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NEW PROCEDURE TO ESTIMATE LIQUEFACTION RESISTANCE FROM PENETRATION RESISTANCE USING FIELD RECORDS

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ABSTRACT

It is common practice to evaluate liquefaction potential from correlations between liquefaction resistance as determined from field performance of soil deposits during past earthquake events and in-situ penetration test results. Historically, Seed and co-workers started the correlation with SPT N values. In this approach, an extensive database of field performance was established for soil deposits which did or did not liquefy during past earthquake events. In this paper, the different factors and components required to estimate in situ liquefaction resistance are reviewed taking into consideration the recent developments of the approach (e.g. Youd et al. (2001), Seed et al. (2003) and Idriss and Boulanger (2006)). The review leads to a discussion aiming to reach the most practical basic variables that need to be considered in development of simplified empirical procedure to estimate liquefaction resistance. The well established database of field records (Cetin et al., 2000) is then used to develop a simplified empirical chart to estimate in situ liquefaction potential of relatively young normally consolidated granular (clean or nonplastic silty) level ground deposits. This newly developed chart shall serve as additional simple practical tool to aid geotechnical engineers in liquefaction analysis using SPT N values.

Keywords: Liquefaction, Penetration Resistance, Field Records

INTRODUCTION

The most common practice to evaluate liquefaction potential (initiation or triggering) is to the use correlation between liquefaction resistance as determined from field performance of soil deposits during past earthquake events and in-situ penetration test results. Historically, Seed and co-workers started the correlation with SPT N values. Such effort started with the "simplified" procedure by Seed and Idriss (1971). Using the correlation between liquefaction resistance and penetration test results relies on an extensive database of field performance for soil deposits which did or did not liquefy during past earthquake events. At each site, the layer with the lowest penetration resistance was considered to be the critical layer and the average standard penetration test blow count N value was selected as representative for that layer. The N value for that layer was corrected for in-situ testing procedure to N_{60}, which was further corrected for the influence of effective overburden pressure to $(N_1)_{60}$ using an empirical equation among the many available in the literature. The $(N_1)_{60}$ was further corrected for the influence of grain properties. The equivalent uniform cyclic stress ratio at the critical layer is estimated using the Seed and Idriss (1971) simplified equation using peak ground acceleration, total and effective overburden pressures, and mass participation reduction factor, r_d. The cyclic stress ratio is then plotted versus $(N_1)_{60}$. The line or curve separating the "did liquefy" and "did not liquefy" defines the cyclic resistance ratio or simply liquefaction resistance.

There are many studies dealing with or contributing to this approach. The involvement of these studies include a) further development of the database of field records; b) deterministic or probabilistic

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treatment of the data in the correlation; and c) introduction or modification of one or more of the components (or corrections to be discussed in the following sections) of the simplified liquefaction resistance assessment procedure. The introduced corrections (e.g. correction for influence of fines content) are either adopted or statistically regressed using the database of field records. The mentioned studies include, but may not be limited to, Seed and Idriss (1971), Seed et al. (1975), Seed (1979), Tokimatsu and Yoshimi (1983), Seed et al (1984), Jamiolkowski et al. (1985), Ambraseys (1988), Lio et al. (1988), the early study by Newmark and Hendron (Hendron, 1990), Castro (1995), Fear and McRoberts (1995), Ishihara (1993), Terzaghi et al. (1996), NCEER (1997), Cetin et al. (2000), Seed et al. (2001), Youd et al. (2001), and Idriss and Boulanger (2006).

In this paper, the different factors and components required to estimate in situ liquefaction resistance are reviewed. The review leads to a discussion aiming to conclude the most practical basic variables needed to be considered in the development of a simplified empirical procedure. The well established database of field records (Cetin et al., 2000) is then used to develop a simplified empirical chart to estimate in situ liquefaction potential of relatively young normally consolidated granular (clean or nonplastic silty) level ground deposits. This newly developed chart shall serve as an additional simple practical tool to aid geotechnical engineers in liquefaction analysis using SPT N values.

FACTORS AND COMPONENTS OF THE CURRENT EMPIRICAL APPROACH

This section provides a review of all the components of the current empirical chart(s). These components form the basic framework for the development of any correlations. These components are either regressed from the empirical data (Cetin et al., 2000) or adopted to calibrate the empirical data and therefore, to develop the empirical correlation. Basic understanding of the concept and/or theory behind the use of each component is essential during both the development of the correlation and the use of the correlation to carry out the liquefaction analysis.

The two components of K_σ and K_α are not discussed in this paper. As liquefaction analysis of level ground is the main aim of the paper, the influence of initial static shear of sloping ground or of level ground subjected to shear using the factor K_α is beyond the scope of the paper. If the liquefaction analysis needs to be carried out for a layer under relatively high effective consolidation pressure, the factor, K_σ, needs to be evaluated. The latter subject is currently under investigation and research. Therefore, the discussion in this paper is limited to relatively shallow depths at effective overburden pressure of less than 160 kPa.

Estimation of Equivalent Uniform Cyclic Stress Ratio Using Seed and Idriss Simplified Procedure

The earthquake-induced equivalent uniform seismic shear-stress ratio, CSR or $\tau(\text{seismic})/\sigma'_{vo}$, is calculated using the Seed and Idriss (1971) equation:

$$CSR = \frac{\tau(\text{seismic})}{\sigma'_{vo}} = 0.65 \frac{a_{max}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} r_d \qquad (1)$$

where a_{max} is the maximum ground surface acceleration in gals, g is the acceleration due to gravity (980 gals), σ_{vo} is the total overburden pressure and σ'_{vo} is the effective overburden pressure at depth of consideration, and r_d is a mass participation reduction factor, r_d, that takes into account the difference between theoretical rigid body and flexible body. The 0.65 is a reduction factor to convert the peak cyclic shear stress ratio to equivalent uniform cyclic stress ratio.

Mass Participation Reduction Factor

As mentioned above, the r_d reduction factor is needed in equation (1). It reflects the difference of dynamic behavior between elastic deformable ground and rigid ground. Variation of r_d with depth has been studied by various investigators. However, large discrepancies exist between the results. The r_d factor is determined by response analysis using numerical methods without field verification using actual ground motion array records measured after important earthquakes with exception of few cases (e.g. Hwang et al., 1995). The depth dependent r_d factors given by Seed and Idriss (1971) were the first in the literature. The average profile is shown in Figure (1). Other r_d factors were provided by other investigators such as Nishiyama et al. (1977), Ishihara (1977), Iwasaki et al. (1978), Imai et al. (1981), Liao and Whitman (1986a), Kingsley (1988), Maugeri et al. (1989), Idriss (1999), and Cetin and Seed (2004). The ranges or average of the profiles of some of these r_d factors with depth are shown in Figure (1).

Iwasaki et al. (1978) showed that the range of r_d factors was broad and significantly influenced by intensity and frequency content of input ground motion, soil characteristics, and soil depth. Iwasaki et al. suggested an average relation (Figure 1) that is widely used in the Japanese practice and was suggested by Terzaghi et al. (1996).

Idriss (1999) provided a set of r_d factors (Figure 1) that are dependent on both depth and earthquake magnitude, M. Cetin and Seed (2004) provided r_d factors that are function of depth, earthquake magnitude, surface ground acceleration, and shear wave velocity of the top 12 m of the deposit. Idriss and Boulanger (2006) thought that introducing so many factors may be an over complication and "implied accuracy that is not warranted at this time". Idriss and Boulanger, therefore, suggested the use of the factors by Idriss (1999). Figure (1) shows that the factors provided by both the average Seed and Idriss and those by Iwasaki et al. are conservative as compared to the factors provided by other investigators.

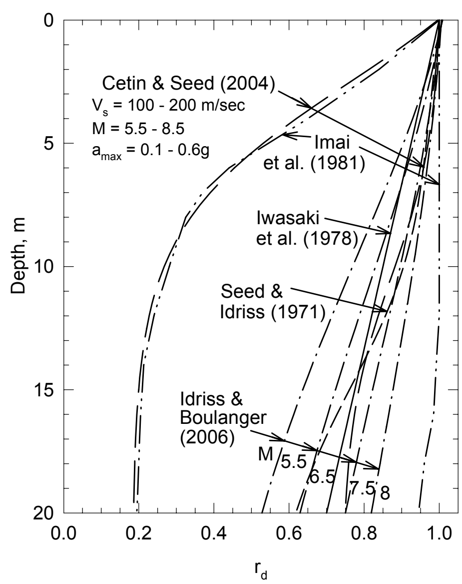

Figure 1. Profile of mass participation factor proposed by various investigators

Earthquake Magnitude Scaling Factor

The earthquake magnitude scaling factor, MSF, is used to correct CSR for the influence of duration of shaking or equivalent number of uniform stress cycles as represented by earthquake magnitude. The following equation (2) is used to convert CSR_M at any magnitude to an equivalent $CSR_{M=7.5}$ for an earthquake magnitude of 7.5.

$$CSR_{M=7.5} = \frac{CSR_M}{MSF} \quad (2)$$

The factors provided by Seed and Idriss (1982) were the first in the literature. Figure (2) shows MSF factors provided by other investigators (Tokimatsu and Yoshimi, 1983; Ambresys, 1988; Arango, 1996; Idriss, 1999; Idriss in Youd et al., 2001; and Seed et al., 2003). The relationship from Idriss (1999) as expressed in equation (3) shall be used in this paper in subsequent sections.

$$MSF = -0.085 + 6.9 \ e^{\left(\frac{-M}{4}\right)} \qquad MSF \leq 1.8 \qquad (3)$$

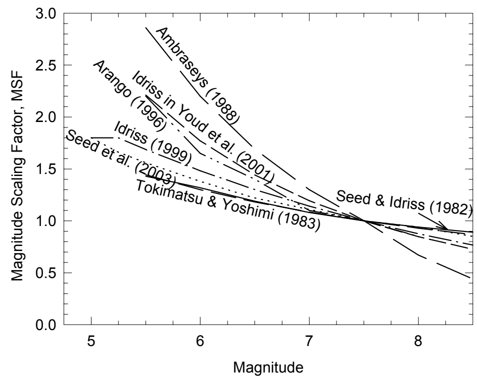

Figure 2. Values of Magnitude Scaling Factor proposed by various investigators (After Idriss and Boulanger, 2006)

Correction For SPT Procedures

The measured SPT N values need to be corrected to N_{60} for; a) short rod length, b) non-standardized sampler configuration, c) borehole diameter, and d) hammer energy efficiency. The corrections are to be done following the guidelines by Seed et al. (1985), Skempton (1986) and Youd et al. (2001).

SPT Correction for Overburden Pressure

The SPT N_{60} values are to be corrected for the effect of overburden pressure to $(N_1)_{60}$ at about 1tsf (about 100 kPa). The correction is carried out according to the following equation (4)

$$(N_1)_{60} = C_N \ N_{60} \qquad (4)$$

The factor C_N is estimated using one of the so many relationships shown in Figure (3). Idriss and Boulanger (2006) provided C_N factors that are dependent on $(N_1)_{60}$ values. In order to evaluate these factors, an iterative procedure should be used.

Fines Content Correction

The presence of fines tends to influence the liquefaction resistance versus $(N_1)_{60}$ relationship. The standard penetration test is a dynamic test. During the test, silty sands may develop excess porewater pressures that decrease the penetration resistance. Therefore, as the fines content of the sand increases, N-values decrease. Field performance data for silty sand deposits, with relatively wide range of fines content, were used to develop corrections for N-values (Tokimatsu and Yoshimi, 1983; Seed et al., 1984).It has been common practice to correct $(N_1)_{60}$ to equivalent clean sand $(N_1)_{60\text{-}CS}$ using the following expression:

$$(N_1)_{60-CS} = (N_1)_{60} + \Delta(N_1)_{60} \qquad (5)$$

where $\Delta(N_1)_{60}$ is empirically determined based on fines content, FC. Figure (4) shows the relationships in the literature to estimate $\Delta(N_1)_{60}$ using fines content.

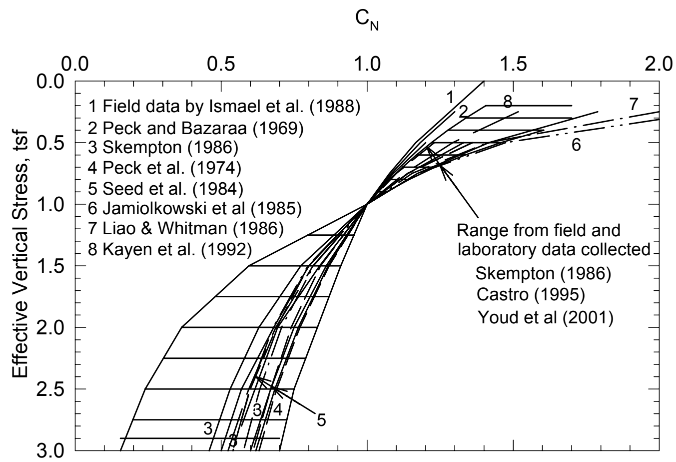

Figure 3. C_N curves from field and laboratory data and interpreted relationships by various investigators

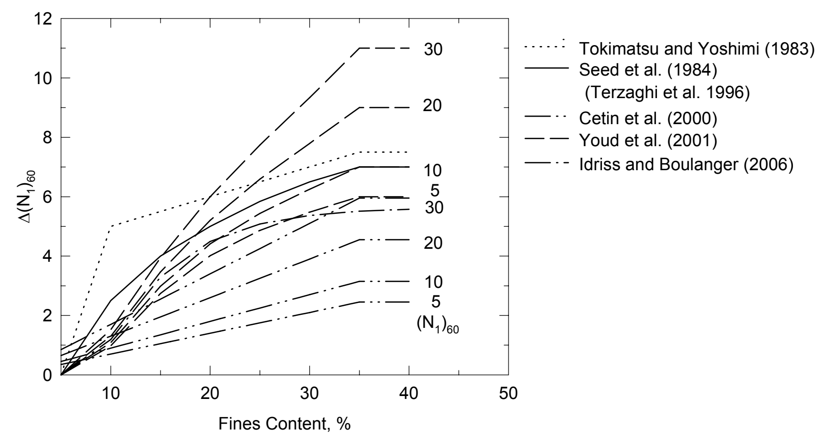

Figure 4. $\Delta(N_1)_{60}$ versus Fines Content relationships in the literature

The liquefaction resistance of silty sand deposit depends not only on fines content, but also on the nature or the plasticity of these fines. However, the focus of this paper is not on the plastic silty material.

Cyclic Resistance Ratio versus $(N_1)_{60\text{-}CS}$ Correlation

Figure (5) shows the cyclic resistance ratio, CRR, versus $(N_1)_{60\text{-}CS}$ correlations by Seed et al. (1984), Youd et al. (2001) and Idriss and Boulanger (2006). It should be noted that the curve of Seed et al. (1984) correlation passes through the origin. Most of the correlations developed after the NCEER(1997), consider the NCEER(1997) modification that the correlation curve does not pass through the origin.

PRINCIPAL PRACTICAL FACTORS THAT INFLUENCE EMPIRICAL CORRELATION: DISCUSSION

In this section, the factors that contribute to the several components overviewed in the previous section are discussed. The discussion attempts to clear and resolve any interdependence among the factors aiming to conclude the basic, practical, and non-dependent or non-redundant factors that influence the empirical correlation liquefaction resistance and in situ penetration resistance SPT N values.

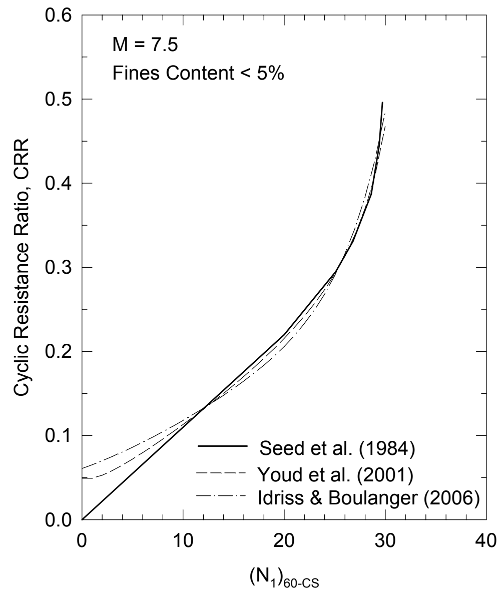

Figure 5. Available Empirical cyclic resistance ratio, CRR, versus $(N_1)_{60\text{-}CS}$ relationships

The cyclic shear stress ratio equivalent to earthquake magnitude, used to develop the empirical correlation, depends on ground surface acceleration, a_{max}, effective and total overburden pressures that are depth dependent, and mass participation factor. The later is dependent on depth (Seed and Idriss, 1971; and Iwasaki et al., 1978), and magnitude (Idriss, 1999), ground surface acceleration, and shear wave velocity of the top 12 (Cetin and Seed, 2004). The shear wave velocity depends on both density and in situ stresses.

The SPT $(N_1)_{60\text{-}CS}$ values, used in the empirical correlation or in liquefaction analysis, require; a) SPT procedure corrections that are essential; b) fines content correction that is essential, and c) correction for effective overburden pressure.

The depth is used to calculate effective overburden pressure. Both depth and effective overburden pressure are used several times to carry out liquefaction analysis; a) normalize the shear stress to calculate cyclic stress ratio, b) contribute to estimating shear wave velocity if not measured in situ, c) estimate mass reduction participation factor , and d) estimating C_N to correct N_{60} values for the effect of overburden pressure. The increase in effective pressure decreases $(N_1)_{60\text{-}CS}$, decreases the normalized cyclic stress ratio, and decreases the mass participation factor that consequently further decreases the cyclic stress ratio. Therefore, it is believed that effective overburden pressure is a fundamental factor in liquefaction resistance empirical correlation.

The interdependence of both C_N and r_d correction factors on depth or effective overburden pressure suggests the possibility of eliminating both correction factors from the empirical correlation proposed and discussed in the next section. Beside simplicity, the advantage of eliminating both correction factors from the proposed empirical correlation is to minimize the level of uncertainty associated with the possible very wide range of values of both correction factors at certain depth.

The elimination of C_N correction factor in the development of empirical correlation means the reliance on $N_{60\text{-}CS}$ instead of $(N_1)_{60\text{-}CS}$. The $N_{60\text{-}CS}$ is the SPT N values corrected for both field testing procedure and fines content.

It is believed that earthquake magnitude and maximum surface ground acceleration are raw and fundamental factors to represent the seismic event in liquefaction analysis as compared to magnitude and cyclic shear stress ratio.

DEVELOPMENT OF SIMPLE PRACTICAL EMPIRICAL CHART

The discussion in the last section is used as a base to develop a new simple practical empirical chart for liquefaction analysis. The well established database of field records by Cetin et al. (2000) is used to develop the proposed chart. Cetin et al. (2000) did not use some of the data records in the database collected by Seed et al. (1984). In this study, all the data is used in the development of the new correlation. Cetin et al. (2000) reported ranges of the parameters in the database based on possible uncertainties of the source of the data. With the exception of less than 5 to 10% of the database, the average values reported in the database is used during the course of the proposed chart development. In the less than 5 to 10 % exceptions, the values of the parameters considered in this paper are within the range of values reported by Cetin et al. (2000). The following sections show the development of the proposed chart step by step.

Maximum Surface Ground Acceleration

The maximum surface ground acceleration, a_{max}, is used in the chart instead of the cyclic stress ratio. Therefore, no need to estimate cyclic stress ratio or to estimate mass participation reduction factor with all the uncertainties associated to its calculations.

Earthquake Magnitude Scaling Factor

The earthquake magnitude scaling factor, MSF, proposed by Idriss (1999) (equation 3) is used to adjust a_{max} to maximum surface ground acceleration equivalent to earthquake magnitude, M, of 7.5, $a_{max\text{-}M=7.5}$, using the following equation:

$$a_{max-M=7.5} = \frac{a_{max-M}}{MSF} \tag{6}$$

$$MSF = -0.085 + 6.9\ e^{\left(\frac{-M}{4}\right)} \qquad\qquad MSF \le 1.8 \tag{3}$$

SPT Corrected for Testing Procedure

The SPT blow counts corrected for testing procedure, N_{60}, is used in the proposed chart. The corrected values of N_{60} reported in Cetin et al. (2000) are used in the empirical correlation.

Fines Content Correction

The fines content, FC, is used to correct N_{60} to equivalent clean sand $N_{60\text{-}CS}$ using the following expression (similar to the one provided by Youd et al. (2001)):

$$N_{60-CS} = \alpha' + \beta' N_{60} \tag{7}$$

where α' and β' to be evaluated

$$\alpha' = 0 \ \text{ for } \ FC \le 5\% \tag{8a}$$

$$\alpha' = \exp\left[1.5 - \left(\frac{150}{FC^2}\right)\right] \ \text{ for } \ 5 \prec FC \prec 35\% \tag{8b}$$

$$\alpha' = 4 \ \text{ for } \ FC \ge 35\% \tag{8c}$$

$$\beta' = 1.0 \ \text{ for } \ FC \le 5\% \tag{8d}$$

$$\beta' = \left[0.99 + \left(\frac{FC^{1.5}}{1000}\right)\right] \text{ for } 5 \prec FC \prec 35\% \tag{8e}$$

$$\beta' = 1.2 \text{ for } FC \geq 35\% \tag{8f}$$

A graphical presentation of fines content correction is shown in Figure 6.

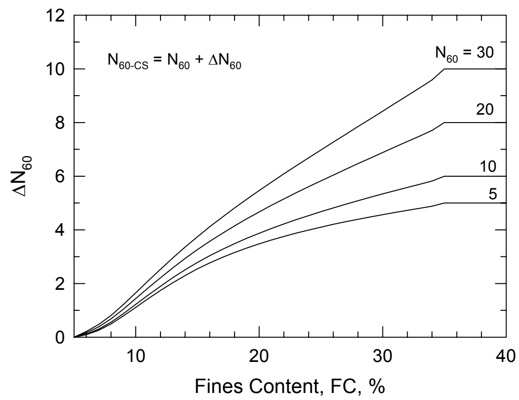

Figure 6. Graphical presentation of correcting SPT N_{60} values for fines content used to develop the proposed chart

Effective Overburden Pressure

The effective overburden pressure, σ'_{vo}, is used as a fundamental variable in the proposed empirical chart. It is not used for any correction or normalization.

The Empirical Chart

Field records database of Cetin et al. (2000) are divided to several groups, each group corresponds to a certain range of effective overburden pressure. Maximum surface ground acceleration, a_{max}, is plotted versus $N_{60\text{-}CS}$ for each group of effective overburden pressure range (Figure 7). For reference, a similar plot is prepared for all the data in the database (Figure 7). For each group, the curve separating liquefied and non-liquefied sites is drawn. All the curves in Figure (7) are used to prepare the proposed chart in Figure (8). Each curve in Figure (8) represents the relationship between resistance maximum ground surface acceleration, $a_{max\text{-}R}$, versus SPT N_{60} values for a certain effective overburden pressure, for fines content less than 5%, and for earthquake magnitude of 7.5.

USE OF THE CHART

The proposed chart (Figure 8) can be used to perform liquefaction analysis at a certain depth using the following simple procedure:

1) The effective overburden pressure, σ'_{vo}, is calculated.
2) Measured SPT N values are corrected for SPT procedure to N_{60} using the same corrections (Seed et al. 1984 and Skempton 1986) used by Cetin et al. (2000).
3) Equivalent clean sand $N_{60\text{-}CS}$ is estimated using Equations (7 and 8).
4) Resistance maximum ground surface acceleration equivalent to earthquake magnitude of 7.5, $a_{max\text{-}R\text{-}M=7.5}$, is determined from Figure (8) Using both σ'_{vo} and $N_{60\text{-}CS}$. Interpolation might be required.

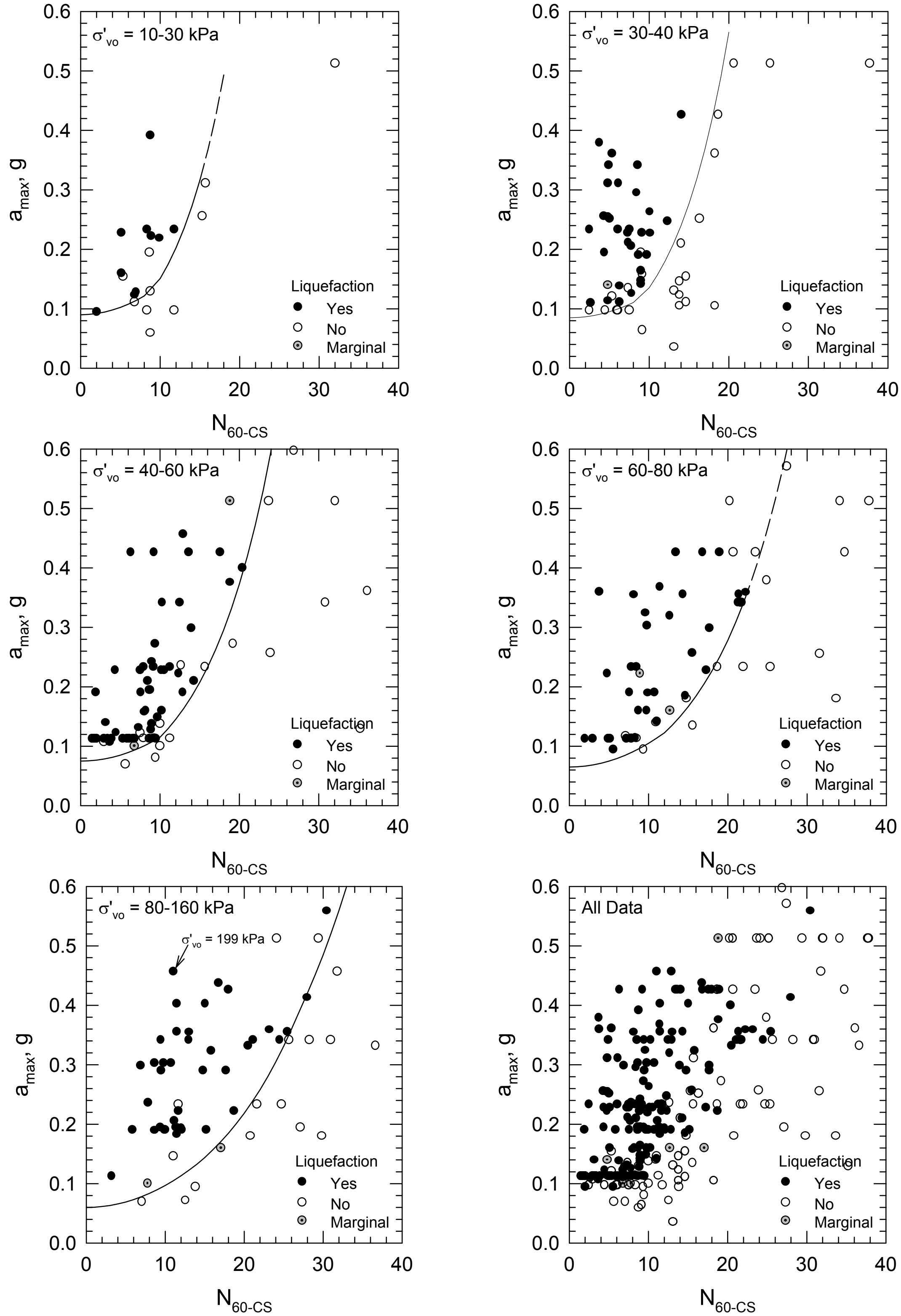

Figure 7. Empirical chart development - M=7.5

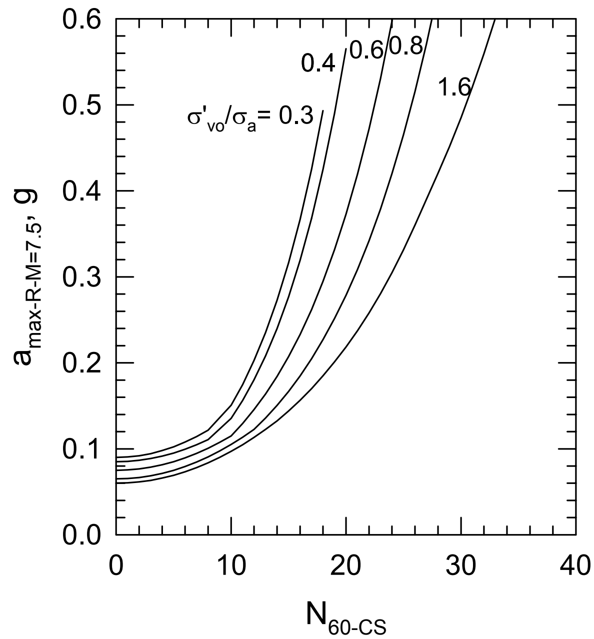

Figure 8. Proposed simple chart: Resistance maximum ground surface acceleration – Equivalent clean sand SPT N_{60-CS} – Effective overburden pressure Empirical relationship (M=7.5, FC≤5% and σ_a=100kPa)

5) Resistance maximum ground surface acceleration at earthquake magnitude M in the site under consideration, $a_{max-R-M}$, using the following equation:

$$a_{max-R-M} = a_{max-R-M=7.5} \text{ MSF} \tag{9}$$

where MSF is calculated using Equation (3).

6) Factor of safety against liquefaction, F_L, can be calculated using the following equation:

$$F_L = \frac{a_{max-R-M}}{a_{max-M}} \tag{10}$$

SUMMARY AND CONCLUSIONS

Factors and components required to estimate liquefaction potential from the correlation between liquefaction resistance as determined from field performance of soil deposits during past earthquake events and in-situ penetration test results are reviewed taking into consideration the recent developments of the approach (e.g. Youd et al. (2001), Seed et al. (2003) and Idriss and Baulanger (2006)).

The SPT $(N_1)_{60-CS}$ values, used in the empirical correlation or in liquefaction analysis, require only the essential; a) SPT procedure corrections; and b) fines content correction. The interdependence of both C_N and r_d correction factors on depth or effective overburden pressure encouraged the elimination of both correction factors from the proposed empirical correlation.

The well established database of field records (Cetin et al., 2000) is then used to develop simplified empirical chart to estimate in situ liquefaction potential of relatively young normally consolidated granular (clean or nonplastic silty) level ground deposits.

The new simple correlation (Figure 8) is a relationship between resistance maximum ground surface acceleration, a_{max-R}, versus SPT N_{60} values for various values of effective overburden pressures, for fines content less than 5%, and for earthquake magnitude of 7.5. The resistance maximum ground surface acceleration in Figure (8) is corrected to Earthquake magnitudes other than 7.5.

The newly developed chart shall serve as additional simple practical tool to aid geotechnical engineers in liquefaction analysis using SPT N values.

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