0898

PROBABILISTIC ASSESSMENT OF LIQUEFACTION INITIATION HAZARD

K. Onder CETIN[1], Raymond B SEED[2] And Armen DER KIUREGHIAN[3]

SUMMARY

This paper presents the results to date of ongoing studies to develop improved, probabilistically-based correlations for the use of SPT data for evaluation of resistance to “triggering” or initiation of cyclic liquefaction. Although these studies are ongoing, the relationships developed at this stage are considered to represent a sufficient advance over previously available, similar relationships as to merit their exposition at this time.

The relationships presented herein have a number of significant advantages over previous probabilistic and “deterministic” relationships currently available. These include:

- 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.
- A large number of “new” field case history data were collected and similarly evaluated.
- 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.
- The Bayesian parameter estimation method was used to develop and evaluate correlations. This method 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 effective overburden stress, and (b) magnitude-correlated duration weighting factors (for magnitudes other than $M_W = 7.5$)

INTRODUCTION

Seismic soil liquefaction continues to be a challenging problem, and attracts considerable attention from researchers all around the world. The term liquefaction has been used to define various different aspects of shear strength reduction, such as flow failure or cyclic softening; within the context of this study, liquefaction is going to be characterized by surface manifestations, such as sand boils, lateral spread, or extensive settlement, etc. The studies presented herein are 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.

[1] Graduate Student Researcher, University of California at Berkeley
[2] Professor, University of California at Berkeley
[3] Professor, University of California at Berkeley

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), as presented in Figures 1 and 2 (dashed lines). 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), and more recently by Youd and Noble (1997). Figure 1 shows the relationship proposed by Liao et al., expressed as contours of probability of triggering of liquefaction for "clean" sands. The relationship proposed by Youd and Noble is, similarly, presented in Figure 2.

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>0.3). This higher range of CSR >0.3 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 binary regression of logistic models. The way the likelihood function was formulated did not permit separate treatment of some significant aleatory and epistemic sources of uncertainty, and has high overall variance or uncertainty in the proposed correlation. Liao et al. (1998) updated the treatment of magnitude-scaling factors, but the overall correlation did not vary much.

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, binary regression, 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. Differences with other details of the data processing and screening, and development of this correlation, again resulted in high overall variance or uncertainty.

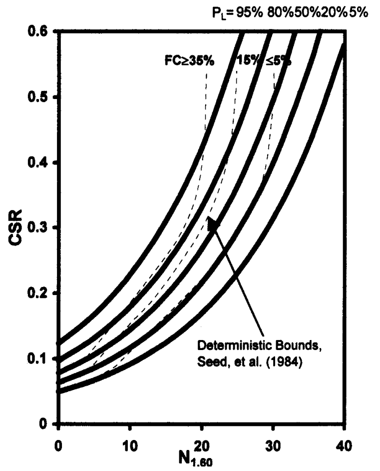

Figure 1 : Probabilistic Triggering Correlation for Clean Sands (Fines Content<12%) for M=7.5 as Proposed by Liao, et al. (1988)

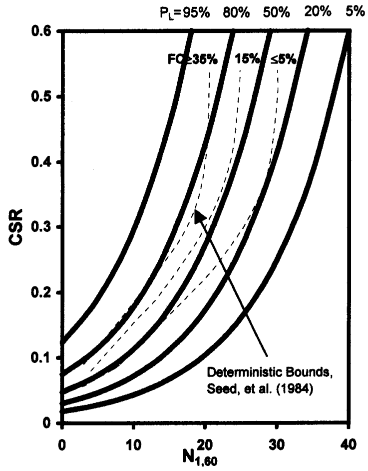

Figure 2 : Probabilistic Triggering Correlation for Clean Sands for M=7.5 as Proposed by Youd and Noble (1997)

Overall, these three relationships are all excellent efforts, and represent the best of their types. However, more can be achieved, 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.

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 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., (b) evaluation of local site effects and directionality and source mechanism effects on shaking intensities at case sites, and (c) estimation of equivalent CSR at depth.
3. For all case histories, estimates of variance or uncertainty in both CSR and corrected $N_{1,60}$ were evaluated and incorporated in the analyses. The CSR was modelled 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. The N-value was modelled 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.
4. Based on 1, 2 and 3 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.
5. The Bayesian parameter estimation method (Box and Tiao, 1973), with newly developed enhancements to deal with specific issues raised by this overall problem (Cetin, 1999), 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 uncertainties, (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.

DATA PROCESSING AND ANALYSES

Case History Collection and Processing

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 (Youd et al., 1997). One 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. In these new studies, Magnitude-dependent r_d-values were used, as shown in Figure 3, to estimate CSR at depth. The values of r_d shown in this figure were based on (1) studies by Golesorkhi and Seed (Golesorkhi, 1989), (2) similar studies by Idriss and Golesorkhi (Idriss, 1997), and (3) ongoing studies as a part of these current efforts. These differed relatively little from the earlier values of Seed et al. (1984) used in previous studies (the M=7.5 line in Figure 3) for shallow depths, and 90% of the data points eventually used in these current studies were found to occur at depths of between 10 and 30 feet, as also shown in this figure.

Additional new case history data were next collected, mainly (but not entirely) from events post-dating 1984, and these cases were similarly processed. A total of more than 400 case histories were considered in these studies. After screening for quality indices, a total of 191 cases were retained and used. Figure 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 equivalent uniform CSR and corrected N-values.

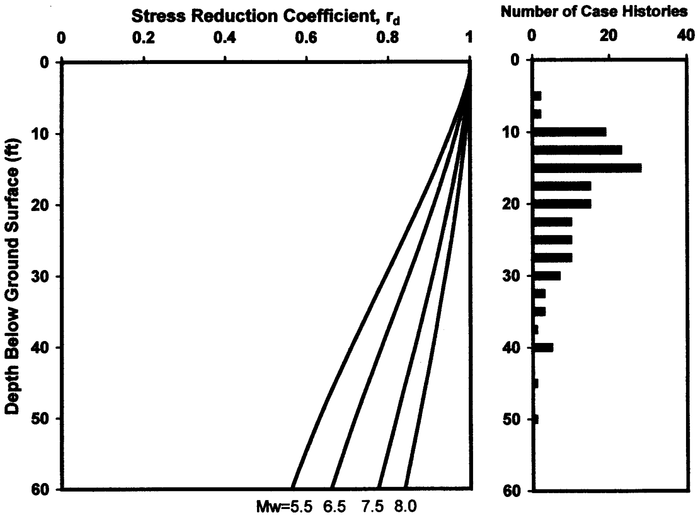

Figure 3: Magnitude-Dependent r_d-Values Used in These Studies

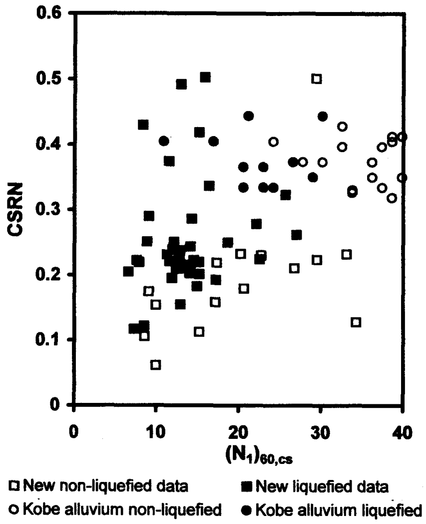

Figure 4: New Case History Data (Class C or Better) Used in These Studies

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:

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

Class B:

- Equipment and procedural details affecting SPT data well-defined, and
- $0.2 < C.O.V._{CSR} \leq 0.35$,
- or satisfies Class A but less than 3 N-values in the critical stratum.

Class C:

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

Class D:

- Equipment and procedural details affecting SPT data not well-defined, or 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
- Poor site performance data/documentation, or
- 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.

Table 1 : Field Case History Data Distribution by Quality and Performance Qualifications Used in These Studies

Database	Class A	Class B	Class C	(Class D)
Seed et al. (1984) Non-liquefied	11	29	5	-
Seed et al. (1984) Liquefied	10	31	7	-
Seed et al. (1984) Marginally Liq.	3	1	-	-
Seed et al. (1984) Deleted	-	-	-	(29)
New Database Non-liquefied	10	7	-	-
New Database Liquefied	23	16	3	-
Kobe Alluvium	-	35	-	-
Data Currently Used	57	119	15	-
			Total=191	(Deleted)

The new data collected and processed for these current studies was of generally high overall quality, as indicated by Table 1. Overall, approximately 400 data were processed and screened. 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 191 data of Class C or better, after deletion of 29 "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.

Three additional data sets were examined. The first of these was a "small magnitude" data set developed by Youd (1997). 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. 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, and (b) with this data, but 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 in the final overall correlations presented herein.

A second additional data set examined was a proprietary data set from alluvium sites just inboard of the well-known coastal fills at Kobe, Japan. These cannot yet be reported in detail, but they are expressed graphically in Figure 4. The Kobe "alluvial" data is particularly valuable, as it represents data falling mainly in the high CSR range (CSR>0.3) where useful data is relatively sparse. A third data set available was a similar, proprietary set of data from the "Masado" fills at Kobe. The Kobe "Masado" fill data is biased by interference of gravels with the SPT, and has not been used in these studies to date. Attempts are underway to screen these data for gravel effects, in which case some of these data may be incorporated at a later time.

Bayesian Analyses

The Bayesian approach for parameter estimation is based on the well-known updating formula (Ang and Tang 1975):

$$f(\theta) = c \cdot L(\theta) \cdot p(\theta) \tag{1}$$

In this expression, p(θ) is known as the prior probability density function, L(θ) is the likelihood of realization of the available observations, and f(θ) is the posterior probability density function. In simple terms, what the Bayesian updating model does is to update our "prior" knowledge by using the newly gained information from the observations.

Limit State Functions for Seismic Soil Liquefaction

It is important to choose a limit state function which is flexible enough to capture the almost asymptotic behavior for high levels of CSRN. For this purpose, Liao et al. developed a model with two explanatory variables, $N_{1,60}$ and CSRN. Youd and Noble (1997) introduced the magnitude of the earthquake into liquefaction models as another load term, rather than "externally" correcting for magnitude correlated duration effects. For the sake of complete and explicit representation of the significant liquefaction variables, a limit state function, which incorporates $N_{1,60}$, and fines content (FC) as the capacity terms, and CSR, M_w and σ'_v as the load terms, and where the error terms, e_N and $e_{\ln(CSR)}$ represent the uncertainties in estimating $N_{1,60}$ and ln(CSR), was developed as follows:

$$\begin{aligned} g\left(N_{160}, e_N, CSR, e_{\ln(CSR)}, M_w, FC, \sigma'_v, \Theta\right) = {} & N_{160} + e_N - \theta_1 \cdot \left[\ln(CSR) + e_{\ln(CSR)}\right] - \theta_2 \ln(M_w) \\ & + \theta_3 \cdot FC - \theta_4 \cdot \ln(\sigma'_v) + \theta_5 + \gamma \end{aligned} \tag{2}$$

A site will be predicted to liquefy if it falls above the limit state function, or, in other words, if the following expression is satisfied:

$$g\left(N_{160}, e_N, CSR, e_{\ln(CSR)}, M_w, FC, \sigma'_v, \Theta\right) \le 0 \tag{3}$$

The opposite should be satisfied for the non-liquefied sites. If it is assumed that the observations from each case history and site are statistically independent, then the likelihood of observing k liquefied and n-k nonliquefied sites can be simply written as proportional to the product of corresponding probabilities given as follows:

$$L(\Theta,\Gamma) \propto P\left[\bigcap_{i=1}^{k}\left\{g\left(N_{160,i}, e_{N,i}, CSR_i, e_{\ln(CSR),i}, M_{w,i}, FC_i, \sigma'_{v,i}, \Theta\right) \le 0\right\} \bigcap_{i=k+1}^{n}\left\{g\left(N_{160,i}, e_{N,i}, CSR_i, e_{\ln(CSR),i}, M_{w,i}, FC_i, \sigma'_{v,i}, \Theta\right) > 0\right\}\right] \tag{4}$$

The model parameter, γ, which represents the variables that are not explicitly present in the limit state function (such as the grain size distribution, grain shapes, and fabric characteristics as well as permeability and drainage path effects, etc.), estimates how much each prediction is off from the real observation. An unbiased model is expected to predict the liquefaction triggering potential correctly in the mean sense. Thus, the γ term can be reasonably assumed to be normally distributed with zero mean and standard deviation, σ_γ, which will also be updated through Bayesian analyses. Last but not least, the error terms also will conventionally be represented as normally distributed with zero means and estimated standard deviations, which are different for each case history depending on the availability and the quality of data. Based on these assumptions, the likelihood function can be written as the products of standard normal cumulative density functions as given below:

$$L(\Theta,\Gamma) \propto \prod_{i=1}^{k} \Phi\left(-\frac{g\left(N_{160,i}, CSR_i, M_{w,i}, FC_i, \sigma'_{v,i}, \Theta\right)}{\sqrt{e_{N,i}^2 + \theta_1^2 \cdot e_{\ln(CSR),i}^2 + \sigma_\gamma^2}} \right) \cdot \prod_{i=k+1}^{n} \Phi\left(\frac{g\left(N_{160,i}, CSR_i, M_{w,i}, FC_i, \sigma'_{v,i}, \Theta\right)}{\sqrt{e_{N,i}^2 + \theta_1^2 \cdot e_{\ln(CSR),i}^2 + \sigma_\gamma^2}} \right) \qquad (5)$$

Development of Correlations

Bayesian Updating analyses were performed using a modified version of the computer program BUMP (Geyskins, Der Kiureghian, and Monteiro, 1993). As discussed previously, all data were modeled not as "points", but rather as distributions, with variances in both CSR and $N_{1,60}$. The Bayesian updating procedure was simultaneously applied to a number of contributing variables, and the posterior statistics for the model parameters are summarized on Table 2.

Table 2 : Posterior Statistics for the Model Parameters

	θ_1	θ_2	θ_3	θ_4	θ_5	σ_γ
Mean	14.15	35.89	0.117	2.21	49.49	2.40
Standard Deviation	1.60	10.43	0.06	1.21	21.09	0.73

The findings are illustrated in Figures 5 through 8, and are expressed in Equations 2 through 8 and Table 2. Figure 5 shows the proposed probabilistic relationship between duration-corrected equivalent cyclic stress ratio (CSRN), and fines-corrected penetration resistances ($N_{1,60,cs}$), for an effective overburden stress of $\sigma'_v = 2000$ 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.

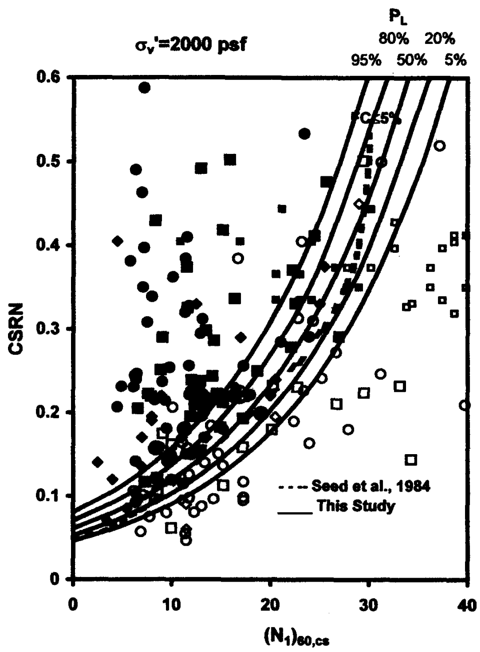

Figure 5: Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and $\sigma'_v = 2000$ psf., and the Relationship for "Clean Sands" Proposed by Seed, et al. (1984)

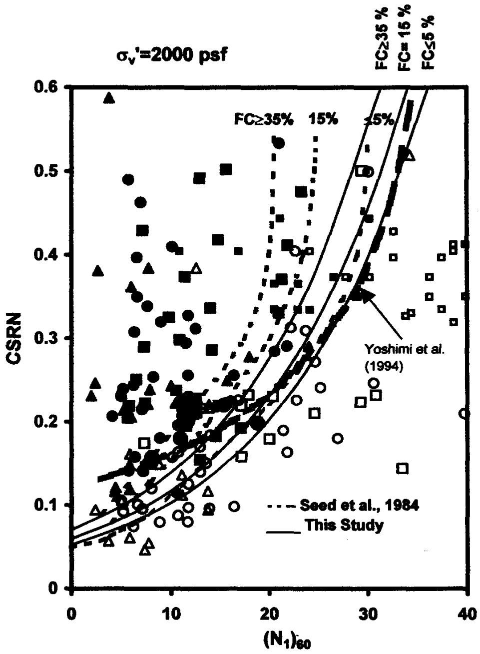

Figure 6: Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation for M_w=7.5 and $\sigma'_v = 2000$ psf., with adjustments for Fines Content Shown.

Figure 6 shows proposed boundary curves for "deterministic" evaluation, and in this figure N-values are not corrected for fines. 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. Also shown in Figure 6 is the boundary curve proposed by Yoshimi et al. (1994), based on high quality cyclic simple shear testing of frozen samples. The line of Yoshimi et al. is arguably unconservatively biased at very low densities (low N-values) as these loose samples densified during thawing and reconsolidation. Their testing provides potentially valuable insight, however, at high N-values where reconsolidation densification was less significant.

Both the probabilistic and recommended deterministic (based on P_L = 20%) relationships of Figures 5 and 6 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

$$CSRN = CSR_{EQ} / DWF_M \tag{6}$$

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 7 summarizes a number of recommendations, and shows the recommendations of the NCEER Working Group (Youd et al., 1997). In these current studies, this important and controversial factor could be derived as a part of the Bayesian updating analyses. The recommended magnitude-correlated duration weighting factor is also shown on Figure 7.

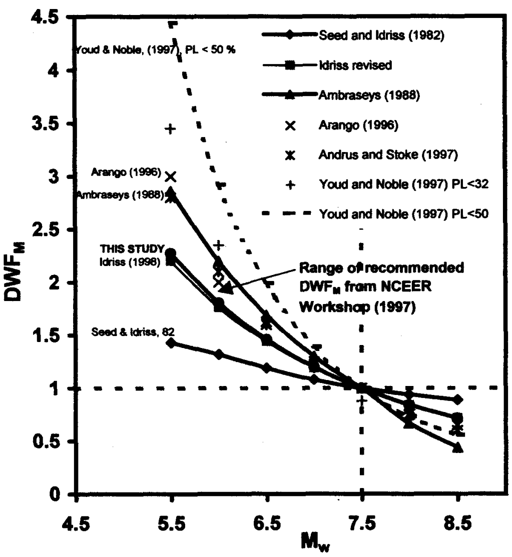

Figure 7: Recommended Magnitude-Correlated Duration Weighting Factor

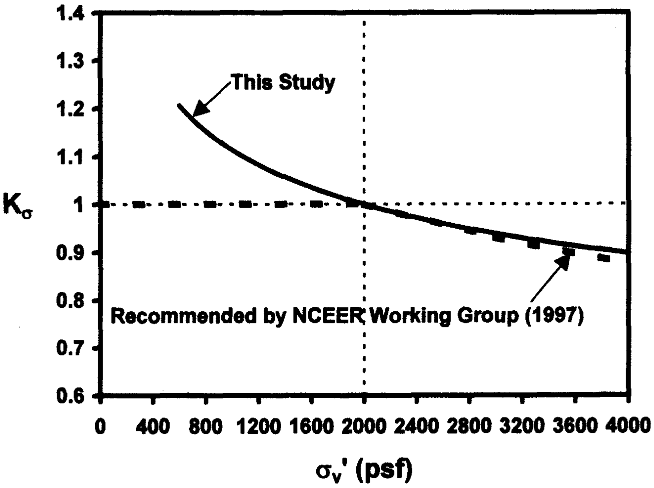

Figure 8: Values for K_σ Developed and Used in These Studies.

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 conventional normalization of N-values for overburden effects (C_N). 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 8 presents the recommendations of the NCEER Working Group (Youd et al., 1997) as well as this study's findings over the range for which they are statistically valid. 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

$$CSR_{liq} = CSR_{liq,1atm} \cdot K_\sigma \tag{7}$$

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

$$N_{1,60,CS} = N_{1,60} \,.\, C_{FINES}\,, \quad \text{where } C_{FINES} = 0.117 \cdot \left(\frac{FC}{N_{1,60}}\right), \quad \text{lim: } 5\,\% \leq FC \leq 35\,\% \tag{8}$$

and 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 6, the maximum fines correction resulted in an increase of N-values of about +4.1 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 +7.5 blows/ft. proposed by Seed et al. (1984).

CONCLUSION

The correlations presented herein represent ongoing work. Completion of these studies will include: (1) processing and incorporation of a limited number of additional case history data, and (2) performance of site- and event-specific seismic response analyses for as many case histories as feasible (those for which suitable data and input motions can be developed). These efforts are for enough along that it can be seen that their impact on the overall correlations will be minor. The database can be shown to be essentially "saturated", so that addition of data does not intrinsically further reduce variance or uncertainty. The very low variance achieved in these new correlations reflects both the availability of adequate data, and also significant care in the processing, screening, and use of these data to develop the overall correlations presented.

LIST OF REFERENCES

1. Ang, A. H. S., Tang, W. (1975). "Probability Concepts in Engineering Planning and Design", John Wiley & Sons, New York.
2. Box, G. E. P., Tiao, G. C. (1973). "Bayesian Inference in Statistical Analysis", Addison-Wesley Series, Addison-Wesley Publishers.
3. Cetin, O. (1999), "SPT-Based Probabilistic Evaluation of Seismic Soil Liquefaction Potential", Doctoral Dissertation, in progress, Dept. of Civil and Environmental Engineering, University of California at Berkeley.
4. Geyskens, P., Der Kiureghian and A., Monterio, P. (1993). "Bayesian Updating of Model Parameters", Research Rept. No. UCB/SEMM-93/06, Dept. of Civil and Environmental Engineering, University of California at Berkeley.
5. Golesorkhi, R. and Seed, H. B. (1989). "Factors Influencing the Computational Determination of Earthquake-Induced Shear Stresses in Sandy Soils", Dept. of Civil and Environmental Engineering, University of California at Berkeley.
6. Idriss, I. M. (1997). Personal Communication.
7. Liao, S. S. C., Veneziano, D. and Whitman, R. V. (1988). "Regression Models for Evaluating Liquefaction Probability", Journal of Geotechnical Engineering, Vol. 114, No 4, April, pp.389-410.
8. Liao, S. S. C., Lum, K. Y. (1998). "Statistical Analysis and Application of the Magnitude Scaling Factor in Liquefaction Analysis", Geotechnical Special Publication No. 75, ASCE.
9. Seed, H. B., Tokimatsu, K., Harder, L. F. and Chung, R. M. (1984). "The Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations", Report No. UCB/EERC-84/15, University of California at Berkeley.
10. Seed, R. B. and Harder, L. F. (1990). "SPT-Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength", Proceedings, H. Bolton Seed Memorial Symposium, May, 1990, University of California at Berkeley, Bi-Tech Publishers.
11. Youd, T. L. and Idriss, I. M. (1997). "Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils", Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, SUNY, Buffalo, New York.
12. Youd, T. L. and Noble, S. T. (1997). "Liquefaction Criteria Based on Statistical and Probabilistic Analyses", Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, SUNY, Buffalo, New York.

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 Dr's. M. J. Bennett, J. C. Tinsley, S. Toprak, R. Kayen, 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 and Dr. K. Tokimatsu, both for their assistance in obtaining and evaluating case history data, as well as for their insight and comments. Finally, the authors wish to thank Dr. I. M. Idriss for his suggestions, and for sharing his ongoing work regarding duration weighting factors and magnitude dependent r_d.