Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 291

PROCEDURE TO EVALUATE LIQUEFACTION-INDUCED SETTLEMENT BASED ON SHEAR WAVE VELOCITY

Fred (Feng) Yi [1]

ABSTRACT

As a major geologic hazard, evaluation of liquefaction-induced settlement is very important for the design of structures. Extensive research has been performed on the calculation of liquefaction-induced settlement based on the standard penetration test (SPT) and cone penetration test (CPT) data by various researchers (Tokimatsu & Seed, 1987; Zhang et al., 2002; Idriss & Boulanger, 2008). However, few published papers can be found that address the calculation of liquefaction-induced settlement based on shear wave velocity. This paper presents a new empirical relationship between the post-liquefaction volumetric strain of clean sands and corrected shear wave velocity, $(V_{s1})_{cs}$, based upon the works of Ishihara and Yoshimine (1992) and Yoshimine et al (2006). A detailed procedure to evaluate post-liquefaction settlement is discussed. The results are compared with observed data and those results based on SPT and CPT data utilizing existing methods. This approach not only provides a new method to estimate the liquefaction-induced settlement based directly on shear wave velocity data but also provides a cost effective tool for verifying CPT data with a small cost increase to measure shear wave velocity during the standard CPT testing.

Introduction

It is well known that loose sand deposits tend to densify when subject to earthquake shaking. For saturated sand deposit, excess pore water pressure builds up during the earthquake excitation, leading to loss of strength or liquefaction. After the shaking, excess pore water pressure dissipates toward a zone where water pressure is relatively lower, usually the ground surface. The dissipation usually accompanied by a reconsolidation of the loose sand (Ishihara and Yoshimine 1992). The reconsolidation is manifested at the ground surface as vertical settlement, usually termed as liquefaction-induced settlement or seismic settlement.

Seismic settlements have been observed after nearly all major earthquakes. For example, in the 1964 Niigata earthquake, significant liquefaction-induced settlements resulted in enormous

[1]Senior Geotechnical Engineer, C.H.J. Incorporated, Colton, CA 92324

destruction of buildings and other structures all over the City of Niigata (Tokue 1976). Because of the tremendous damage to above ground structures and underground lifelines caused by seismic settlement, its evaluation and prediction becomes very important for the design and construction of structures located in areas susceptible to liquefaction. The earliest study of the behavior of soil during vibration can be traced back to the early 1950's (Mogami and Kubo 1953). Since the early 1970's, extensive research has been performed on the calculation of seismic settlement (Silver and Seed 1971; Tokimatsu and Seed 1987; Ishihara and Yoshimine 1992; Zhang et al. 2002; Idriss and Boulanger 2008). Several methods have been proposed by individuals to predict seismic settlement. Most of the currently published methods for evaluating seismic settlement are based on either the standard penetration test (SPT) (Tokimatsu and Seed 1987; Ishihara and Yoshimine 1992) or the cone penetration test (CPT) (Zhang et al. 2002; Idriss and Boulanger 2008; Yi 2009). Few published papers can be found that address the calculation of seismic settlement based on shear wave velocity (V_s, hereafter), although V_s measurement has gained common usage for exploration of subsurface soils and has been utilized in the evaluation of liquefaction potential (Andrus and Stokoe 2000), Therefore, this paper intends to present an approach for estimating liquefaction-induced settlement in saturated sand based directly on V_s. The approach includes a detailed procedure for calculating the factor of safety against liquefaction (FS_{liq}, hereafter), maximum shear strain (γ_{max}, hereafter), and post-liquefaction volumetric strain (ε_v, hereafter). The performance of the proposed method was evaluated by comparing the results with observed data and with those results calculated based on SPT and CPT data utilizing currently widely accepted methods.

Seismic Settlement of Saturated Sands

The effect of liquefaction has long been understood (Mogami and Kubo 1953) and was more thoroughly brought to the attention of engineers and seismologists in the 1964 Niigata, Japan, and Alaska earthquakes (Seed and Lee, 1966). Although the densification of sand caused by vibration was recognized in the early 1960's (Barkan 1962), it was not until the early 1970's, with the pioneer works of Silver and Seed (1971) and Lee and Albaisa (1974) that research on earthquake-induced settlement really began. Tokimatsu and Seed (1987) note that there was about a 10 year gap in the research since the original research in about 1975. The research was resumed in the mid 1980's (Tatsuoka et al., 1984; Tokimatsu and Seed, 1987). Since then, several simplified methods have been proposed for evaluating seismic settlement in saturated sands. These methods can generally be classified into two groups. The methods in the first group were developed during the 1970's and 1980's, and are generally based on the relationship between cyclic stress ratio, corrected SPT blow counts, and volumetric strain (Silver and Seed, 1971; Tokimatsu and Seed, 1987). The methods in the second group were developed in the early 1990's, with the paper by Ishihara and Yoshimine (1992) being the first publication in the category, generally based on $FS_{liq} \sim \gamma_{max} \sim \varepsilon_v$ relationships, and were modified and improved by various researchers (Zhang et al., 2002; Yoshimine et al., 2006; and Idriss and Boulanger, 2008) for application to both SPT and CPT data.

The procedure presented hereafter utilizes the following steps:

Step 1. Assess the liquefaction potential based on Andrus and Stokoe's method (Andrus and Stokoe 2000; Andrus et al. 2004).

Step 2. Calculate γ_{max} and ε_v based on the results of simple shear tests performed at the University of Tokyo (Ishihara and Yoshimine 1992; Yoshimine et al. 2006) extrapolated for the application to V_s data.
Step 3. Calculate liquefaction-induced settlement.

The related previous work and the proposed new relationships with V_s are discussed in the following sections.

Evaluation of Factor of Safety against Liquefaction

The FS_{liq} is defined as the ratio of cyclic resistance ratio (CRR_M) that will cause liquefaction of the soil to the cyclic stress ratio (CSR) developed in the soil by the earthquake.

$$FS_{liq} = CRR_M / CSR \tag{1}$$

Cyclic Stress Ratio (CSR)

In the simplified procedure (Seed and Idriss 1971), the CSR developed in the soil is calculated from a formula that incorporates ground surface acceleration, total and effective stresses in the soil at different depths (which in turn are related to the location of the ground water table), non rigidity of the soil column, and a number of simplifying assumptions. Seed and Idriss (1971) formulated the following equation for calculation of CSR.

$$CSR = \tau_{av} / \sigma_{v0}' = 0.65(a_{\max} / g)(\sigma_{v0} / \sigma_{v0}')r_d \tag{2}$$

where τ_{av} is the average equivalent uniform cyclic shear stress caused by the earthquake and is assumed to be 0.65 of the maximum induced stress, $a_{\max}$ is the peak horizontal acceleration at ground surface generated by the earthquake, g is the acceleration of gravity, σ_{v0} and σ_{v0}' are the total and effective overburden stresses, respectively, and r_d is a stress reduction coefficient. Several methods have been published by individuals for the calculation of r_d (Seed and Idriss 1971; Lao and Whitman 1986; Seed et al 2003). The expression proposed by Idriss (1999) which considers the effect of earthquake moment magnitude was used by this author for estimating an average value of r_d .

Cyclic Resistance Ratio (CRR)

Andrus and Stokoe (2000) developed a shear wave velocity based CRR curve for uncemented, Holocene-age soils with 5% or less fines at an earthquake magnitude of 7.5 as shown in Eq. 3.

$$CRR_{7.5cs} = 0.022\left[\frac{(V_{s1})_{cs}}{100}\right]^2 + 2.8\left[\frac{1}{215-(V_{s1})_{cs}} - \frac{1}{215}\right] \tag{3}$$

where subscript *cs* is the abbreviation for *clean sand* (soils with 5% or less fines), and $(V_{s1})_{cs}$ is the overburden stress-corrected shear wave velocity as defined in Eq. 4 to take into account the

influence of the state of stress in the soil.

$$(V_{s1})_{cs} = K_{cs} V_{s1} = K_{cs} V_s (p_a / \sigma_{v0}')^{0.25} \tag{4}$$

where V_{s1} is the overburden stress-corrected shear wave velocity of sandy soils, p_a is the reference stress of 100 kPa or equal to atmospheric pressure, and K_{cs} is a fines content (*FC*) correction factor. Juang et al (2002) suggested a relationship for estimating K_{cs} based on V_{s1} and *FC*. It is preferred that the measured *FC* be used for these corrections. If measured data is not available, *FC* estimated from CPT data (Yi, 2009a) can also be used.

Research indicates that other corrections, such as earthquake magnitude, overburden pressure, and static shear stress, can also be made to the *CRR* (Seed and Idriss 1982, Seed 1983, Idriss and Boulanger, 2008). For any earthquake moment magnitude *M*,

$$CRR_M = CRR_{7.5cs} (MSF) K_\sigma \tag{5}$$

where *MSF* is the magnitude scaling factor and K_σ is the overburden correction factor. Several expressions have been proposed by individuals for these corrections. The most recently published work by Idriss and Boulanger (2008) has been utilized by this author.

Magnitude Scaling Factor (MSF)

Various relationships between magnitude scaling factor and earthquake moment magnitude have been proposed (Seed and Idriss 1982; Idriss 1999). By studying the relations between the number of equivalent uniform stress cycles and earthquake magnitude, Idriss (1999) suggested the magnitude scaling factor as:

$$MSF = 6.9 \cdot \exp(-M/4) - 0.058 \le 1.8 \tag{6}$$

Overburden Correction Factor, K_σ

Laboratory cyclic triaxial compression tests show that while liquefaction resistance of a soil increases with increasing confining pressure, the resistance, as measured by the stress ratio, is a nonlinear function that decreases with increased normal stress. Seed (1983) suggested a correction factor, K_σ, to incorporate this nonlinearity for overburden pressures greater than 100 kPa. Although various expressions for an overburden correction factor have been proposed by a number of researchers, this author recommends the use of K_σ proposed by Boulanger and Idriss (2004).

$$K_\sigma = 1 - C_\sigma \ln(\sigma_{v0}' / p_a) \le 1.1 \tag{7a}$$

where the coefficient C_σ can be expressed in terms of corrected shear wave velocity.

$$C_\sigma = \frac{1}{18.9 - 3.1[(V_{s1})_{cs} / 100]^{1.976}} \le 0.3 \tag{7b}$$

Post-Liquefaction Volumetric Strain of Clean Sand

Relative Density, D_R

The initial relative density (D_R) of sand is a very important parameter affecting the cyclic response of sands and is widely used in geotechnical laboratory testing. Several relationships between relative density and SPT blow counts have been proposed in the past (Terzaghi and Peck 1967; Tokimatsu and Seed 1987; Idriss and Boulanger 2008). By studying published data (Figs. 1 and 2), Yi (2009b) proposed a relationship between D_R and $(V_{s1})_{cs}$ as expressed in Eq. 8.

$$D_R = 17.974[(V_{S1})_{cs}/100]^{1.976} \quad (\%) \tag{8}$$

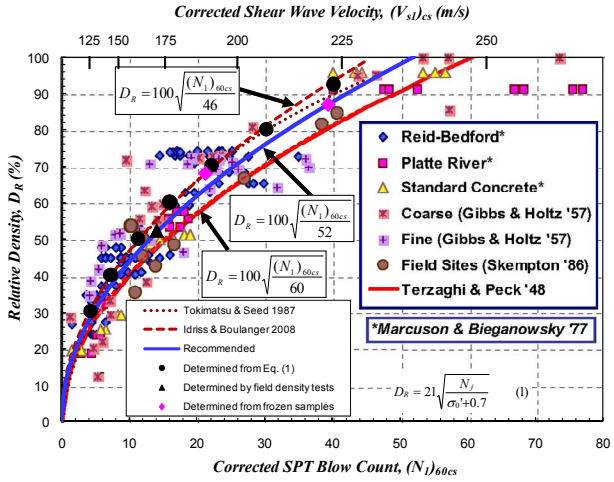

Figure 1 Relationship between relative density and corrected SPT blow counts and corrected shear wave velocity (data from Mayne et al. 2002 and Tokimatsu and Seed 1987)

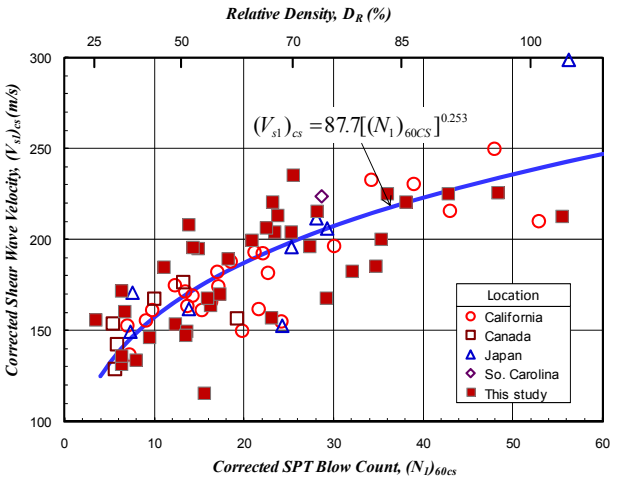

Figure 2. Relationship between corrected shear wave velocity and corrected SPT blow counts for uncemented, Holocene sands (modified from Andrus et al. 2004)

Maximum Shear Strain, γ_{max}

In the process of estimating liquefaction-induced settlement, Ishihara and Yoshimine (1992) discovered that for a given value of D_R, the smaller the factor of safety, the larger the γ_{max}. While at a given value of FS_{liq} less than unity, the larger the D_R, the smaller the γ_{max}. A set of relationships between FS_{liq} and γ_{max} was established for given values of D_R. Yoshimine et al (2006) approximated these relationships with a hyperbolic function as expressed in Eq. 9.

$$\gamma_{\max} = 0 \text{, for } FS_{liq} \geq 2 \tag{9a}$$

$$\gamma_{\max} = 0.035(2 - FS_{liq})\left((1 - F_\alpha)/(FS_{liq} - F_\alpha)\right), \text{ for } 2 > FS_{liq} \geq F_\alpha \tag{9b}$$

$$\gamma_{\max} = \infty \text{, for } FS_{liq} < F_\alpha \tag{9c}$$

where, F_α is a limiting value of FS_{liq} and can be expressed by Eq. 10.

$$F_\alpha = 0.032 + 0.836\left((V_{s1})_{cs}/100\right)^{1.976} - 0.190\left((V_{s1})_{cs}/100\right)^{3.952} \quad (10)$$

with $(V_{1s})_{cs}$ limited to values ≥ 140 (m/s).

By using Eqs. 9 and 10, the original chart by Yoshimine et al. (2006) was modified as shown in Fig. 3 to illustrate the relationship between FS_{liq} and γ_{max} for given values of $(V_{1s})_{cs}$.

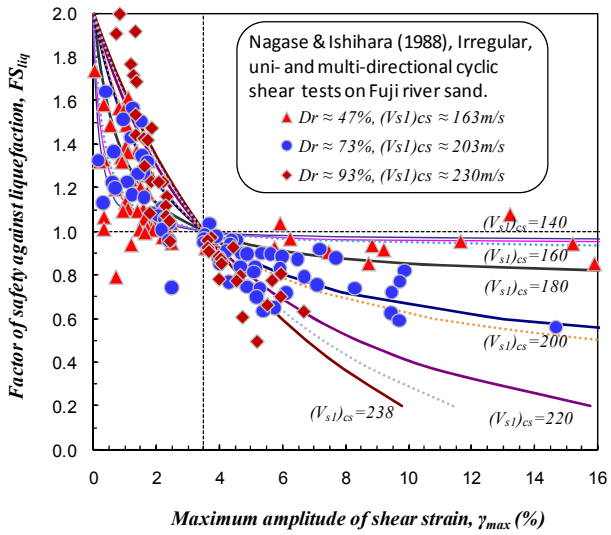

Figure 3. Relationship between FS_{liq} and γ_{max} during irregular loading (modified from Yoshimine et al. 2006, Test data from Dr. Yoshimine)

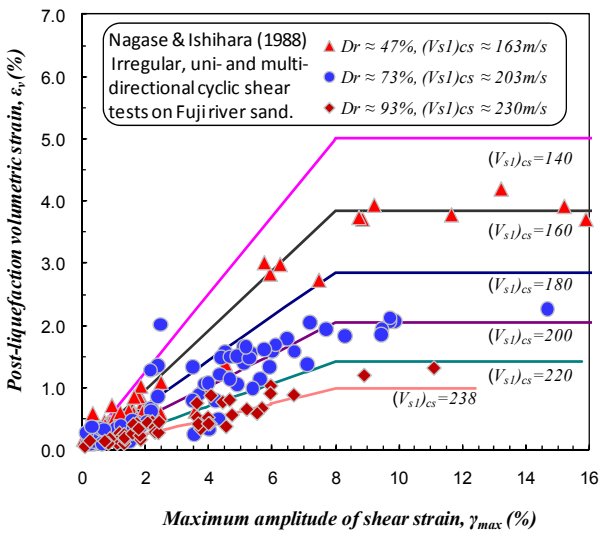

Figure 4. Relationship between ε_v and γ_{max} induced during irregular loading (modified from Yoshimine et al. 2006, Test data from Dr. Yoshimine)

Post-Liquefaction Volumetric Strain, ε_v

Ishihara and Yoshimine (1992) observed that the ε_v of clean sand that occurs during post-liquefaction reconsolidation was directly related to γ_{max} developed during undrained cyclic loading and to the initial D_R (or expressed by $(V_{1s})_{cs}$) of the sand.

$$\varepsilon_v = 1.5 \cdot \exp\left(-0.449\left((V_{s1})_{cs}/100\right)^{1.976}\right) \cdot \min(0.08, \gamma_{\max}) \quad (11)$$

For the given values of $(V_{1s})_{cs}$, the relationship between ε_v and γ_{max} induced during irregular cyclic loading is shown in Fig. 4. By coupling the results of Figs. 3 and 4, the relationship between ε_v and the FS_{liq} for different $(V_{1s})_{cs}$ can be derived as plotted in Fig. 5. Nagase and Ishihara's (1988) test results indicate that although ε_v increases with the increase of γ_{max}, it tends to converge on a limited value at given initial state (D_R or V_s). This convergency is shown in Figs. 4 and 5 and in Eq. 11 which is at a γ_{max} of 8% per Yoshimine et al. (2006). This limited volumetric strain is expressed in Eq. 12 in terms of shear wave velocity. Figure 6 illustrates the convergency of ε_v for different FS_{liq}.

$$\varepsilon_{v,\lim} = 12 \cdot \exp\left[-0.449\left((V_{s1})_{cs}/100\right)^{1.976}\right] (\%) \quad (12)$$

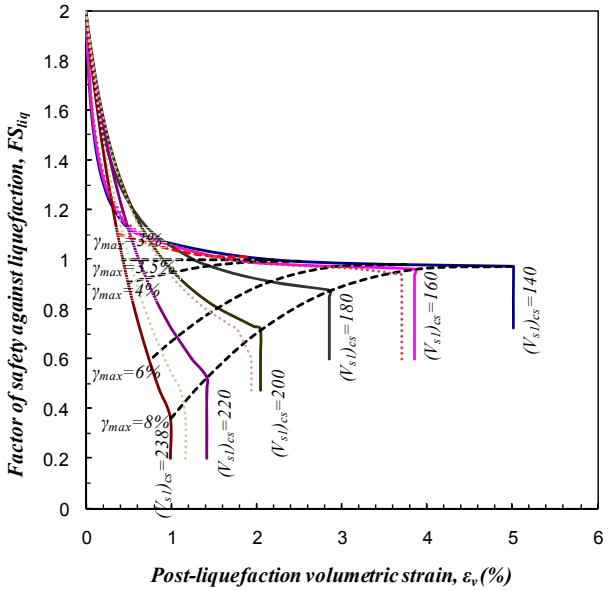

Figure 5. Relationship between FS_{liq} and ε_v of clean sand for given $(V_{1s})_{cs}$ (modified from Yoshimine et al. 2006)

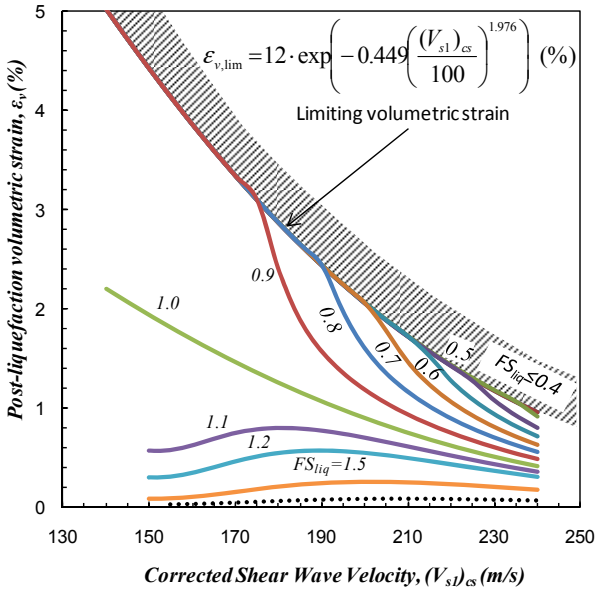

Figure 6. Relationship between ε_v and $(V_{1s})_{cs}$ for given FS_{liq} with limiting volumetric strain

Seismic Settlement of Saturated Sand

Idriss and Boulanger (2008) indicates that the ground surface settlement for one-dimensional reconsolidation can be computed by equating the vertical strains to the volumetric strains (as is appropriate for one- dimensional reconsolidation) and then integrating the vertical strains over the depth interval of concern:

$$S_{v,1D} = \int_0^{z_{\max}} \varepsilon_v \cdot dz \quad (13)$$

Example of Seismic Settlement Calculations

The 1989 Loma Prieta earthquake caused extensive liquefaction within the area of Moss Landing, located in Monterey Bay, California, approximately 21 km from the earthquake source. After the earthquake, intensive field investigations were performed by the University of California at Davis (Boulanger et al. 1995, 1997) and others, utilizing SPT borings and CPT soundings. In the UC-Davis investigation, shear wave velocities were measured using a Hogentogler piezoelectric seismic cone. The investigation report, which includes SPT and CPT logs and shear wave velocity data as well as the original CPT data files, was downloaded by this author from Professor Ross W. Boulanger's website (http://cee.engr.ucdavis.edu/faculty/boulanger/).

The entrance kiosk at the State Beach access road, where significant liquefaction-induced

settlement and lateral deformation occurred, was selected to demonstrate the calculations following the proposed procedures.

Per the investigation report of Boulanger et al. (1995), liquefaction-induced lateral spreading caused extensive damage to the State Beach access road. At the entrance kiosk, a lateral deformation of 0.3 ~ 0.6 m and a vertical settlement of up to 0.3 m were observed. One CPT sounding with shear wave velocity measurement and one SPT boring was available for this location. Based on the SPT log and laboratory test results, subsurface soils at this location generally consist of a poorly graded fine-grained sand layer with fines content of between 0 and 1% to a depth of approximately 8.4 m below the existing ground surface. These soils in turn were underlain by interlayered clay, sand, and gravelly sand.

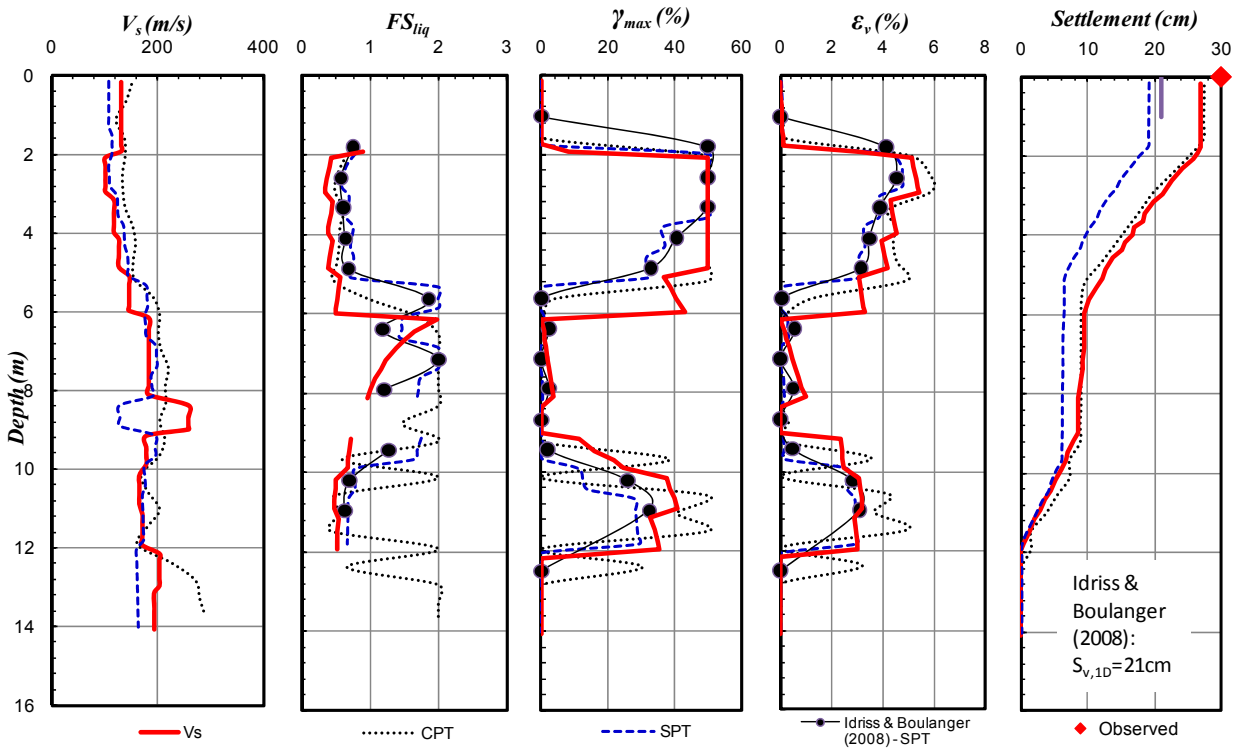

Figure 7. Sample calculation of $S_{v,1D}$ at the entrance kiosk, Moss Landing State Beach, based on V_s data, compared with CPT and SPT results as well as Idriss and Boulanger's (2008) calculation results based on SPT data (after Idriss and Boulanger 2008) and corrected shear wave velocity (a_{max}=0.25g)

The FS_{liq}, γ_{max}, ε_v, and one-dimensional seismic settlement were calculated based directly on measured V_s data following the procedures described in the previous sections. The results are plotted in Fig. 7. For comparison, calculation results based on SPT and CPT data using the equations included in the MNO-12 "Soil Liquefaction during Earthquakes" (Idriss and Boulanger, 2008) are also illustrated in Fig. 7. The measured SPT blow counts and CPT tip resistance were converted to shear wave velocity for comparison. Results calculated by Idriss and Boulanger (2008) based on the same SPT data are also plotted in the graphs. It can be seen that the results calculated based directly on V_s data are very close to the observed settlement

values and generally agree well with those calculated based on SPT and CPT data, especially with CPT data. They are also consistent with the results calculated by Idriss and Boulanger (2008).

Conclusions

A set of equations is proposed based on previous studies for calculating liquefaction-induced settlement directly utilizing shear wave velocity data. The equations have been presented in the order of the calculation sequence. The proposed method was tested by utilizing data from a site in Moss Landing where extensive surface deformations were observed after 1989 Loma Prieta earthquake. By using the proposed equations, the factor of safety, maximum shear strain, post-liquefaction volumetric strain, and one-dimensional seismic settlement were calculated based directly on measured V_s data, compared with the observed settlement as well as the results calculated based on SPT and CPT data using existing methods. The results indicate good correlation with the observed values and the results obtained by using the existing methods.

An important advantage of the proposed method is that with a small cost increase in the field investigation, this method provides a verification of the predicted results using different field investigation data. For example, rather than just performing normal CPT sounding, both CPT and V_s data can be obtained during the same operation by using seismic cone.

Acknowledgments

The author appreciates the support and help by Mr. Robert J. Johnson, PE, GE, and Mr. Allen D. Evans, PE, GE, in the preparation of this manuscript.

References

Andrus, D.A. and K.H. Stokoe, 2000. Liquefaction Resistance of Soils from Shear Wave Velocity, *J. Geot. and Geoenv. Engrg.*, 126 (11), 1015-1025

Andrus, D.A., P. Piratheepan, B.S. Ellis, J. Zhang, and C.H. Juang, 2004. Comparing liquefaction evaluation methods using penetration-V_s relationships, *Soil Dyn. and Earthquake Engrg*, 24 (9-10), 713-721

Barkan, D.D. 1962. Dynamics of Bases and Foundations. McGraw Hill Inc., New York:

Boulanger, R. W. and I. M. Idriss, 2004. State normalization of penetration resistances and the effect of overburden stress on liquefaction resistance. *Proc., 11th Int. Conf. on Soil Dyn. and Earthquake Engrg., and 3rd Int. Conf. on Earthquake Geot. Engrg.*, D. Doolin et al., eds., Stallion Press, Vol. 2, 484-491.

Boulanger, R. W., I. M. Idriss, and L. H. Mejia, 1995. Investigation and evaluation of liquefaction related ground displacements at Moss Landing during the 1989 Loma Prieta earthquake. *Report No. UCD/CGM-95/02*, Department of Civil and Environmental Engineering, UC-Davis

Idriss, I.M. 1999. An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential", in *Proceedings, TRB Workshop on New Approaches to Liquefaction*, *FHWA-RD-99-165*, *FHWA*, Washington, D.C.

Idriss, I. M., and R. W. Boulanger, 2008. *Soil Liquefaction during Earthquake*, Earthquake Engineering

Research Institute, EERI Publication MNO-12.

Ishihara, K., and M. Yoshimine, 1992. Evaluation of settlements in sand deposits following liquefaction during earthquakes, *Soils and Foundations* 32(1), 173–188.

Juang, C.H., T. Jiang, and R.D. Andrus, 2002. Assessing probability-based methods for liquefaction potential evaluation, *J. Geot. and Geoenv. Engrg.*, 128(7), 580-589.

Lee, K.L. and A. Albaisa, 1974. Earthquake-induced settlement in saturated sand, *J. Soil Mech. and Found. Div.*, 100 (4), 387-400.

Liao, S. C. and R. V. Whitman, 1986, Overburden correction factors for SPT in sand, *J. Geot. Engrg.*, ASCE, 112 (3), 373-377.

Mayne, P.W., B. Christopher, R. Berg, and J. DeJong, 2002. Subsurface investigations - geotechnical site characteriza-tion, *FHWA-NHI-01-031, FHWA*, Washington, D.C., 301 pages.

Nagase, H. and K. Ishihara, 1988. Liquefaction-induced compaction and settlement of sand during earthquakes, *Soils and Foundations*, 28 (1), 66-76.

Mogami, T., and K. Kubo, 1953. The behavior of soil during vibration, *Proc. 3rd Inter. Conf. on Soil Mech. And Found. Engrg.*, Vol 1, 152-155

Seed, H.B. 1983. Earthquake Resistance Design of Earth Dams, *Symposium on Seismic Design of Earth Dams and caverns*, ASCE, New York, 41-64.

Seed, H.B. and K.L. Lee, 1966. Liquefaction of saturated sands during cyclic loading, *J. Soil Mech. and Found. Div.*, 92 (6), 105-134

Seed, H.B., and I.M. Idriss, 1971. Simplified procedure fore valuating soil liquefaction potential, *J. Soil Mech. and Found. Div.*, 97 (9), 1249–273.

Seed, H.B., and I.M. Idriss, 1982. Ground motions and soil liquefaction during earthquake, *Earthquake Engineering Research Institute*, Oakland, CA, 134 pages.

Silver, M. L., and Seed, H. B., 1971. Volume changes in sand during cyclic loading, *J. Soil Mech. and Found. Div.*, 97 (9), 1171–182.

Tatsuoka, F., T. Sasaki, and S. Yamada, (1984). Settlement in saturated sand induced by cyclic undrained simple shear, *Proc., 8th Word Conf. Earthq. Engrg.*, San Francisco, CA, 95-102.

Terzaghi, K. and R. B. Peck, 1967. *Soil Mechanics in Engineering Practice*, 2nd edn., John Wiley, NY.

Tokue, T., 1976. Characteristics and mechanism of vibratory densification of sand and role of acceleration, *Soils and Foundations*, 16 (3), 1-18

Tokimatsu, K. and H.B. Seed, 1987. Evaluation of settlements in sands due to earthquake shaking, *J. Geot. Engrg.*, 113 (8), 861-878.

Yi, F. 2009a, Case Study of CPT Application to Evaluate Seismic Settlement in Dry Sand, Manuscript submitted to *The 2nd International Symposium on Cone Penetration Testing*, Huntington Beach, California, USA, May 9-11, 2010.

Yi, F., 2009b, Procedure to Evaluate Seismic Settlement in Dry Sand Based on Shear Wave Velocity, Manuscript submitted to *The 9th U.S. National and 10th Canadian Conference on Earthquake Engineering (9USN/10CCEE)*, Toronto, Canada, July 25-29, 2010.

Yoshimine, M., H. Nishizaki, K. Amano, and Y. Hosono, 2006. Flow deformation of liquefied sand under constant shear load and its application to analysis of flow slide of infinite slope, *Soil Dyn. and Earthquake Engrg.*, 26 (2-4), 253-264.

Zhang, G., P. K., Robertson, and R. W. I. Brachman, 2002. Estimating liquefaction-induced ground settlements from CPT for level ground, *Canadian Geot. J.*, Ottawa, 39: 1168-1180