Annual Project Summery Report for 10/01/01-9/30/02

Development of a Simplified Reliability-Based Method for Liquefaction Evaluation

USGS Grant Number: 02HQGR0058

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NEHRP Element: PT

Key Words: Liquefaction, Site Effects, Probabilistic Seismic Hazard, Amplification

Non-Technical Summary

Despite major uncertainties, evaluation of liquefaction potential of soils is still routinely carried out deterministically in practice. This is attributed to the lack of familiarity among geotechnical engineers, who perform most liquefaction evaluations, of the concepts and procedures in reliability theory, and the lack of data to carry out probabilistic analyses. A review of probabilistic liquefaction evaluation procedures also reveals that there is currently no comprehensive approach that accounts for all sources of uncertainties in liquefaction evaluations. Usually, only seismic demand is analyzed stochastically while analysis of seismic capacity is carried out deterministically. Moreover, available probabilistic methods do not take into consideration recent improvements in the state-of-the-art in liquefaction evaluation. The objective of the study summarized in this report is to develop a simplified reliability-based method for liquefaction evaluation. The method is based on the Seed and Idriss "simplified procedure" for deterministic liquefaction evaluation (using SPT, CPT and shear-wave velocity data), and uses the Taylor Series Reliability Method to determine the probability of liquefaction at a given site. The Taylor Series method is easy to use and employs parameters that are familiar to geotechnical engineers. In the absence of attenuation relationships, determination of seismic demand is based on the USGS National Seismic Hazard Map together with a procedure to account for local site effects on ground surface acceleration. The proposed method clearly delineates the magnitudes of the uncertainties that arise from seismic sources, local site effects, liquefaction criteria and evaluation procedures, and variability in parameters.

Background and Significance

The most commonly used method to evaluate liquefaction potential of a site is the "simplified procedure" originally developed by Seed and Idriss (1971). The method has been modified and improved on several occasions since it was developed. A review of the current state-of-practice in liquefaction evaluation using the simplified procedure is given in the “1996 NCEER and 1998 NCEE/NSF Workshops on Evaluation of Liquefaction Resistance” (Youd et al., 2001), referred to as “NCEER Report” in this summary. The current version of the simplified procedure calculates the factor of safety *FS* against liquefaction of a level ground in terms of the cyclic stress ratio CSR (the demand), and the cyclic resistance ratio CRR (the capacity) according to:

$$FS = \left(\frac{CRR_{7.5}}{CSR}\right) MSF \cdot K_\sigma \tag{1}$$

where $CRR_{7.5}$ =cyclic resistance ratio for magnitude 7.5 earthquakes, MSF = magnitude scaling factor, and K_σ = correction for non-linear effects of confining stress.

CSR is estimated using the Seed and Idriss (1971) equation:

$$CSR = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) r_d \tag{2}$$

where $a_{\max}$ =peak horizontal acceleration at the ground surface generated by the earthquake, g=acceleration due to gravity, σ_{vo} and σ'_{vo} are the total and effective overburden stresses, respectively, and r_d =stress reduction coefficient. The three most routinely used methods to evaluate the liquefaction resistance *CRR* are: 1) using the Standard Penetration Test (SPT), 2) using the cone penetration test (CPT), and 3) using seismic shear wave velocity V_s.

Despite the significant uncertainties in the different variables involved in the above method, liquefaction risk assessment is in practice still rooted in deterministic analysis. Methods for probabilistic and statistical liquefaction risk analysis have been proposed since the late 1970's, but they are complex, and they have been used mainly for important projects and critical facilities. While there have been tremendous strides in the development of probabilistic seismic demand and risk analysis in other fields, application of probabilistic liquefaction analysis is still beyond the normal practice of most geotechnical engineers. Reliability calculations provide a means of evaluating the combined effects of uncertainties, and a means of distinguishing between conditions where uncertainties are particularly high or particularly low. Reliability analyses also provide a logical framework for choosing factors of safety that are appropriate for the degree of uncertainty and the consequences of failure.

Duncan (2000) discussed the reasons why reliability analysis has not been used in routine geotechnical practice. First, reliability theory involves terms and concepts that are not familiar to most geotechnical engineers. Second, it is commonly perceived that using reliability theory would require more data, time, and effort than are available in most circumstances. These concerns need to be addressed if probabilistic liquefaction evaluation procedures are to be more-widely used in practice.

The two main issues in the development of probabilistic methods for liquefaction risk analysis based on the simplified procedure are: 1) the uncertainty in demand particularly the maximum ground acceleration $a_{\max}$ and the earthquake magnitude M_w required to the estimate the magnitude scaling factor *MSF*, and 2) the uncertainty in the capacity. For the latter, the uncertainties are due to the natural variability of soil and geotechnical properties, the uncertainties introduced by the in-situ testing procedures, and most importantly, the uncertainties introduced by the simplified model. Probabilistic liquefaction analysis has been often treated from the separate points of view of seismologists, geotechnical engineers and experts in probability and statistics. Rarely has probabilistic liquefaction analysis been treated as a multi-disciplinary problem.

Several models for probabilistic seismic demand have been developed, and usually analysis of capacity is carried out deterministically in conjunction with probabilistic analysis of ground shaking (e.g., Youd and Noble 1977, Atkinsons et al. 1984, Todorovska 1998). Procedures that evaluate probabilistic seismic capacity often deal only with specific aspects of the liquefaction evaluation. For instance, the procedures of Liao et al. (1988), and Youd and Noble (1997) deal mainly with the statistical and probabilistic analysis of field data based on SPT measurements.

Probabilistic *CRR* vs. SPT blow count curves have been developed that are more rigorous in delineating liquefaction and non-liquefaction in terms of probabilities than the original deterministic simplified procedure. However, other important uncertainties have not been included in probabilistic liquefaction evaluation. In addition to the need to statistically analyze the data used in the *CRR* vs. SPT blow count criterion (or CPT and V_s-based criteria), there are significant uncertainties in the several empirical correction factors that are used in the procedure.

Another important source of uncertainty is the natural variability of soil properties. This variability is manifested mainly in the scatter in the SPT blow count. This variability has been accounted in the liquefaction potential mapping of San Francisco, CA by Kavazanjian et al. (1985) and of Charleston, SC by Elton and Hadj-Hamou (1990). In comparison, Liao et al. (1988) use the minimum Standard Penetration Blow count measured in granular layers as the critical blow count for their analysis. In terms of SPT blow counts alone, it appears that there is a lack of consistent treatment of uncertainties in dealing with probabilistic liquefaction evaluation. Current probabilistic liquefaction criteria are based mainly on SPT, although other tests like CPT and V_s measurements are increasingly being used. With the increasing CPT and V_s database, it is now possible to establish probabilistic liquefaction criteria for CPT and shear wave velocity measurements as well, and for combinations of test results from different in situ tests.

Model and procedural uncertainties also need to be accounted for in the reliability procedure. Examples are the factor r_d and the correction factors applied to the SPT blow counts (or similarly for CPT and V_s-data). In all current probabilistic liquefaction procedures, these factors are treated as non-random variables despite the uncertainties involved and the wide range of values proposed for these parameters.

Methods and Procedures

Probability of Liquefaction

Probability of liquefaction is calculated from the joint probability of the conditional probability of liquefaction, and the probability distribution of the earthquake load parameters:

$$P(FS=1) \approx \lambda T \int_{\Omega} \int_{\Psi} P(FS=1|\Omega,\Psi) \cdot g(\Psi) d\Psi d\Omega \tag{3}$$

where $P(FS=1)$=probability of liquefaction, $P(FS=1|\Omega,\Psi) = P_L$=conditional probability of liquefaction (i.e., probability of liquefaction given all other loading conditions for the evaluation of liquefaction), $g(\Psi)$=probability distribution of the earthquake load parameters (accounts for uncertainty in earthquake magnitude, distance, acceleration and amplification), λ=overall rate of occurrence (e.g., number of earthquakes per year) from all potential seismic sources within the vicinity of the project site, T=time period, $\Psi = \Psi(a_{\max}, M_w, ED)$= vector of load parameters $\Omega = \Omega((N_1)_{60}, F_c, ...)$=vector of liquefaction resistance parameters

The latest version of the "simplified procedure", as embodied in the "NCEER Report" will be used as the basis for the probabilistic procedure. The parameters involved in the "simplified procedure" will be treated as random variables. For most parameters, a normal distribution will be assumed, with each parameter having a mean value (or most likely value) and a standard deviation, although the assumption of normally distributed variables will not be a requirement. Model and procedural uncertainties will also be accounted for in the reliability-based approach. The uncertainties in the seismic demand parameters will be treated separately using the USGS National Seismic Hazard Map with a newly developed procedure to account for local site effects on ground surface acceleration. The procedure will be developed for SPT, CPT and shear-wave velocity in situ tests.

The conditional probability of liquefaction P_L is calculated using the Taylor Series Reliability Method (Wolff 1994; USACE 1997, 1998; Duncan 2000). In this method, conditional probability of liquefaction P_L is evaluated using the following steps:

1) Calculate the most likely value of factor of safety F_{MLV} using the best estimate of the values of all the parameters required in Eqs. (1) and (2).
2) Estimate the standard deviations of the quantities involved in Eqs. (1) and (2). Methods for estimating the standard deviations are discussed below.
3) For each of the parameters *i,* calculate the factors of safety F_i^+ and F_i^- corresponding to the best estimate of the parameter *i* increased by one standard deviation and decreased by a similar magnitude, respectively. In calculating F_i^+ and F_i^- all the other variables are kept at their most likely values.

4) Using the Taylor series technique, estimate the standard deviation and coefficient of variation of the factor of safety σ_F using the formula:

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1^2}{2}\right) + \left(\frac{\Delta F_2^2}{2}\right) + \left(\frac{\Delta F_3^2}{2}\right) + ... + \left(\frac{\Delta F_n^2}{2}\right)} \tag{4}$$

and

$$V_F = \frac{\sigma_F}{F_{MLV}} \tag{5}$$

in which $\Delta F_i = F_i^+ - F_i^-$ and n is number of variables involved in the calculation of P_L.

5) Using F_{MLV} and V_F, the conditional probability of liquefaction P_L is determined assuming a log-normal distribution of the factor of safety. This requires the calculation of a reliability log-normal reliability index β_{LN} using the formula:

$$\beta_{LN} = \frac{\ln\left(\frac{F_{MLV}}{\sqrt{1+V_F^2}}\right)}{\sqrt{\ln\left(1+V_F^2\right)}} \tag{6}$$

6) Using β_{LN}, the conditional probability of liquefaction $P\left(FS = 1\middle|\Omega, \Psi\right)$ can be determined using tables for standard cumulative normal distribution, which can be found in textbooks in probability and reliability, or calculated from built-in statistical functions in Excel. The standard cumulative normal distribution can also be programmed directly. Using Excel, Duncan (2000) has developed a table giving values of probability as function of F_{MLV} and V_F.

Procedures for Estimating Variability

To provide comprehensive estimates of the probability of liquefaction, the different variables involved in the "simplified procedure" and the uncertainties related to these variables are analyzed and catalogued. To obtain estimates of the standard deviation, methods proposed in Duncan (2000) are used. These include:

1) Direct calculation from data - if sufficient data are available, the standard deviation σ can be obtained from the equation:

$$\sigma = \sqrt{\frac{\sum\left(x_i - \bar{x}\right)}{N-1}} \tag{7}$$

where $\bar{x}$ is the average value, x_i is the i^{th} value of the parameter, and *N* is the number of data.

2) From published values - there is now an increasing database on the variability of many geotechnical engineering parameters and in situ tests. Coefficients of variation COV of several geotechnical parameters and in situ tests are given in Duncan (2000). For instance, the coefficient of variation for SPT blow count (*N*) is estimated to be from 15-45% (Harr 1984, Kulhawy 1992). Given the coefficient of variation *COV* and mean value $\bar{x}$, the standard deviation σ of a parameter can be calculated as:

$$\sigma = \mathrm{COV} \cdot \bar{x} \tag{8}$$

3) The "three-sigma rule" - this rule of thumb described by Dai and Wang (1992) is based on the fact that 99.73% of all values of a normally distributed parameter fall within three standard deviations of the average. Knowing the *HCV* = highest conceivable value and *LCV*=the lowest conceivable value, the standard deviation can be estimated as:

$$\sigma = \frac{HCV - LCV}{6} \tag{9}$$

Once the standard deviation and the average value is known, the COV can be calculated as:

$$\text{COV} = \frac{\sigma}{\bar{x}} \tag{10}$$

A note should be given on the determination of COVs of parameters which vary linearly against another variable. It can be shown that using suitable transformations, a constant COV can be obtained for these parameters over their entire range of values. Consider for instance, the stress reduction factor r_d whose average, $-1 \cdot \sigma$ and $+1 \cdot \sigma$ values can be approximated by linear functions up to a certain depth *z*:

$$(r_d)_{ave} = 1 - a \cdot z \,, \quad (r_d)_{-\sigma} = 1 - b \cdot z \quad , \quad (r_d)_{+\sigma} = 1 - c \cdot z$$

Using Eqs. (9) and (10), the COV of r_d can be calculated as:

$$\text{COV}(r_d) = \frac{(b-c)z}{1 - a \cdot z} \tag{11}$$

As can be seen, $\text{COV}(r_d)$ varies linearly with *z*. On the other hand, the COV of 1-r_d can be shown to be constant:

$$COV(1 - r_d) = \frac{(b-c)z}{c \cdot z} = \frac{b-c}{a} \tag{12}$$

Note that the approach can give a reasonably constant COV even if the parameter varies non-linearly. The advantage of this approach is that the variability of different parameters can be more conveniently compared with a single constant COV for each parameter. Using the three procedures discussed above, COVs are obtained for the different parameters required in the "simplified procedure." These COVs should be used only as initial estimates in the absence of any data. Users of the proposed procedure should use more reliable COVs whenever they can be obtained.

Probabilistic Seismic Demand

Table 1 provides a list of parameters that are required to determine the seismic demand CSR. Note that the parameters given in Table 1 are also needed for the simplified procedure using CPT and V_s data. As mentioned above, the probability of liquefaction will be calculated from the joint probability of the conditional probability of liquefaction, and the probability distribution of the earthquake load parameters. Thus, some of the parameters given in Table 2 will be treated as "deterministic" parameters in the calculation of the conditional probability of liquefaction, and these parameters are the maximum ground acceleration $a_{\max}$, moment magnitude M_w, and epicentral distance *ED*. The probabilities connected with these three parameters can be calculated using probabilistic attenuation relationships. If attenuation relationships are not available, the USGS Seismic Hazard Web Page may be used to obtain first estimates of the required probabilistic demand parameters.

Table 1 - Components of CSR in the simplified procedure

Parameter	Average value and estimated COV
Maximum ground acceleration, $a_{\max}$	1) Determined from probabilistic attenuation relationships, or from the USGS Seismic Hazard Web Page. 2) Treated as "deterministic" parameters in calculation of conditional probability of liquefaction.
Moment magnitude, M_w	
Epicentral distance, *ED*	
Magnitude scaling factor, *MSF*	Average from Youd et al. (2001): $MSF = \frac{10^{2.84}}{M_w^{3.24}}$ Lower bound from Idriss (1995): $MSF = \frac{10^{0.99}}{M_w^{1.13}}$ Upper bound from Youd and Noble (1997): $MSF = \frac{10^{4.18}}{M_w^{4.78}}$ COV from three-sigma rule: $\mathrm{COV}\left(\lvert MSF - 1\rvert\right) = 22\%$
Stress-reduction coefficient, r_d	Average from Seed and Idriss (1971): $r_d = 1 - 0.01z$ for $z \le 10\,\mathrm{m}$, $r_d = 1.15 - 0.025z$ for $z > 10\,\mathrm{m}$ Lower bound values from Seed and Idriss (1971): $r_d = 1 - 0.015z$ for $z \le 10\,\mathrm{m}$, $r_d = 1.3 - 0.045z$ for $z > 10\,\mathrm{m}$ Upper bound values from Cetin and Seed (2001): $r_d = 1 - 0.005z$ for $z \le 10\,\mathrm{m}$, $r_d = 1.08 - 0.013z$ for $z > 10\,\mathrm{m}$ COV from Eq. (9): $\mathrm{COV}\left(1 - r_d\right) = 17\%$
	Average from Cetin and Seed (2001): $r_d = 1 - 0.0318z$; $z \le 12\,\mathrm{m}$, $r_d = 0.546 - 0.006z$ for $z > 12\,\mathrm{m}$ $-1 \cdot \sigma$ values from Cetin and Seed (2001): $r_d = 1 - 0.0485z$; $z \le 12\,\mathrm{m}$, $r_d = 0.346 - 0.006z$ for $z > 12\,\mathrm{m}$ $+1 \cdot \sigma$ values from Cetin and Seed (2001): $r_d = 1 - 0.0159z$; $z \le 12\,\mathrm{m}$, $r_d = 0.736 - 0.006z$ for $z > 12\,\mathrm{m}$ COV from Eq. (9): $COV\left(1 - r_d\right) = 51\%$
Dry and moist unit weights, γ_d and γ_m	Based on in-place density data from several USBR dams: Average value: use actual data Soil type — COV (γ_d) — COV (γ_m) GP-GW — 7-13% — 7-9% SM-SL — 5-10% — 6-12% SP-SW — 6% — 9%

The determination of the probabilistic seismic demand parameters from the USGS Seismic Hazard Web Page is based on the USGS National Seismic Hazard Map (Frankel et al. 1997). This procedure uses the peak ground acceleration (PGA), the spectral acceleration (SA) and the de-aggregation matrices provided in the USGS Geohazards web page (http://geohazards.cr.usgs.gov/eq/). The web page provides only soft rock PGA and SA which must be converted to surface acceleration $a_{\max}$ to account for local site effects. The uncertainties due to local site effects are treated separately from the uncertainties due to seismic source, magnitude and recurrence. The soft rock PGA and SA and the magnitude M_w for the design earthquake are, therefore, treated as "non-random" variables in the determination of the maximum ground surface acceleration $a_{\max}$ and the magnitude scaling factor *MSF*. Conversion of the PGA and SA data to $a_{\max}$ and the method to account for the uncertainties in local site effects are discussed below.

The seismic demand parameters $a_{\max}$ and M_w based on the procedure described below are used in Eqs. (1) and (2) in determination of the conditional probability of liquefaction. In calculating the conditional probability of liquefaction, the uncertainties in M_w due to local site effects and the uncertainties in *MSF* are included in the calculation of the standard deviation σ_F and the coefficient of variation of the factor of safety V_F in Eqs. (4) and (5). The conditional probability of liquefaction is then multiplied by the probability of exceedance (PE) corresponding to the PGA and SA values used in determining $a_{\max}$ and M_w. The USGS web page provides PGA and SA values at three periods (0.2, 0.3 and 1.0 sec) with 10%, 5% and2% probability of exceedance in 50 years (Frankel et al., 1997). These PE's correspond to return times of approximately 500, 1000 and 2500 years, and annual frequencies of exceedance of $2.1 \cdot 10^{-3}$, $1.03 \cdot 10^{-3}$ and $4.04 \cdot 10^{-4}$, respectively.

Conversion of the PGA and SA data from the USGS National Seismic Hazard Map to maximum surface acceleration $a_{\max}$ should be ideally based on site response analysis. If such analysis is not possible, a simple procedure has been recently developed at Virginia Tech to provide quick estimates of $a_{\max}$ based on local site conditions (Green, 2001). The proposed procedure is intended for use in sites where detailed seismologic information is not available, and for making preliminary estimates where such information is available. The PGA and SA, obtained by inputting a site's zip code or latitude/longitude in the USGS web page, is converted to maximum ground surface acceleration based on the observed relationship between the characteristics of the rock outcrop motions and the peak accelerations of uniform soil profiles (i.e., soil profiles having constant shear wave velocity with depth). In the simplest version of the procedure, the maximum surface acceleration $a_{\max}$ is determined from the short-period spectral acceleration $SA_{0.2}$ corresponding to 0.2 sec from the USGS Map and the NEHRP (1998) amplification factors F_a for different site classes.

$$a_{\max} = F_a pga \approx F_a \frac{SA_{0.2}}{2.5} \tag{13}$$

In this equations, $SA_{0.2}/2.5$ is taken to be approximately equal to the rock outcrop *pga* (Dobry et al., 2000). This simplified procedure is shown in Fig. 1 below. Sites B to E refer the NEHRP site classes. The sites are classified according to the average shear wave velocity, average SPT resistance or average undrained shear strength of the soil deposit. Results of Golesorkhi (1989) indicate that F_a is only dependent on the rock site characteristics and the soft rock *pga* and only to less extent to the earthquake magnitude M_w.

There is currently very little data on the variability of F_a for specific site conditions. An example of the variability of the relationship between surface and rock acceleration is given in Fig. 2, which is taken from Golesorkhi (1989). Based on the results of Golesorkhi (1989), and Idriss (1990 and 1991), a preliminary estimate of the COV for F_a is about 52.5%.

In addition to the method based on the NEHRP site classes, a more sophisticated "parabolic" procedure, which provides a range of values of a_{max} as function of the fundamental period and the impedance ratio between the soil and the bedrock, was also developed (Green, 2001). The procedure calculates equivalent uniform soil profiles corresponding to more realistic non-uniform profiles. The input to both the simplified and the "parabolic" procedures are the shear stiffness and the thickness of the soil layers. The shear stiffness can be determined from the shear wave velocity or SPT -N values. The proposed procedures can, therefore, be used to estimate the uncertainties in site amplification effects without the need for specific site response analysis.

The proposed procedure for determining earthquake magnitude M_w is not new. It is commonly used by seismologists in quantifying the mean magnitude of the seismic event that causes a ground-motion exceedance at a chosen return period. The mean magnitude M_w is obtained by de-aggregating the results from the USGS Seismic Hazard web page (McGuire and Shedlock 1981, Frankel et al. 1997). The magnitude M_w is required to estimate the magnitude scaling factor *MSF*.

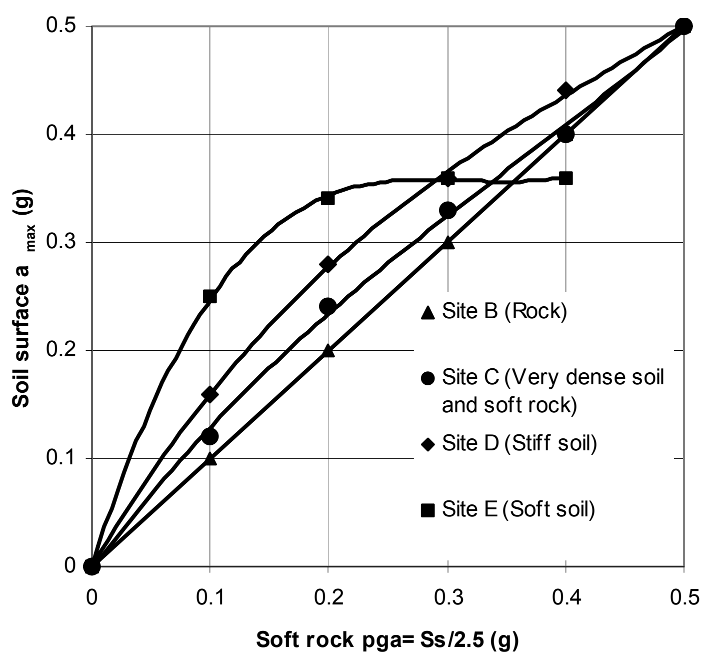

Fig. 1 - Surface a_{max} as function of soft rock PGA and NEHRP site class.

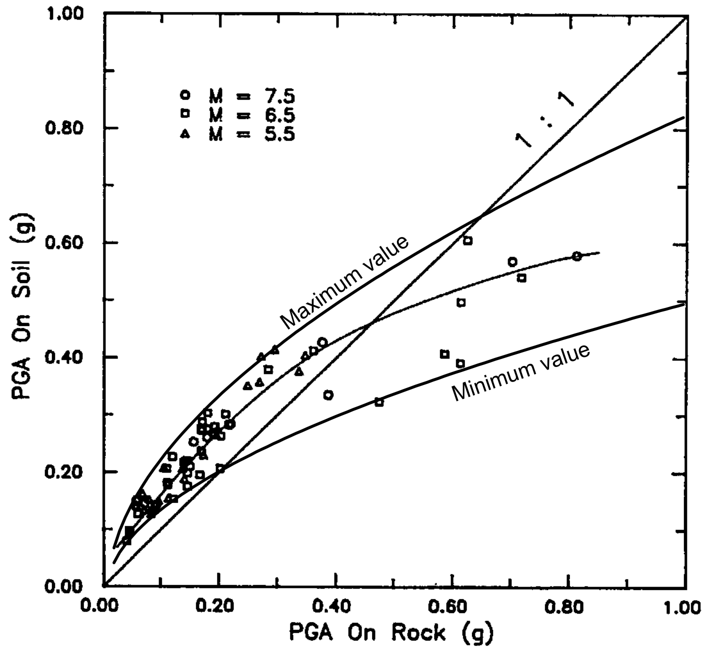

Fig. 2 – Variability in soil amplification (Golesorkhi, 1989).

COVs of CSR Parameters

The COV for the magnitude scaling factor *MSF* shown in Table 1 is determined from the range of *MSF* values suggested in the "NCEER Report." The Magnitude Scaling Factor accounts for earthquake magnitudes different from M_w=7.5. Two sets of data are used for average values and for estimates of the COVs of the stress-reduction factor r_d: 1) the original range of r_d-data presented by Seed and Idriss (1971), and 2) the results of 2073 site response analyses carried out by Cetin and Seed (2001). For both sets of data, the average and range of r_d-values vs. depth *z* are approximated by bilinear relationships. As can be seen from Table 1, the COV of $1\text{-}r_d$ based on Cetin and Seed's (2001) data is much higher than that from the COV based on Seed and Idriss (1971). The COV from Cetin and Seed's (2001) results are based on more data points. However, the results of Cetin and Seed (2001) are not yet as widely accepted as the data from Seed and Idriss (1971). The users of the method will be able to input their desired values of this and the other COVs involved in the method. The final set of data listed in Table 1 are for the dry and moist unit weight of soils γ_d and γ_m. These are needed to calculate the total and effective vertical stresses, σ_{vo} and σ'_{vo}, required in Eq. 2. The COVs for these parameters are estimated based on actual in-place density measurements from several USBR dam sites. The COVs for soil dry and moist densities are given for different soil types.

SPT-Based Liquefaction Evaluation

Due to space limitations, only the procedure for the simplified-reliability based liquefaction evaluation using SPT data will be described in this summary report, and thus the determination of *COVs* for CPT and V_s data will not be presented. The procedures for the simplified-reliability based liquefaction evaluation using CPT and V_s data will be similar to that using SPT data. The criterion for liquefaction resistance based on SPT is embodied in the CRR vs. $(N_1)_{60}$ chart obtained from liquefaction case histories where earthquake and SPT data are available. $(N_1)_{60}$ is the SPT blow count normalized to an overburden pressure of approximately 100 kPa and a hammer energy of 60%. The NCEER Report recommends the following analytical expression to calculate $CRR_{7.5}$ from $(N_1)_{60}$:

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{[10(N_1)_{60} + 45]^2} - \frac{1}{200} \quad (14)$$

This equation is valid only for $(N_1)_{60}$ <30 and clean granular sands. For sands with fines content, the $(N_1)_{60}$ needs to corrected to obtain an equivalent clean sand value, $(N_1)_{60CS}$ according to the following relation:

$$(N_1)_{60CS} = \alpha + \beta(N_1)_{60} \quad (15)$$

where α and β=are coefficients determined from the fines content, *FC*. Equations for determining α and β are given in Table 2. These equations are treated deterministically. Several other parameters affect SPT results and these parameters are applied as correction factors to $(N_1)_{60}$:

$$(N_1)_{60} = N_m C_N C_E C_B C_R C_s \quad (16)$$

Table 2 lists these parameters together with their average values and the recommended COVs for each parameter. Short descriptions of how the COVs were determined are also given. The COV for C_N is based on data collected by Castro (1995). The COVs of C_E , C_B and C_s are based on the range of values recommended in the NCEER report. The COV of the rod length correction factor C_R is based on data published by Skempton (1986).

The stress correction factor K_σ accounts for the nonlinear effects of confining stress on liquefaction resistance. The K_σ equation recommended in the NCEER report is based on Hynes and Olsen (1999) and is given as:

$$K_\sigma = \left(\frac{\sigma'_{vo}}{P_a} \right)^{f-1} \quad (17)$$

where f is dependent on the relative density D_r. To eliminate relative density and simplify the calculation of K_σ, the parameter f was directly to SPT blow count via well-known relationships between relative density and SPT resistance. The resulting relationship between f and $(N_1)_{60}$ is shown in Table 2. The parameter K_σ should be strictly considered as a correction factor to CRR, however, since the procedure for the determination of K_σ now directly uses the SPT blow count, this parameter is listed as part of the SPT-based CSR parameters. Using laboratory and compiled values of K_σ from Hynes and Olsen (1999), the COV for 1- K_σ is estimated to be about 12%.

Table 2 - Components of CRR for SPT-based liquefaction evaluation.

Parameter	Average value and estimated COV
SPT blow count, N_{SPT}	Average value: use actual data COV=15-40% (from Harr 1984 and Kulhawy 1992) Better estimates of COV are currently being developed
Percent fines, FC	Based on sieve data from several USBR Dams: Average value: use actual data COV=31.5%
α and β	Use deterministic equations from NCEER Report to calculate α and β: α=0 and β=5.0 for $FC \leq 5\%$ $\alpha = \exp\left[1.76 - \frac{190}{FC^2}\right]$ and $\beta = \left[0.99 + \frac{FC^2}{1000}\right]$ for 5%< $FC < 35\%$ α=5 and β=1.2 for $FC \geq 35\%$
Overburden correction factor, C_N	Based on data from Castro (1995): Average value: $C_N = \frac{2.2}{\left(1.2 + \sigma'_{vo} / P_a\right)}$ COV $(1 - C_N)$=23.1%
Energy correction factor, C_E	Based on data for different types of hammers in NCEER Report: Donut hammer: Average=0.75, COV=11% Safety hammer: Average=0.95, COV= 9% Automatic hammer: Average=1.05, COV= 9%
Borehole diameter correction factor, C_B	Based on data for NCEER Report: Average=1.07, COV=1%
Rod length correction factor, C_R	Based on data from Skempton (1986): Average=0.82, COV=24%
Sample correction factor, C_S	Based on data from NCEER Report: Sample with liner: Average=1.0, COV=0% Sample without lines: Average=1.2, COV= 3%
Stress correction factor, K_σ	Based on data from Olsen (1984): Average value: $K_\sigma = \left(\frac{\sigma'_{vo}}{P_a}\right)^{f-1}$; $f = 1 - 0.5\sqrt{\frac{(N_1)_{60}}{23.2\sigma'_{vo} + 32.2}}$ COV(1- K_σ)=12% Note: σ'_{vo} and $(N_1)_{60}$ are treated as deterministic parameters in the calculation of K_σ.

The COVs of the correction parameters given in Eq. (16) account for the "procedural uncertainties" related to the conduct of the SPT. In addition to these "procedural uncertainties", inherent uncertainties in SPT resistance due to variability of the properties of the soil itself must be accounted for. Initial estimates of COV for SPT blow count from tests with the same test conditions indicate values of 15-45% (Harr 1984; Kulhawy 1992). Better estimates for COV due to inherent variability in material SPT resistance are currently being studied. Since uncertainties on all parameters in the liquefaction evaluation procedures are now accounted for, the liquefaction criterion given in Eq. (14) is treated deterministically.

Example Calculation – Effect of Variability in $(N_1)_{60}$ *on Probability of Liquefaction*

Table 3 illustrates the use of the proposed procedure in estimating the factor of safety *FS* and conditional probability of liquefaction P_L. The procedure is applied to different $(N_1)_{60}$-values and assuming CSR=0.1. In this table, the uncertainties in the liquefaction evaluation have all been lumped together into the SPT resistance $(N_1)_{60}$, and it is assumed that the COV in $(N_1)_{60}$ from all sources of uncertainty is 10%. Following the procedures described above, CRR values corresponding to the best estimate of the parameter (CRR_{ave}), best estimate plus one standard deviation CRR^+, and best estimate minus one standard deviation CRR^- are calculated. Using these three estimates, the COV of CRR is calculated and from which the probability of liquefaction is determined. As can be seen, P_L generally decreases with increasing *FS* except for $(N_1)_{60}$ of 25 of higher. The increase in P_L with increasing for increasing *FS* for $(N_1)_{60} \geq 25$ is attributed to the difficulty in obtaining an accurate range in CRR values from the liquefaction criterion given in Eq. (14) for $(N_1)_{60}$ approaching 30. Procedures are being developed to improve the estimate of P_L for $(N_1)_{60}$ larger than 25.

Table 3 – Example calculations showing the factor safety and the corresponding probability of liquefaction for COV($(N_1)_{60}$)=10%, CSR=0.1 and for different values of $(N_1)_{60}$.

$(N_1)_{60}$	CRR^+	CRR^-	CRR_{ave}	COV(CRR)	*FS*	P_L
1	0.049	0.049	0.049	0.009	0.49	100.0%
5	0.076	0.068	0.072	0.103	0.72	99.9%
10	0.122	0.104	0.113	0.156	1.13	23.6%
15	0.175	0.145	0.160	0.189	1.60	0.77%
20	0.242	0.192	0.215	0.233	2.15	0.06%
25	0.353	0.249	0.292	0.355	2.92	0.17%

Summary and Discussions

A simplified reliability-based method for liquefaction evaluation was developed using Seed and Idriss (1971) "simplified procedure" for liquefaction evaluation, and the Taylor Series Reliability Method to determine the probability of liquefaction. The reliability-based method for SPT-based liquefaction evaluation was presented, but the method can also be applied to CPT and V_s-based procedures. A procedure for the determination of seismic demand using the USGS National Seismic Hazard Map was proposed. This procedure can be used in the absence of probabilistic attenuation relationships. Estimates of the Coefficients of Variation (COV) for the different parameters in the liquefaction evaluation were obtained from different sources.

The proposed procedure differs from other probabilitic procedures which treat the liquefaction criterion (Eq. 14) probabilistically. Probabilistic liquefaction criteria have been developed by Liao et al. 1988, Youd and Noble (1997), Toprak et al. 1999, and Cetin et al. 2001 based on available case histories of liquefaction. In these procedures, uncertainty in liquefaction is based on a probabilistic liquefaction criterion without regards to the different possible of sources of uncertainty and the quality of available data for the site being evaluated. In contrast, the proposed procedure treats the liquefaction criterion deterministically, but calculates the probability of liquefaction due to different sources of uncertainties in the procedure and the required parameters. The advantage of the method is that the magnitudes of the uncertainties from different components of liquefaction evaluation procedure can be clearly delineated. Another advantage is that calculation of the probability of liquefaction can be refined if COVs that are better than the estimates provided in the study are obtained.

From the estimates of the COVs of the different parameters, it can be seen that some of the major sources of uncertainties in estimating of liquefaction potential are procedural. In particular, estimates of the magnitude scaling factor *MSF* (COV= 22%), the stress-reduction factor r_d (COV=51%), and the rod-length correction factor C_R (COV=24%) provide three of the highest sources of uncertainties in determining CRR. In using the USGS Seismic Hazard Map to determine CSR, one very important source of uncertainty is the amplification factor F_a (with COV of as high as 52.5%). These COV estimates indicate the importance of further research in reducing the uncertainties in the procedural parameters in the simplified procedure.

Reports Published and to be Published

1) Woods. C. (2002), "Development of A Simplified Reliability-Based Method for Liquefaction Evaluation," project report, Virginia Tech, Blacksburg, VA (in preparation).

2) Excel Spreadsheets for Probabilistic Liquefaction Evaluation, Virginia Tech, Blacksburg, VA (in preparation).

Availability of Processed Data

All processed data are available from the PI's in hardcopy and electronic (Excel) formats. Excel programs, when completed, will also be available by contacting the P.I.s. Prof. Gutierrez can be reached at his e-mail address: magutier@vt.edu and telephone number: (540) 231-6357. Prof. Duncan can be at his address: jmd@vt.edu and telephone number: (540) 231-5013.

Acknowledgement

Assistance, valuable comments and discussions from Prof. I.M. Idriss are gratefully acknowledged.

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