Figure 4-5(a) shows a collection of laboratory data, and the recommendations of Seed and Harder

(1990) for the additional correction factor K_σ. Figure 4-5(b) presents the similarly-based recommendations of the NCEER Working Group (NCEER, 1997). Both of these use a factor to correct the normalized resistance to liquefaction at an initial effective overburden stress of 1 atmosphere ($CSR_{liq,1atm.}$) as

$$CSR_{liq} = CSR_{liq,1atm} \cdot K_\sigma \qquad \text{(Eq. 4-4)}$$

These current studies were not very sensitive to K_σ, as the range of σ'_v in the case history data base was largely between $\sigma'_v = 600$ to 2,600 lb./ft^2., but it was possible to "regress" K_σ as part of the Bayesian updating. The results are shown in Figure 4-6, over the range of $\sigma'_v \approx 600$ to 3,500 lb/ft^2 for which they are considered valid. These are in good agreement with the earlier recommendations of Figure 4-5. The field case history data of these current studies are <u>not</u> a sufficient basis for extrapolation of K_σ to much higher values of σ'_v.

The earlier relationships proposed by Seed et al. (1984), Liao et al. (1988, 1998), Youd and Noble (1997), and Toprak (1999) were all stated to be normalized to an effective overburden stress of approximately $\sigma'_v = 1$ Atmosphere (2,000 lb/ft^2). The correlation of Seed et al. (1984) was never formally corrected to $\sigma'_v = 1$ atm., however, as it was noted that the field case histories of the database were "shallow", and approximately in this range. The database was, however, <u>not</u> centered at $\sigma'_v = 1$atm., but rather at lesser overburden (Mean $\sigma'_v \approx 1{,}300$ lb/ft^2), and this proves to render this earlier relationship slightly unconservative if taken as normalized to $\sigma'_v = 1$atm. For correctness, and to avoid ambiguity, both the earlier relationship of Seed et al. (1984), and the correlation developed in these current studies, need to be formally normalized to $\sigma'_v =$

1atm. Accordingly, in these studies, <u>all</u> data are corrected for K_σ-effects (by Equation 4-5 and the relationship of Figure 4-6); not just those data for which σ'_v was greater than 1 atm.

Figures 4-7 and 4-8 show the proposed new correlations, this time for σ'_v =1 atm., to illustrate the slight shift involved in fully and consistently normalizing all the data. This is not significant for "shallow" cases (where $\sigma'_v < 1$ atm.), and both the original relationship of Seed et al. (1984) and the new relationships of Figures 4-1 through 4-8 are appropriate. For <u>deeper</u> conditions, however, where K_σ <u>must</u> be employed, failure to fully normalize <u>all</u> data would render the correlations somewhat unconservative.

A number of earthquakes contributed disproportionally to the database, and this posed a risk of biasing the results. This was addressed by means of a number of adjustments. Case histories from the 1989 Loma Prieta Earthquake experienced unusually short durations of shaking due to the relatively symmetric nature of the event's bi-lateral rupture mechanism. Accordingly, the "magnitude" representing this event was judgmentally downgraded to M_W=6.5 for purposes of evaluating the magnitude-correlated duration weighting factor (DWF_M). Similarly, directionality effects compressed the arriving energy pulses in the Port region at Kobe during the 1995 Kobe Earthquake, so the assigned magnitude here was downgraded slightly to M_W=6.7. Finally, owing to the similarity of seismic excitation in a relatively close proximity, the seismic loading (CSR) data for the Kobe Port region and the Loma Prieta data sets were analytically treated as internally correlated, with assigned correlation factors based on judgement. The analyses were then repeated, without modeling this internal correlation, and the results were found not to differ significantly. The uncorrelated model (requiring no a priori judgmental assignment of internal correlation) was used as the final basis for the studies presented herein.

A final, and very difficult issue, was the fact that the data sets assembled over-represented "closed" data points (liquefied sites) relative to "open" data points (non-liquefied sites.) The final data set contained roughly twice as many liquefied as non-liquefied data, and most large data sets assembled by prior researchers were found to have similar ratios. The problem is that this represents a sampling disparity problem, and is not an unbiased reflection of actual field occurrences. Simply put, post-earthquake field investigators are more inclined to perform borings and tests at liquefied sites, than at sites where no apparent liquefaction occurred. Given finite research budgets, it would be asking too much to expect researchers to randomly space their SPT borings at non-liquefied sites in the hope of encountering non-liquefied soils of potentially liquefiable type.

This unavoidable sampling disparity produces a bias in the results, as the artificially disproportionate number of "liquefied" data push against the under-represented "non-liquefied" data. Two approaches were invoked to address this problem. The first was to consult with experts, and to attempt to develop expert consensus regarding a weighting factor that can be applied to eliminate this bias. All experts consulted agreed that the bias was real, and that a corrective weighting factor (W_{NL}) for the non-liquefied data should be greater than 1.0. The most common range was on the order of W_{NL}=1.5 to 2.

The second approach was to treat the weighting factor as a variable in the Bayesian Updating analyses performed, and to assess the weighting factor that provided the best overall model "fit". This was found to be a factor of about 1.5. Finally a sensitivity study was performed, and it was found that a scaling factor of 1.5 produced only a modest shift in the correlations, as illustrated in Figure 4-9, and that it would be potentially over-conservative to leave the sampling disparity problem unaddressed. Accordingly, all "non-liquefied" data were scaled by a weighting factor of W_{NL}=1.5. This was not done, however, by weighing the non-liquefied data by this factor, as that would have increased the "apparent" amount of overall case history data, and would have produced biased (reduced) estimates of model uncertainty. Instead, all "liquefied" data were weighted by a factor of W_L=0.8, and all "non-liquefied" data were weighted by a factor of W_{NL}=1.2, resulting in a ratio of $W_{NL}/W_L = 1.5$ without significantly increasing or decreasing the "apparent" overall number of data.

All figures and equations in this report present correlations developed using the slight weighting factors discussed above and illustrated in Figure 4-9.

4.2. Overall Correlation:

The overall correlation can be expressed in parts, as in the previous Section 4.1, and in Figures 4-1 to 4-8, and Equations 4.1 through 4.5. It can also be expressed concisely as a single, composite relationship as:

$$P_L(N_{1,60}, CSR, M_w, \sigma'_v, FC) = \Phi\left(-\frac{\begin{pmatrix} N_{1,60}\cdot(1+0.004\cdot FC) - 13.32\cdot\ln(CSR) - \\ 29.53\cdot\ln(M_w) - 3.70\cdot\ln(\sigma'_v) \\ +0.05\cdot FC + 44.97 \end{pmatrix}}{2.70} \right)$$

(Eq. 4-5)

where P_L is the probability of liquefaction in decimals (i.e. 0.3, 0.4, etc.), and Φ is the standard cumulative normal distribution. Also the cyclic resistance ratio for a given probability of liquefaction can be expressed as:

$$CRR(N_{1,60}, CSR, M_w, \sigma'_v, FC, P_L) = \exp\left[\frac{\begin{pmatrix} N_{1,60}\cdot(1+0.004\cdot FC) - 29.53\cdot\ln(M_w) \\ -3.70\cdot\ln(\sigma'_v) + 0.05\cdot FC + 44.97 + 2.70\cdot\Phi^{-1}(P_L) \end{pmatrix}}{13.32} \right]$$

(Eq. 4-6)

where $\Phi^{-1}(P_L)$ is the inverse of the standard cumulative normal distribution (i.e. mean=0, and standard deviation=1). For spreadsheet construction purposes, the command in Microsoft Excel for this specific function is “NORMINV(P_L,0,1)”.

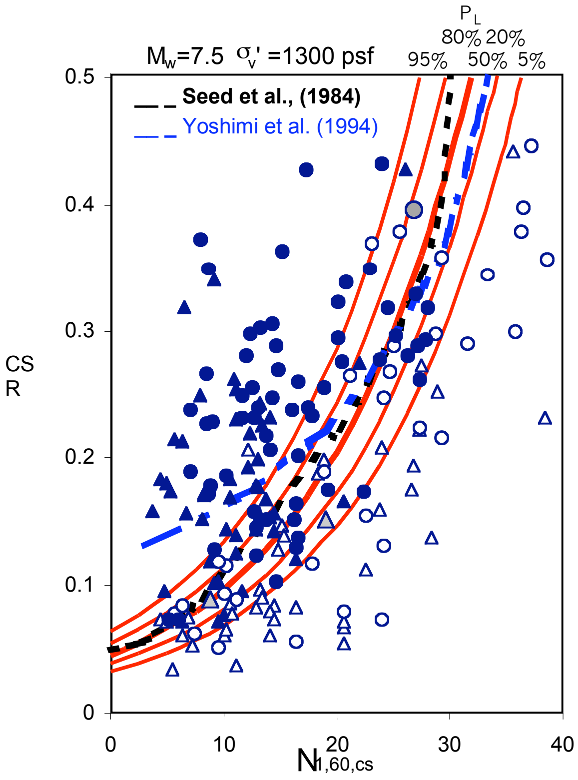


Figure 4-1 : Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=0.65 atm., and the Relationship for "Clean Sands" Proposed by Seed, et al. (1984)

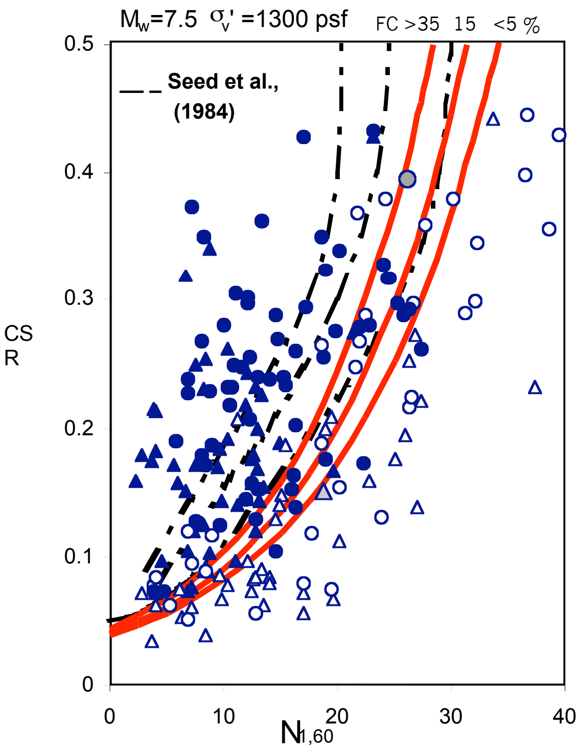


Figure 4-2 : Recommended "Deterministic" SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=0.65 atm., with Adjustments for Fines Content Shown

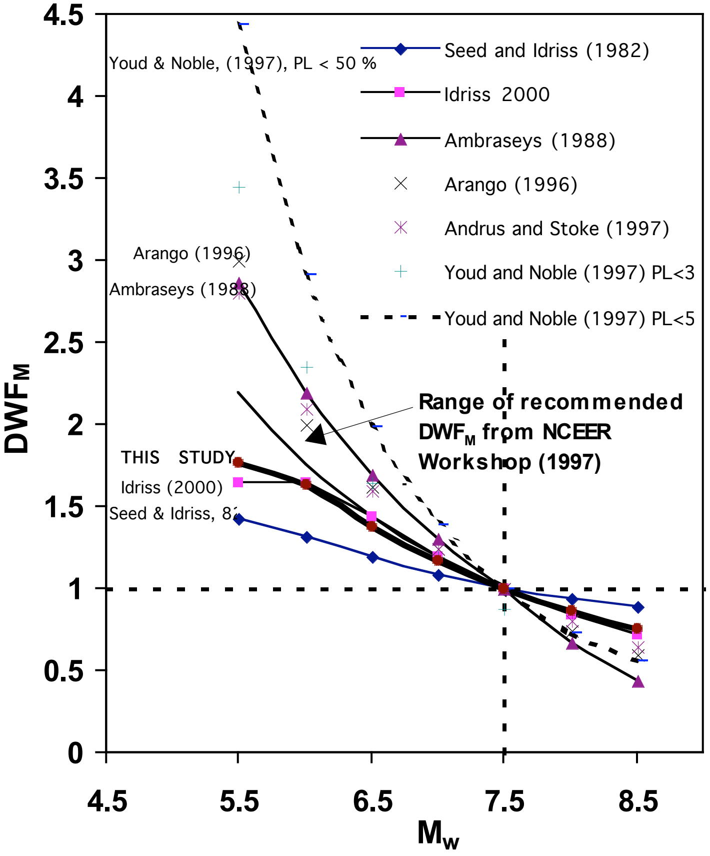


Figure 4-3 : Prevoius Recommendations for Magnitude-Correlated Duration Weighting Factor

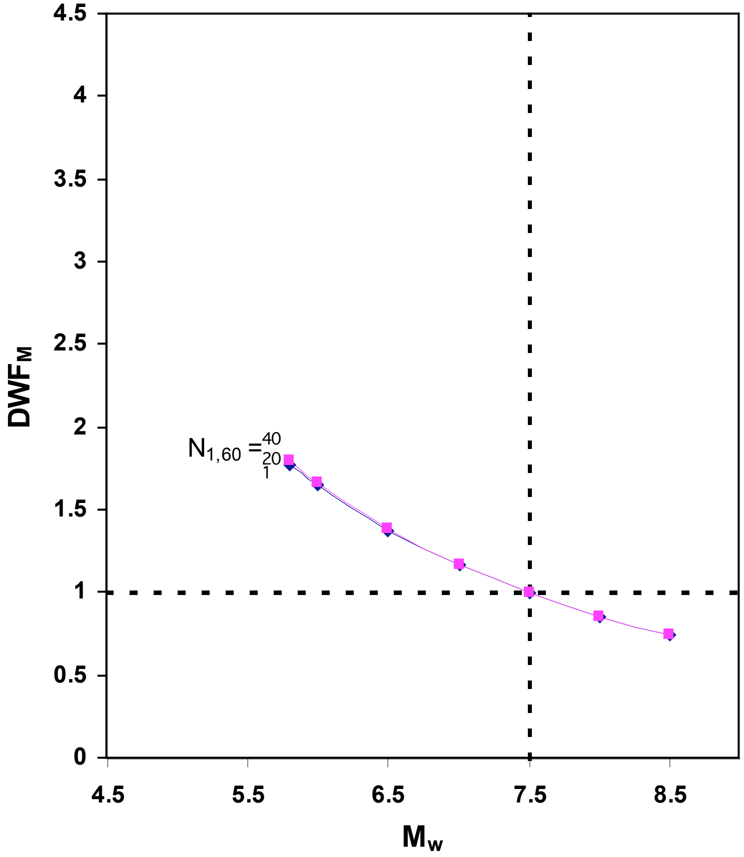
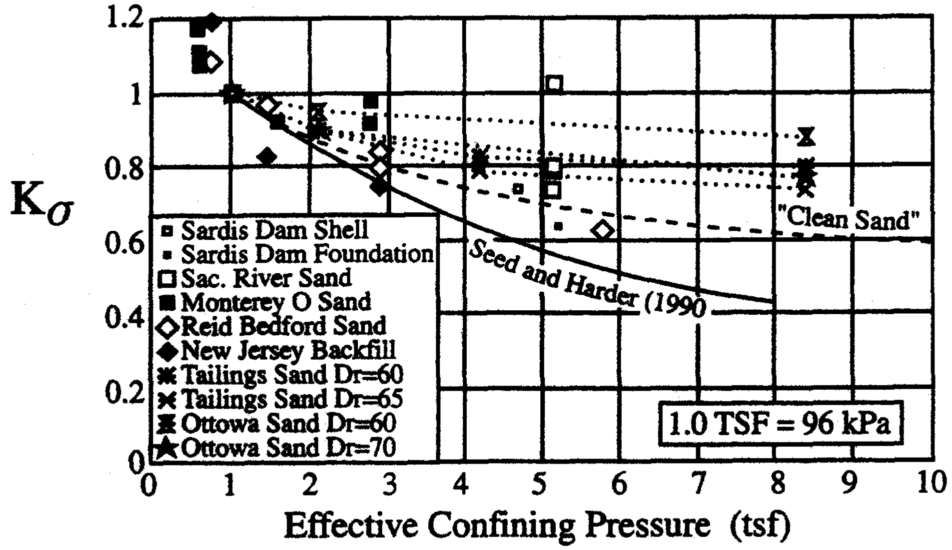
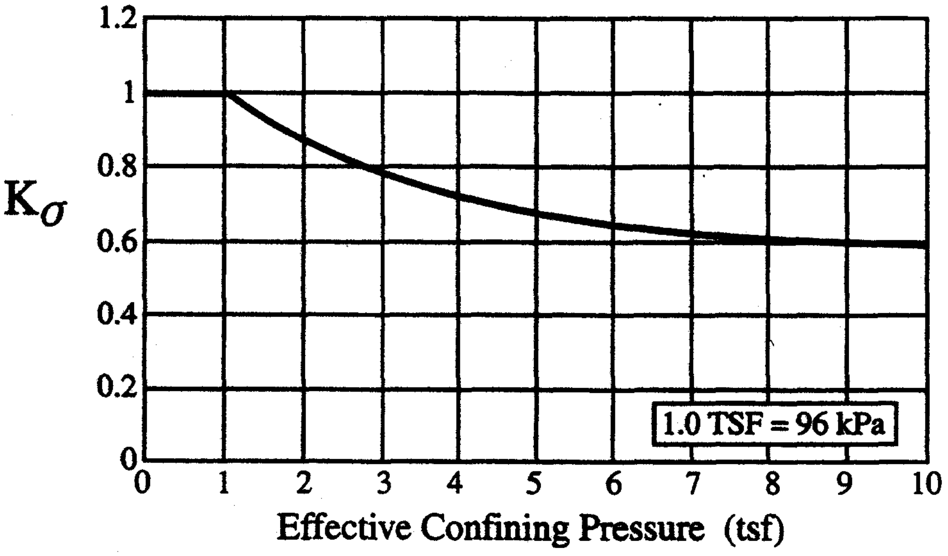


Figure 4-4 : Recommended Magnitude-Correlated Duration Weighting Factor as a Function of $N_{1,60}$



(a) Recommendations of Seed and Harder (1990)



(b) Recommenations of NCEER Working Group (1998)

Figure 4-5 : Previous Recommendations Regarding K_σ

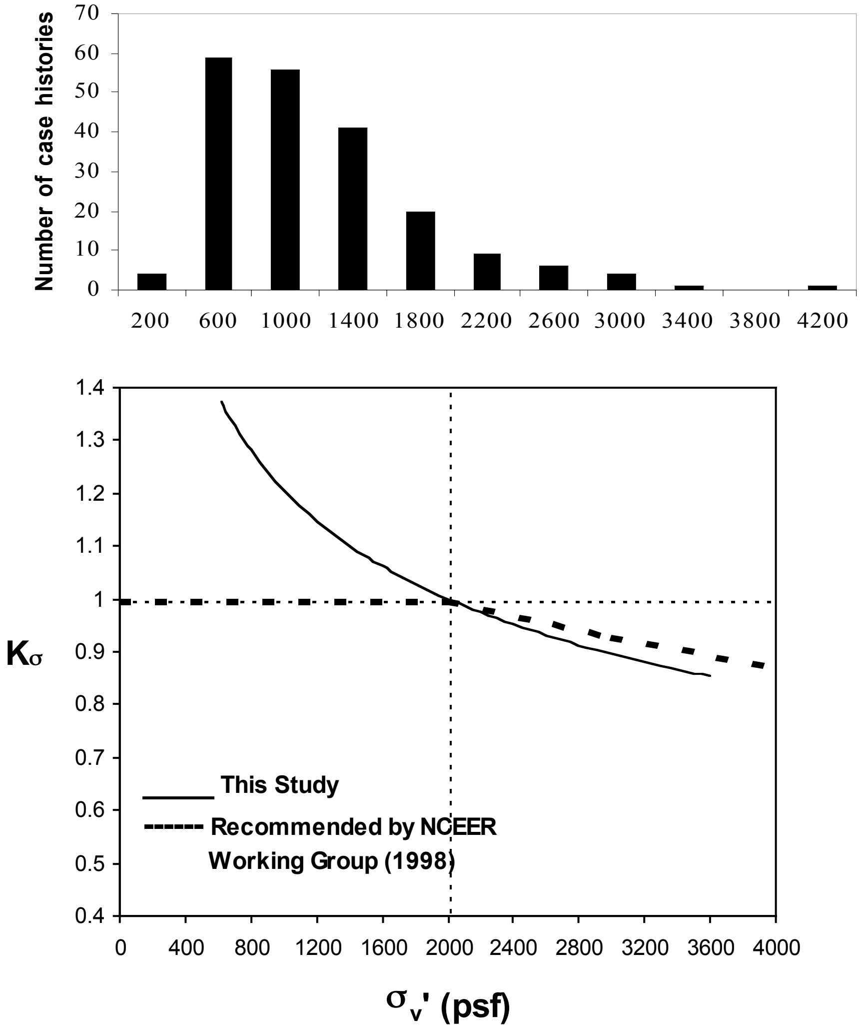


Figure 4-6 : Values of K_σ Developed and Used in These Studies

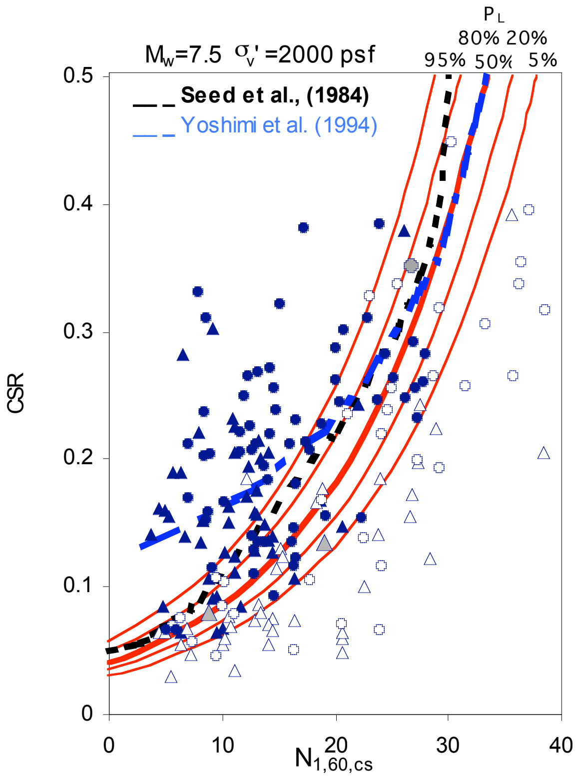


Figure 4-7 : Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=1.0 atm., and the Relationship for "Clean Sands" Proposed by Seed, et al. (1984)

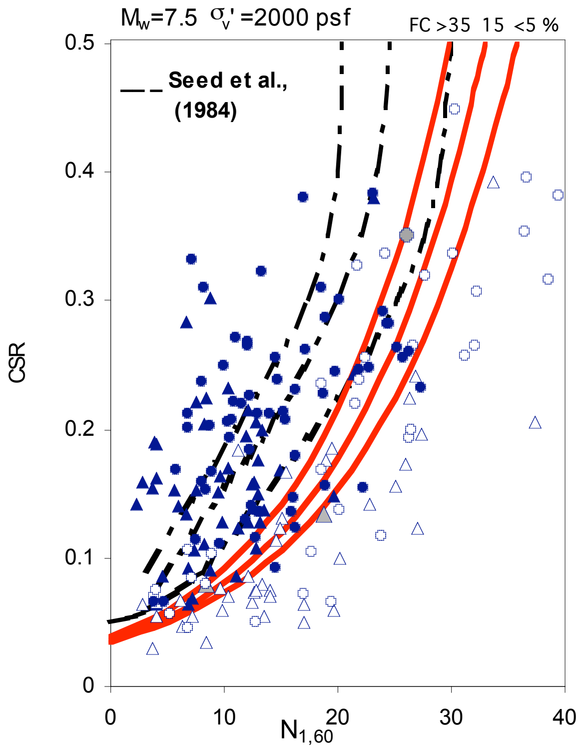


Figure 4-8 : Recommended "Deterministic" SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=1.0 atm., with Adjustments for Fines Content Shown

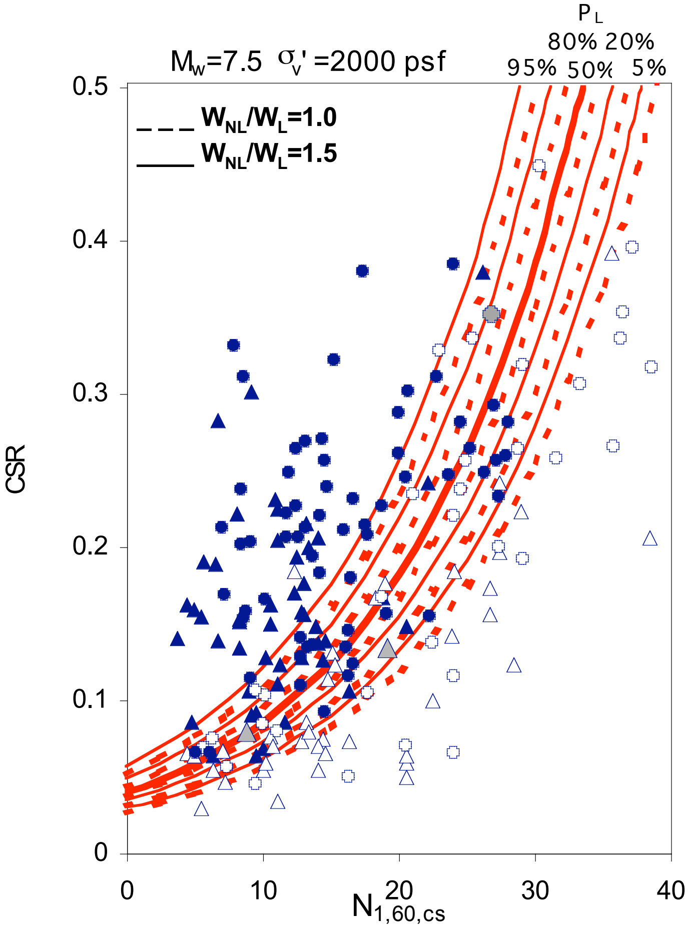


Figure 4-9 : Effect of Weighting of Non-Liquefied Field Case Histories to Address Sampling Disparity

5. SUMMARY AND CONCLUSIONS

The studies presented herein have resulted in the development of improved probabilistic SPT-based correlations for the evaluation of liquefaction triggering potential. The basic probabilistic expression is summarized in Figure 5-1. In this figure, N-values have been normalized for overburden effects (by Eq. 3-5) and have also been corrected for fines content (by Eq. 4-3). The equivalent cyclic stress ratio has been normalized for magnitude-correlated duration effects, using the factor DWF_M based on the relationship of Figure 4-4. Cyclic stress ratios shown have all been further corrected for effective overburden stress effects, based on the relationship shown in Figure 4-6, and Equation 4.4, so that Figure 5-1 is normalized to $\sigma'_v = 1$ atmosphere.

A recommended new "deterministic" correlation, based on the relationship of Figure 5-1, and using $P_L = 20\%$ as a basis, again with fines content adjustment of the "boundary curves" (by Eq. 4-3), is presented in Figure 5-2.

Figure 5-3 shows the three best "previous" probabilistic correlations, as well as the new correlation, all plotted to the same scale and plotted on the same basis ($\sigma'_v \approx$ 1,300 psf, Fines Content ≤ 5%, $M_w = 7.5$). As shown in this figure, the new correlation provides greatly decreased uncertainty (note that the correlation of Liao et al., Figure 5-3(a), does not have a fines correction and so is limited to "clean" sands only). The new correlation is based on a more extensive database than most prior efforts, and on field case history data processed with more current insights, and filtered to higher standards, than most prior studies of this type. As a result, the new correlation provides a significantly improved basis for evaluation of soil liquefaction likelihood.

Finally, in comparing the new correlations with previous correlations, both those probabilistically based (as in Figures 5-3(a) through (c)) as well as the "deterministic correlation of Seed et al. (1984), it should be recognized that the new correlation employs an improved estimation of in-situ CSR (based on both direct site response analyses for 53 field performance case histories, and an improved empirical estimation of r_d for the remaining case histories). Accordingly, the apparent movement of the new correlation to a slightly more conservative position is less pronounced than it would appear in Figures 5-1 through 5-3, as the new recommendations for evaluation of CSR eliminate a conservative bias in CSR estimation, and produce slightly lower CSR values (typically on the order of 5% to 20% lower). In addition to improving accuracy and reducing variance or uncertainty, an additional important advantage of the improved estimation of CSR is the elimination of systematic bias between "empirical" (r_d-based) CSR estimates and CSR values calculated directly from response analyses. Accordingly, the new proposed correlation is also unbiased, and can be used with CSR values evaluated by either of these two methods.

This is especially important when the use of these correlations is extrapolated to assessment of liquefaction triggering potential for sites and conditions (e.g.: slopes, dams, embankments, etc.) for which "simplified" (and one-dimensional) estimates of CSR are insufficient. Accordingly, the new correlation eliminates a previous, systematic source of unconservatism for such applications (for which direct calculation of CSR based on dynamic response analyses is often required in order to account for 2-D and/or 3-D effects of topography and/or stratigraphy).

New field case history data is currently being developed as a result of major earthquakes in both Turkey and Taiwan. These data will be incorporated, and the relationships further refined, as the data become available. Numerical tests show, however, that the database is currently largely “saturated”, so it is unlikely that incorporation of new data from these two additional data sets will significantly affect these new proposed correlations, with the possible exception of some adjustment of the correction for fines content. Overall, these new correlations are well-structured and well-based, and they provide a reliable and well-defined estimate of liquefaction triggering likelihood.

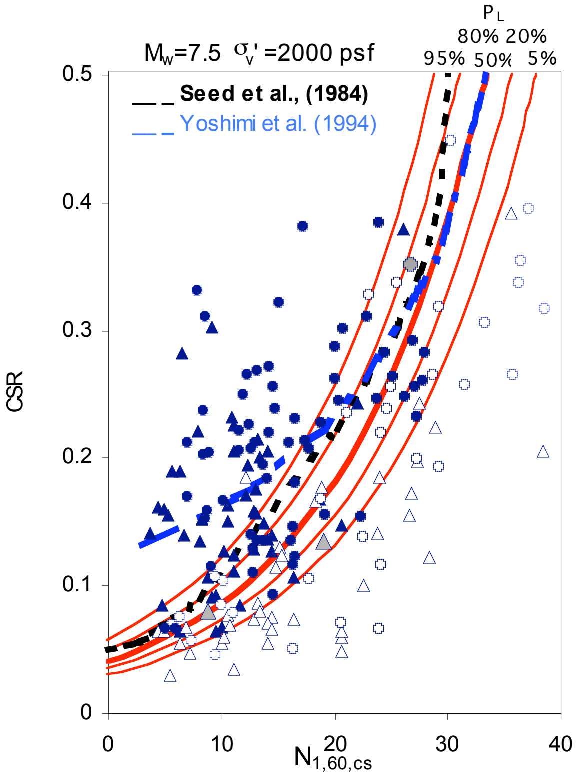


Figure 5-1 : Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=1 atm., and the Relationship for "Clean Sands" Proposed by Seed, et al. (1984)

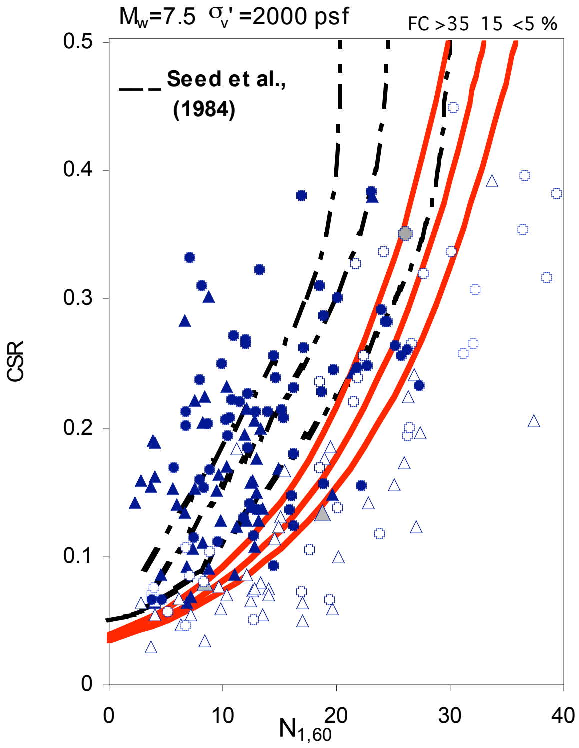
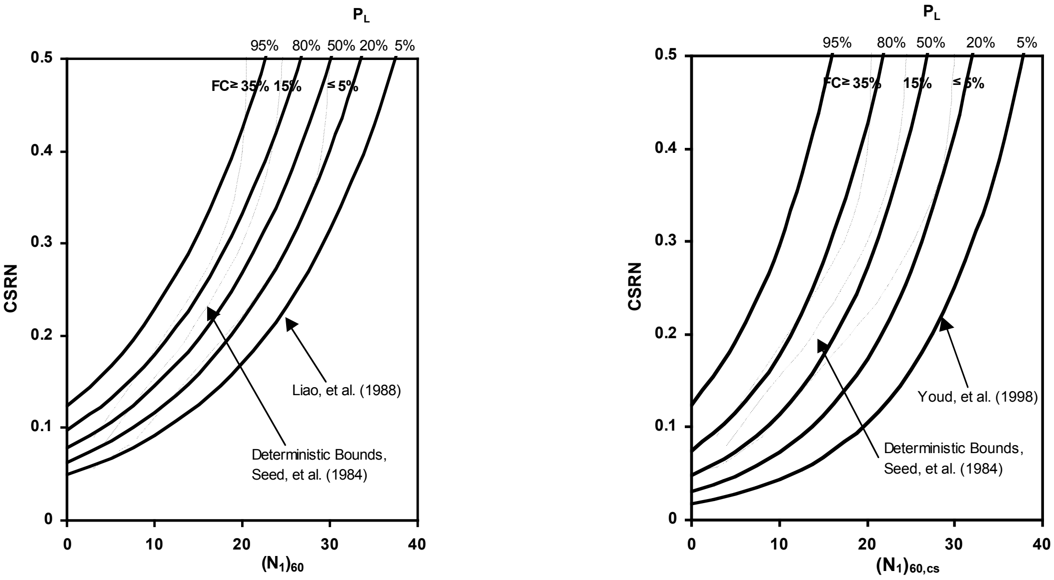


Figure 5-2 : Recommended "Deterministic" SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and σ_v'=1 atm., with Adjustments for Fines Content Shown

Liao et al., 1988 Youd et al., 1998



Toprak et al., 1999 This Study (σ'_v=1300 psf.)

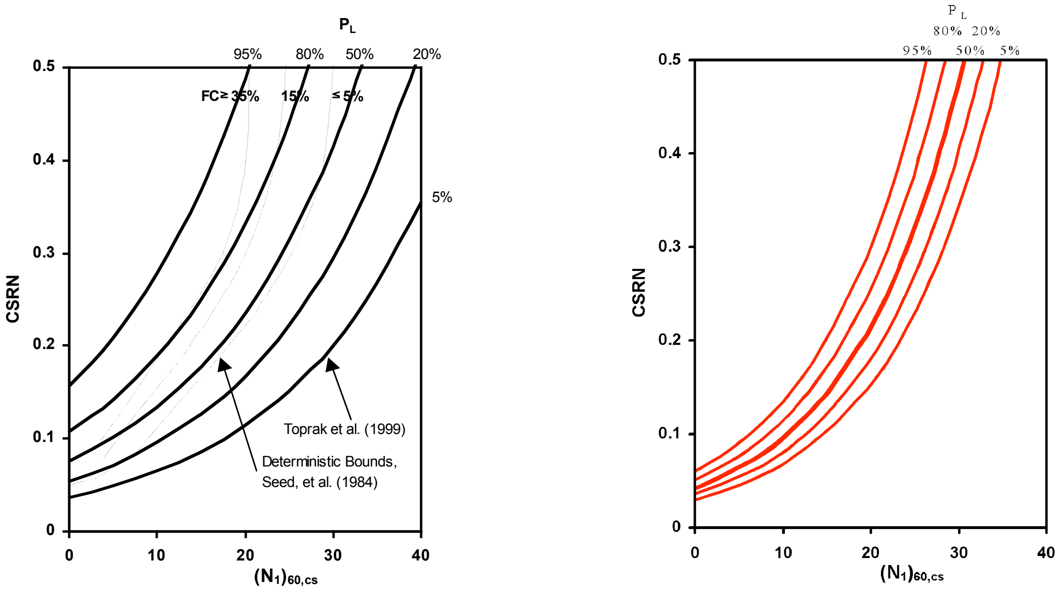


Figure 5-3: Comparison of Best Available Probabilistic Correlations for Evaluation of Liquefaction Potential (All plotted for M_w=7.5, σ'_v=1300 psf, and Fines Content ≤ 5%)

Acknowledgements

Funding for these studies was provided by PG&E, through the PG&E/PEER Center Research Program, under contract No: Z-19-2-133, and this support is gratefully acknowledged. The authors also wish to thank M. J. Bennett, Drs. J. C. Tinsley, S. Toprak, and T. L. Holzer, all from the U.S. Geological Survey (USGS), for their assistance in collecting and interpreting case histories, and for their valuable suggestions. Similarly, the authors are grateful to Dr. T. L. Youd both for his assistance in obtaining and evaluating case history data, as well as for his insight and comments.

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