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CPT BASED LIQUEFACTION RESISTANCE OF SANDY SOILS

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ABSTRACT

Stark and Olson (1995) compiled 180 field case histories of liquefaction and non-liquefaction to develop relationships between liquefaction resistance and corrected CPT tip resistance. In developing some of these case histories, more than one elevation within a single sounding was evaluated. Herein, these case histories have been re-evaluated so that one sounding provides only one case history, reducing the original database to 80 cases. Furthermore, 92 additional case histories of liquefaction and non-liquefaction have been added to the revised database. The revised database now contains 172 independent field case histories of liquefaction and non-liquefaction, and confirms the liquefaction resistance relationships proposed by Stark and Olson (1995). This study also concludes that the procedure of utilizing more than one elevation within a single sounding for evaluating liquefaction resistance is justified. This practice is especially applicable to CPT soundings that penetrate deposits of significantly different geologic age.

INTRODUCTION

Peck (1979) indicated that because of difficulties in understanding and modeling all of the factors that affect the liquefaction resistance of a soil, in-situ penetration testing is the preferred method to estimate liquefaction resistance. In-situ penetration testing includes the cone penetration test (CPT) and the standard penetration test (SPT). The cone penetration test offers several advantages over the standard penetration test including better standardization, precision and accuracy, improved cost-effectiveness, and it provides a nearly continuous record of penetration resistance throughout a soil deposit. For these reasons, the cone penetration test has seen increasing popularity and use for liquefaction assessment. However, the SPT allows a sample to be obtained for gradation purposes and allows verification of liquefaction resistance using existing correlations.

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Recently, the number of field case histories of liquefaction and non-liquefaction where CPT results are available has increased significantly. Stark and Olson (1995) compiled 180 field case histories of liquefaction and non-liquefaction to develop relationships between liquefaction resistance and corrected CPT tip resistance. In developing some of these case histories, more than one elevation within a single sounding was evaluated. The evaluation performed by Stark and Olson (1995) was based on the zones of liquefaction estimated by the original investigators. It should be noted that in nearly every case, the CPT sounding was conducted shortly after the earthquake, and no correction was made to the CPT tip resistance to account for any possible densification effects resulting from earthquake shaking.

Herein, these case histories have been re-evaluated so that one sounding provides only one case history. This reduced the database to 80 cases. In addition, 92 case histories of liquefaction and non-liquefaction presented by Suzuki et al. (1995) and Boulanger et al. (1997) have been added to the revised database. The revised database now contains 172 field case histories of liquefaction and non-liquefaction, and confirms the liquefaction resistance relationships proposed by Stark and Olson (1995).

LIQUEFACTION RESISTANCE FROM CASE HISTORIES AND CPT

Stark and Olson (1995) presented liquefaction resistance relationships based on corrected CPT tip resistance, q_{c1}, and seismic (shear) stress ratio (SSR). Corrected CPT tip resistance is defined as:

$$q_{c1} = q_c * C_q \qquad (1)$$

where

$$C_q = \frac{1.8}{0.8 + \left(\sigma'_{vo} / \sigma'_{ref}\right)} \qquad \text{(Kayen et al. 1992)} \qquad (2)$$

$$C_q \approx C_N = \frac{1}{\left(\sigma'_{vo}\right)^{0.5}} \qquad \text{(Liao and Whitman 1985)} \qquad (3)$$

where σ'_{vo} is the vertical effective stress (and is in terms of tsf, kg/cm^2, or atmospheres for Equation 3), σ'_{ref} is a reference stress equal to one atmosphere (approximately 100 kPa), and C_q and C_N are the overburden corrections for CPT tip resistance and SPT blowcounts, respectively.

The two relationships for C_q correct values of q_c to correspond to a vertical effective overburden stress of approximately 100 kPa. Both relationships provide similar corrections for the range of stresses involved in the case histories presented herein. The correction presented by Kayen et al. (1992) was used for most of the case histories, with the exception of those where overburden information necessary to utilize the correction was unavailable. In these 56 cases, the correction reported by the original investigator(s) was used.

Values of seismic (shear) stress ratio (SSR) used in this study were estimated using the simplified procedure developed by Seed and Idriss (1971) as outlined in Stark and Olson (1995). The procedure outlined in Stark and Olson (1995) was followed for 116 of the case histories and included the earthquake magnitude correction presented by Seed and Idriss (1971) so that the additional cases are comparable to the original cases presented by Stark and Olson (1995). The exceptions to this procedure were those case histories where necessary information was unavailable. In these 56 cases, the values of SSR reported by the original investigator(s) were utilized.

Liquefaction resistance is significantly affected by the fines content of the soil. Fines content (FC) is defined as the percentage by weight passing the #200 sieve. Stark and Olson (1995) presented three relationships to account for the effect of fines content as shown in Figure 1. These boundary lines between liquefaction and non-liquefaction define relationships between the mobilized undrained yield strength ratio and q_{c1} values for sandy soils and magnitude (M) 7.5 earthquakes.

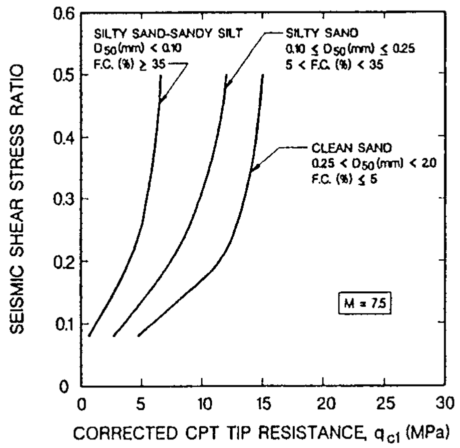

Figure 1. **CPT Based Liquefaction Resistance Relationships for Sandy Soils and M=7.5 Earthquakes (from Stark and Olson 1995)**

Liquefaction Case Histories

Liquefaction and non-liquefaction case histories compiled by Stark and Olson (1995), Suzuki et al. (1995), and Boulanger et al. (1997) are presented in this paper. The case history database is presented in Table 1. Table 1 does not include all of the columns presented in Stark and Olson (1995) due to space constraints. However, the remainder of the data for the original case histories, although not necessary for backcalculation, are presented in Stark and Olson (1995). Table 1 also does not include references for the case histories. The references for all sites, with the exception of the Moss Landing sites (Boulanger et al. 1997) and the cases reported by Suzuki et al. (1995), can be found in Stark and Olson (1995). In the revised database, each case history represents one elevation within a sounding, and only one value of q_{c1} was selected from each sounding. The clean sand case histories reported by Suzuki et al. (1995) were used directly because the information required to analyze the case histories is unavailable. Because of space constraints the clean sand cases obtained from Suzuki et al. (1995) are not included in Table 1. In addition, the silty sand case histories presented by Suzuki et al. (1995) are not included herein because information required for the proper classification of these case histories is unavailable. Boulanger et al. (1997) reported cases of liquefaction and non-liquefaction of clean and silty sands and all of these cases were included in the revised database. This study did not re-interpret the reported critical values of q_c from the cases presented by Suzuki et al. (1995) or Boulanger et al. (1997). The revised database contains 172 case histories of liquefaction and non-liquefaction of sandy soils. The original investigator(s) judged the occurrence of liquefaction at a site from the appearance of sand boils, settlement and/or damage of overlying structures, or lateral ground spreading.

The CPT field data was divided into three categories based on fines content (in percent) and median grain size, D_{50} (in millimeters). The three categories are clean sand ($FC \leq 5$ and $0.25 < D_{50} < 2.0$), silty sand ($5 < FC < 35$ and $0.10 \leq D_{50} \leq 0.25$), and silty sand to sandy silt ($FC \geq 35$ and $D_{50} < 0.10$). Fines content refers to non-plastic to low plasticity fines with a clay size fraction less than 15%, as suggested by Seed et al. (1983). Clay size fraction is defined as the percent by weight finer than 0.002 mm. Fines content was used to classify most of the case histories, and where fines content is not available, median grain size was used for classification.

Liquefaction Resistance of Clean Sands

Figure 2 presents a compilation of 105 liquefaction and non-liquefaction case histories involving clean sand for which CPT data are available. The boundary line presented by Stark and Olson (1995) for clean sand is included in Figure 2. It can be seen that the relationship presented by Stark and Olson (1995) is in good agreement with the available case histories, with only six case histories plotting below the boundary line. As noted by Stark and Olson (1995), the relationship for clean sand is limited to values of D_{50} less than 2.0 mm because: (1) liquefaction case histories in soils with D_{50} greater than 2.0 mm where CPT results are available are limited; and (2) the use of a standard cone penetrometer (ASTM D3441) in coarse sand and gravel (gravel content as low as 5%) may result in artificially large values of q_c.

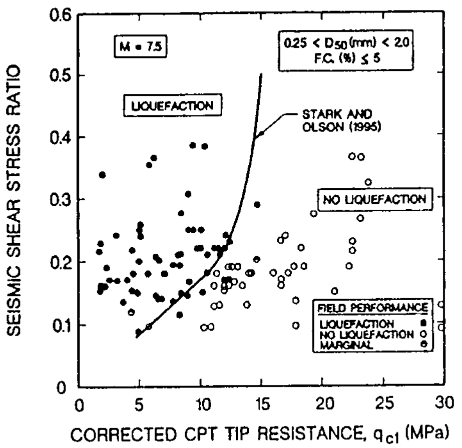

Figure 2. **Relationship between Seismic (Shear) Stress Ratio Triggering Liquefaction and q_{c1} values for Clean Sand and M=7.5 Earthquakes**

Six cases of observed liquefaction fall below the boundary line. The case with a q_{c1} value of about 8.0 MPa and an SSR of 0.14 is touching the boundary line and does not require additional consideration. The cases with q_{c1} values of 7.9, 12.2, and 15 MPa and SSRs of 0.30, 0.17, and 0.11, respectively, were obtained from Suzuki et al. (1995) and no further scrutiny of the data was possible. The case with a q_{c1} value of 12.3 MPa and an SSR of 0.17 was reported by Boulanger et al. (1997). This case involved a layer of sand that was significantly looser in its upper portion than in its lower portion. It is possible that liquefaction occurred in the upper portion first, and pore-water pressure re-distribution led to the liquefaction of the lower portion. If this were the case, the representative q_{c1} value would be lower. The case with a q_{c1} value of 10.2 MPa and an SSR of 0.15 represented a sounding that was conducted in an area that liquefied, but was very near an area of non-liquefaction. Therefore, the reported tip resistance would be on the borderline of non-liquefiable soils.

Liquefaction Resistance of Silty Sands

Figure 3 presents a compilation of 46 liquefaction and non-liquefaction case histories involving silty sand for which CPT data are available. The boundary line presented by Stark and Olson (1995) for silty sand is included in Figure 3. It can be seen that the relationship presented by Stark and Olson (1995) is in good agreement with the available case histories, and only three non-liquefaction case histories plot above the relationship. These three case histories are near the boundary, and probably represent the transition from liquefiable to nonliquefiable conditions, or the variation of parameters such as maximum ground acceleration.

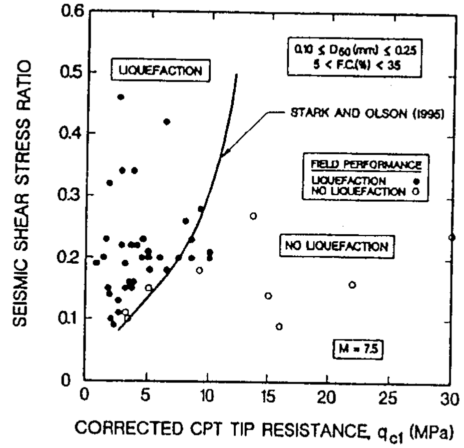

Figure 3. **Relationship between Seismic (Shear) Stress Ratio Triggering Liquefaction and q_{c1} values for Silty Sand and M=7.5 Earthquakes**

The three liquefaction case histories that plot below the boundary line were obtained from Kayen et al. (1992) and Boulanger et al. (1997) as shown in Table 1. The two cases with q_{c1} values of 10 MPa with values of SSR near 0.2 represent cases where the tip resistance and soil type changed considerably over the layer interval. Therefore, if these soils were considered clean sands, liquefaction would have been predicted correctly. The case with a q_{c1} value of 8.5 MPa and an SSR of 0.2 from Boulanger et al. (1997) represents another case where soil type variations over the layer could have affected the interpreted critical q_{c1} value. Further, Boulanger et al. (1997) reported that the maximum ground acceleration could not be determined accurately, and probably ranged from 0.2g to 0.3g, with a value of 0.25g used for interpretation.

Liquefaction Resistance of Silty Sand to Sandy Silt

Figure 4 presents a compilation of 21 liquefaction and non-liquefaction case histories involving silty sand to sandy silt for which CPT data are available. The boundary line presented by Stark and Olson (1995) for silty sand to sandy silt is included in Figure 4. It can be seen that the relationship presented by Stark and Olson (1995) is in good agreement with the available case histories.

Only one of the 21 cases where liquefaction was observed lies outside of the boundary proposed by Stark and Olson (1995). This case history corresponds to the T-25 sounding from the 1976 Tangshan Earthquake (Shibata and Teparaksa 1988). As noted by Stark and Olson (1995), the investigators reported the anomalously large q_{c1} value without explanation, and no further scrutiny was possible.

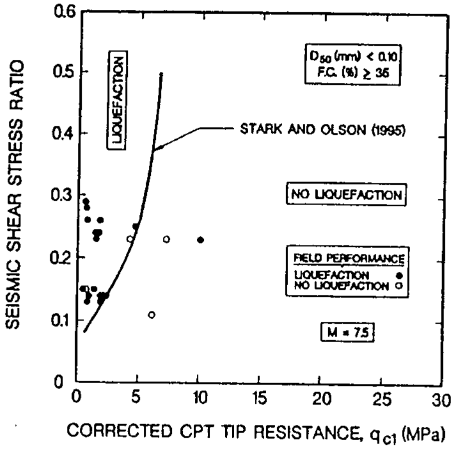

Figure 4. **Relationship between Seismic (Shear) Stress Ratio Triggering Liquefaction and q_{c1} values for Silty Sand to Sandy Silt and M=7.5 Earthquakes**

Two non-liquefaction cases plot above the Stark and Olson (1995) boundary. The case history with an SSR of approximately 0.22 plots near the boundary and probably represents the transition from liquefaction to non-liquefaction. The second case history (near SSR of 0.15) is the Middle School site from the 1975 Haicheng Earthquake. As explained by Stark and Olson (1995), the soil layer that was reported to have liquefied had a clay fraction of more than 20%. This large clay size fraction probably accounts for the low q_{c1} value. Furthermore, a soil with a clay fraction of greater than 15% is unlikely to show typical effects of liquefaction.

In summary, the revised database confirms the applicability of the relationships presented by Stark and Olson (1995) to estimate liquefaction resistance of sandy soils. This study also suggests that the use of q_{c1} values from more than one elevation within a single sounding may be justified. This is especially true for soundings that penetrate strata that are of significantly different geologic age or penetration resistance. For example, soundings at Juvenile Hall, California, described by Bennett (1989), penetrate strata of different geologic age (and significantly different penetration resistance). Bennett (1989) concluded that portions of the upper, younger stratum (with lower penetration resistances) liquefied during the 1971 San Fernando Valley Earthquake, while the lower, older stratum (with higher penetration, resistances) did not liquefy. Boulanger et al. (1997) also used data from more than one elevation (layers with significantly different q_{c1} values) within a single sounding. It is anticipated that lower-bound q_{c1} values could be obtained from both strata to define the site-specific boundary between liquefaction and non-liquefaction.

CONCLUSIONS

The use of the CPT for liquefaction resistance evaluation is becoming increasingly popular. This paper presents a revised database of 172 case histories of liquefaction and non-liquefaction where CPT data are available. The database presented herein was revised from the database presented by Stark and Olson (1995). The revised database uses only one critical value of q_{c1} from each sounding, and confirms the liquefaction resistance relationships presented by Stark and Olson (1995). This study also indicates that it may be acceptable to use more than one critical value of q_{c1} from each sounding, provided that the values of q_{c1} represent soil strata of different geologic age or significantly different penetration resistance. However, if this practice is used, there must be sufficient supporting evidence to clearly define the zones of liquefaction (such as inclinometer data or grain size analysis of surface ejecta).

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APPENDIX I. REFERENCES

Bennett, M.J. (1989). "Liquefaction analysis of the 1971 ground failure at the San Fernando Valley Juvenile Hall, California." *Bulletin of Assoc. of Eng. Geologists*, 26(2), 209-226.

Boulanger, R.W., Mejia, L.H., and Idriss, I.M. (1997). "Liquefaction at Moss Landing during Loma Prieta earthquake." *J. of Geotech. Eng.*, ASCE, 123(5), 453-467.

Kayen, R.E., Mitchell, J.K., Seed, R.B., Lodge, A., Nishio, S., and Coutinho, R. (1992). "Evaluation of SPT-, CPT-, and shear wave-based methods for liquefaction potential assessments using Loma Prieta data." *Proc., 4th Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction; NCEER-92-0019, National Center for Earthquake Engineering Research*, Buffalo, N.Y., 177-192.

Liao, S.C., and Whitman, R.V. (1985). "Overburden correction factors for SPT in sand." *J. of Geotech. Eng.*, ASCE, 112(3), 373-377.

Peck, R.B. (1979). "Liquefaction potential: science versus practice." *J. of Geotech. Eng.*, ASCE, 105(3), 393-398.

Seed, H.B. and Idriss, I.M. (1971). "Simplified procedure for evaluating liquefaction potential." *J. of Geotech. Eng.*, ASCE, 97(9), 1249-1273.

Seed, H.B., Idriss, I.M., and Arango, I. (1983). "Evaluation of liquefaction potential using field performance data." *J. of Geotech. Eng.*, ASCE, 109(3), 458-482.

Shibata, T. and Teparaksa, W. (1988). "Evaluation of liquefaction potentials of soils using cone penetration tests." *Soils and Foundations*, 28(2), 49-60.

"Standard test for deep, quasi-static, cone and friction-cone penetration test of soil — D 3441-86." (1994). *Annual book of standards; Vol. 04.08, Section 4*, ASTM, Philadelphia, PA, 338-343.

Stark, T.D. and Olson, S.M. (1995). "Liquefaction resistance using CPT and field case histories." *J. of Geotech. Eng.*, ASCE, 121(12), 856-869.

Suzuki, Y., Tokimatsu, K., Koyamada, K., Taya, Y., and Kubota, Y. (1995). "Field correlation of soil liquefaction based on CPT data." *Proc., Int. Symp. on Cone Penetration Testing (CPT '95)*, Vol. 2, Linköping, Sweden, October, 1995, 583-588.