EARTHQUAKE-INDUCED SETTLEMENTS IN SATURATED SANDY SOILS

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ABSTRACT

A simplified approach is proposed to estimate the earthquake-induced settlements in saturated sandy soils. The simplified approach consists of a set of equations that can be used to estimate directly the settlements of a saturated sandy soil layer subjected to earthquake loading. The proposed approach is based on Tokimatsu and Seed (1987) procedure, but does not require the use of charts, tables and diagrams and hence it can be conveniently implemented numerically and allows the expeditious analysis of complicated soil profiles. It is particularly useful for sensitivity analyses and for analyzing soil profile with multiple layers. The proposed approach may be able to characterize the liquefaction boundary line that separates liquefaction from non-liquefaction regions. The proposed approach has been used to predict the settlements observed at two sites subjected to different magnitude of earthquakes. The settlement predictions by the proposed method are in reasonably good agreement with those computed by other published approaches and field measurements.

Keywords: earthquake, sandy soil, SPT, volumetric strain, settlement.

INTRODUCTION

The tendency of sands to densify when subjected to earthquake loading is well established. The post-earthquake densification of saturated sand is influenced by the grain size and relative density of the sand, the maximum shear strain induced in the sand, and the amount of excess pore pressure generated by the earthquake. The dissipation of excess pore pressure induces consolidation settlement of the ground (Lee and Albaisa 1974).

A number of procedures have been presented in the literature in the past 20 years to study the earthquake-induced settlement problem and they can vary from relatively complex non-linear dynamic computer models (e.g. DESRA or TARA3FL) to simplified procedures that estimate the consolidation settlement from volumetric strain based on the cyclic stress ratio and normalized SPT-N value. Tokimatsu and Seed (1987) reviewed available procedures and recognized that the primary factors controlling earthquake-induced settlement are the cyclic stress ratio with pore pressure generation, together with the corrected SPT-N value, and earthquake magnitude. Using a correlation between the normalized SPT-N value and relative density and an estimate of the shear strain potential of liquefied soil from the normalized SPT-N and cyclic stress ratio (Seed *et. al*, 1984), Tokimatsu and Seed (1987) developed a chart that allows the volumetric strain after liquefaction in a magnitude of 7.5 earthquake to be estimated directly from the cyclic stress ratio and normalized SPT-N value. Alternatively, Ishihara and Yoshimine (1992) developed a graphic representation to evaluate the post-liquefaction volumetric strain as a function of factor of safety against liquefaction, maximum shear strain and relative density.

The approach developed by Tokimatsu and Seed (1987) is well known and widely used in practice. Although their approach is simple, it often requires the use of charts, tables or diagrams. The approach may be particularly time-consuming when estimations are required at sites having multiple layers of soil with different properties. In this paper, a simplified and practical approach is proposed to estimate the earthquake-induced settlements in saturated sandy soils. The simplified approach consists of a set of equations that can be used to estimate directly the settlements of a saturated sandy soil layer subjected to earthquake loading. The proposed approach is based on Tokimatsu and Seed (1987) procedure, but does not require the use of charts, tables and diagrams and hence it can be conveniently implemented numerically and allows the expeditious analysis of complicated soil profiles. It is particularly useful for sensitivity analyses and for analyzing soil profile with multiple layers. The proposed approach may be able to characterize the liquefaction boundary line that separates liquefaction from non-liquefaction regions. The proposed approach has been used to predict the settlements observed at two sites subjected to different magnitude of earthquakes. The settlement predictions by the proposed approach are in reasonably good agreement with those computed by other published approaches and field measurements.

METHOD OF ANALYSIS

Cyclic Stress Ratio (CSR)

The cyclic stress ratio, CSR, is given by (Seed *et al.*, 1985):

$$CSR_{7.5} = 0.65\left(\frac{\sigma_v}{\sigma_v'}\right)\left(\frac{a_{\max}}{g}\right)(r_d)/\,MSF \qquad (1)$$

Where

$CSR_{7.5}$ = cyclic stress ratio with reference to earthquake magnitude of 7.5;

σ_v = total overburden pressure at the depth considered;

σ_v'= effective overburden pressure at the same depth;

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a_{max} = maximum horizontal acceleration at the ground surface;
g = acceleration due to earth's gravity;
r_d = stress reduction factor; and
MSF = magnitude scaling factor.

Volumetric strain after liquefaction

Excess pore water pressure may be build up when saturated sandy ground is subjected to a sequence of cyclic shear stresses induced by earthquake loading. The dissipation of that excess pore pressure results in reconsolidation volumetric strain (Lee and Albaisa, 1974). The amount of reconsolidation volumetric strain increases with decreasing density of soils, and increases with increasing maximum shear strain developed in the deposit, but is independent of vertical effective stress (Tatsuoka *et al.*, 1984).

Among the various field tests, Standard Penetration Test (SPT) is commonly preferred because of the difficulty and expense associated with obtaining undisturded field samples of sandy soils. In addition, the more extensive databases of sites which have experienced obvious liquefaction, as well as those where no apparent liquefaction occurred have been evaluated for a number of seismic events and related to the Standard Penetration Tests (SPT). The criteria for evaluation of liquefaction behaviour based on SPT appear to be rather robust over the years.

Tokimatsu and Seed (1987) reviewed available procedures and developed an empirical chart that allows the estimate of earthquake-induced volumetric strains in saturated sands based on cyclic stress ratio and normalized SPT values.

Based on these findings, the volumetric strains due to soil liquefaction during an earthquake magnitude of 7.5 may be approximated by the equation:

$$\varepsilon_v = 10\left[(N_1)_{60}\right]^{-0.6} \quad \text{for} \quad \left(\frac{CSR}{(N_1)_{60}}\right) > 0.01 \qquad (2)$$

Where ε_v = volumetric strain and $(N_1)_{60}$ = SPT-N value normalized to an effective overburden of 1 tsf (95.76 kPa) and to an effective energy of 60% of the free-fall energy.

Figure-1 illustrates a liquefaction boundary line and a set of simplified volumetric strain lines defined by equation (2). Also plotted and presented in Figure-1 are measured results from case history information. The computed volumetric strain lines appear to be generally consistent with the measured field cases. It is observed that the data points fall below the liquefaction boundary line are not likely to experience liquefaction behaviour. Hence it may provide a simple way to explore the level of risk of liquefaction based on the cyclic stress and SPT values. However, this observation may or may not be valid in cases other than those in the data set analyzed since the simplified volumetric strain lines are drawn based on limited data points. It is interesting that the simplified volumetric strain lines defined by equation (2) are quite similar with the volumetric strain curves proposed by Tokimatsu and Seed (1987) chart.

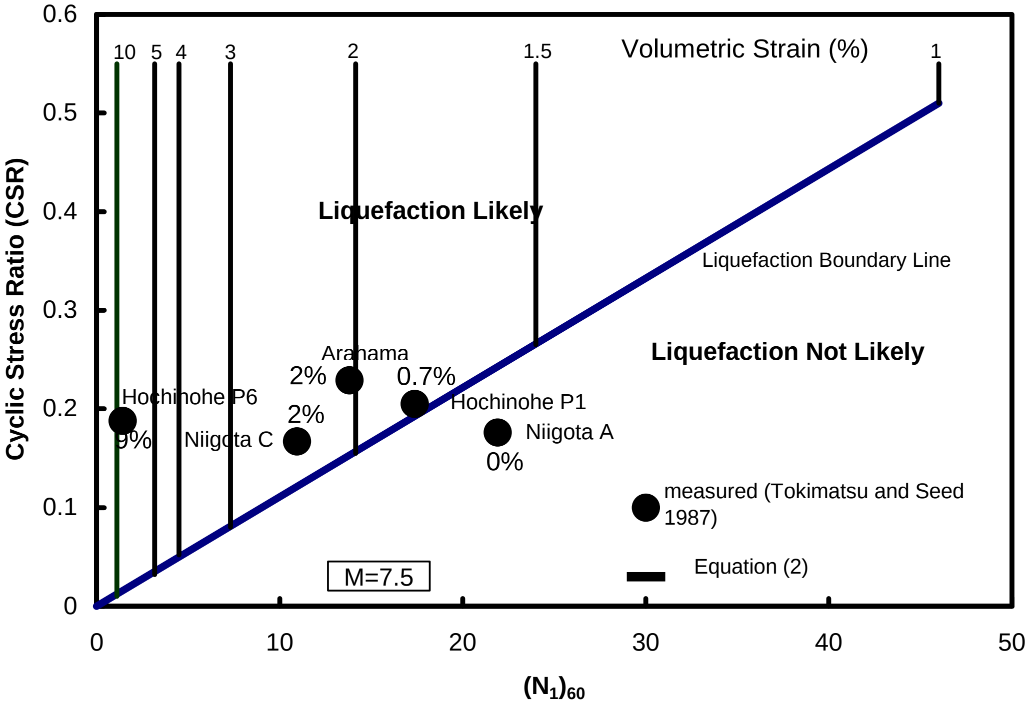

Figure-1. Relationship between cyclic stress ratio, $(N_1)_{60}$, and volumetric strain for saturated sands.

Figure-2 shows the volumetric strains (ε_v) versus $(N_1)_{60}$ computed by equation (2). The computed values agree reasonably well with those suggested by Tokimatsu and Seed (1987). However, equation (2) appears to compute higher volumetric strains than those suggested by Tokimatsu and Seed (1987) at $(N_1)_{60}$ value in excess of 30. Nevertheless, the magnitude of the volumetric strain occurs at $(N_1)_{60}$ greater than 30 may be insignificant.

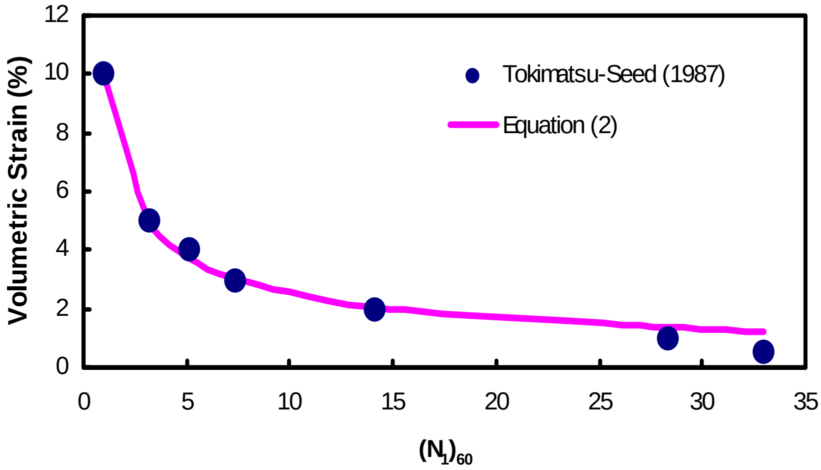

Figure-2. Relationship between volumetric strain and $(N_1)_{60}$.

Magnitude scaling factors (MSF)

The magnitude scaling factors (MSF) have been revised by some researchers (e.g. Arango 1996, Andrus and Stokoe 1997, Youd and Noble 1997, and Idriss 1999). However, the scaling factors suggested by Tokimatsu and Seed (1987) for saturated sands are employed here for the comparison with procedures available in the literature which used the similar scaling factors.

The magnitude scaling factors (MSF) based on the data obtained by Tokimatsu and Seed (1987) may be approximated by the equation:

$$MSF = 2.5 - 0.2M \tag{3}$$

Where M = magnitude of earthquake.

The magnitude scaling factors (MSF) computed by using equation (3) and those tabulated by Tokimatsu and Seed (1987) are in reasonable good agreement as shown in Figure-3.

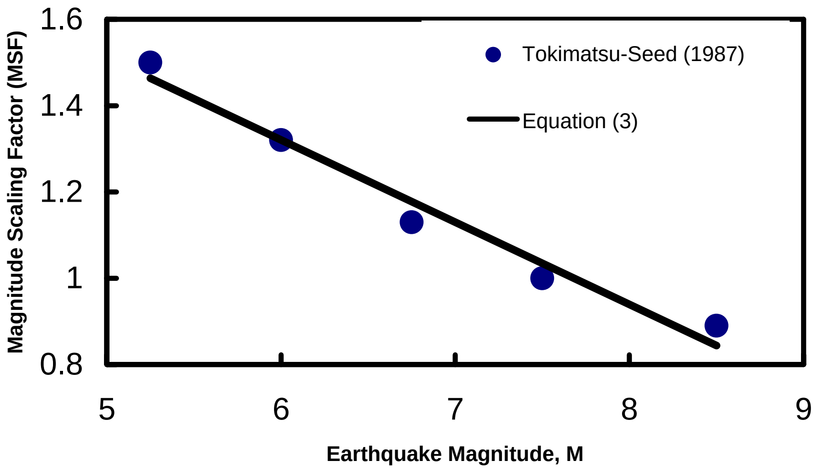

Figure-3. Relationship between magnitude scaling factor and M.

The total settlement, S, for sandy soil is given by:

$$S = \sum_{i=1}^{n} H_i \varepsilon_{vi} \tag{4}$$

Where H_i = thickness for layer i;
ε_{vi} = volumetric strain for layer i; and
n = number of soil layers.

COMPARISON OF RESULTS

Tokachi-Oki earthquake-site P6 Hachinohe, Japan (1968)

The site P6 at Hachinohe in Japan consists of saturated sand deposit that is extremely loose to a depth of about 6m. The detailed description of the subsurface conditions is described by Ohsaki (1970). The maximum acceleration of 0.2g was measured in vicinity of the site P6

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site and M = 7.9. Figure-4 shows the typical $(N_1)_{60}$ distribution with depth for the site P6 at Hachinohe (Ohsaki, 1970 and Tokimatsu and Seed, 1987).

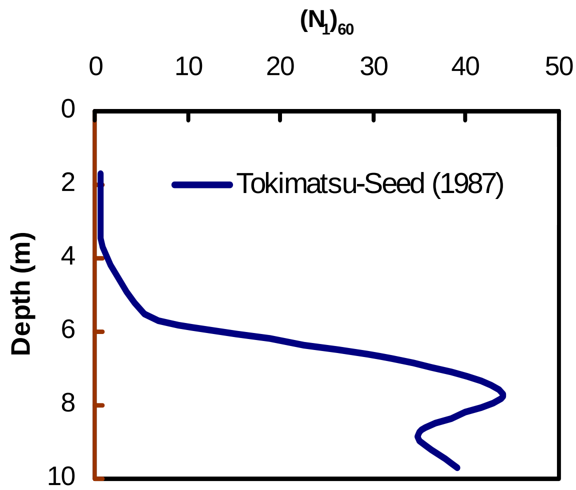

Figure-4. Distribution of $(N_1)_{60}$ with depth.

Figure-5 illustrates the computed cyclic stress (CSR) ratio versus depth using equation (1). The computed cyclic stress ratio (CSR) tends to increase with depth to a depth of about 7m and remain at almost a constant value of 0.225 for larger depths.

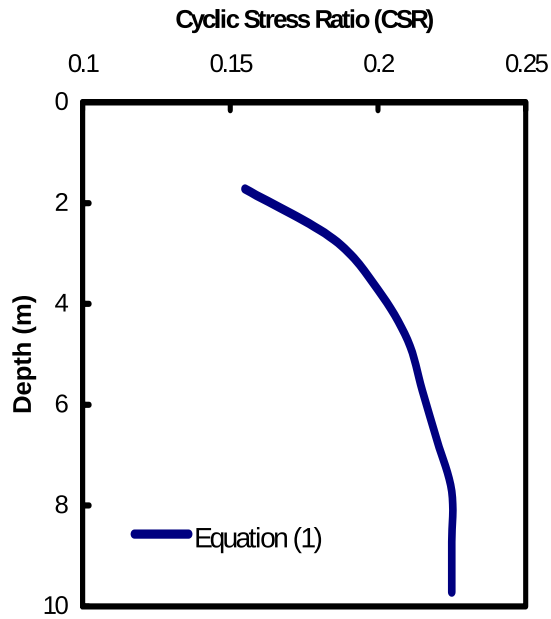

Figure-5. Computed distribution of CSR with depth.

The volumetric strains predicted by Tokimatsu-Seed and the present approaches are shown in Figure-6. The present approach computes slightly higher volumetric strain than Tokimatsu-Seed approach at the depths of 2-4m. Both approaches predict similar volumetric strains at larger depths.

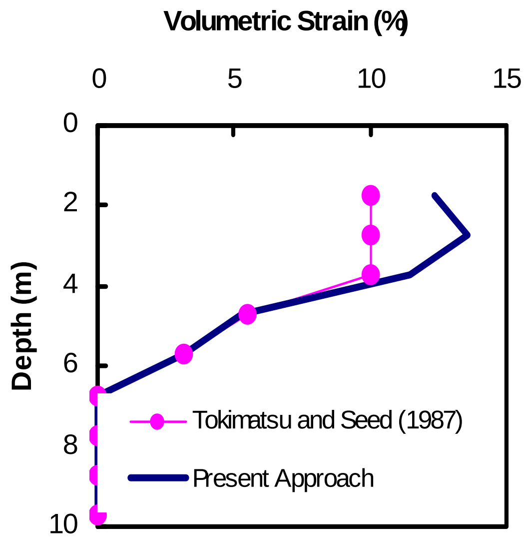

Figure-6. Comparison of computed distributions of volumetric strain with depth.

Figure-7 shows the settlement variation with depth curves predicted by Tokimatsu-Seed and present approaches. As the result of the larger volumetric strains predicted by the present approach at 2-4m depths, it is expected that the corresponding settlements computed by the present approach to be larger than those computed by Tokimatsu-Seed approach. However at depth greater than 4m both approaches predict similar settlements.

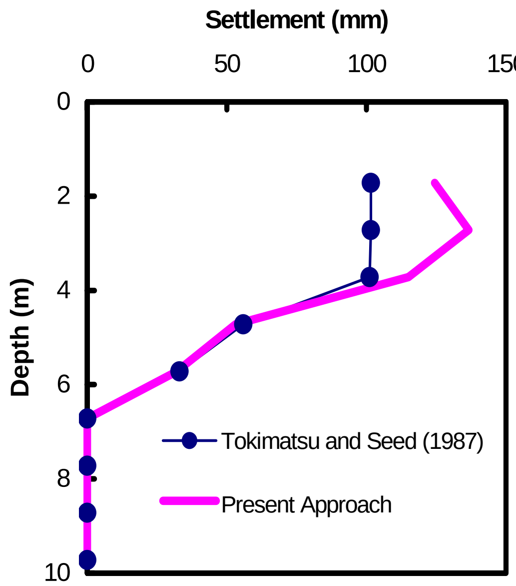

Figure-7. Computed distributions of settlement with depth.

The total settlements predicted by Tokimatsu-Seed and present approaches are compared with the measured post-earthquake settlement at this site as shown in Figure-8. It appears that Tokimatsu-Seed approach (Tokimatsu and Seed 1987) tends to underestimate the settlement by about 11% and the predicted settlement by the present approach

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is closer to the measured settlement. However, both of the approaches provide an acceptable design prediction.

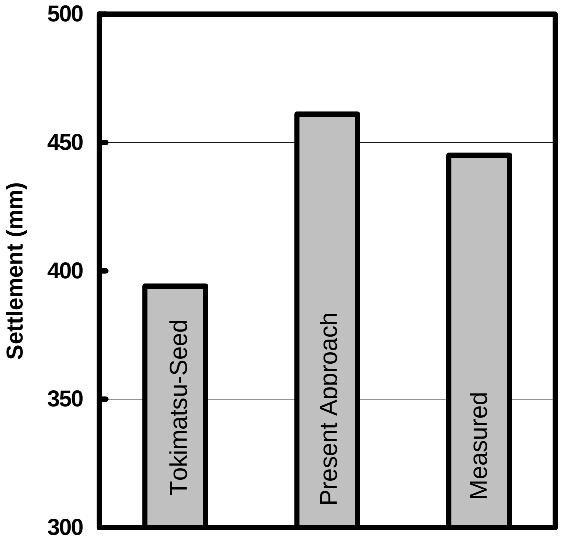

Figure-8. Comparison of computed and measured settlements.

Loma Prieta earthquake, San Francisco (1989)

During the 1989 Loma Prieta earthquake, significant ground settlement was observed in the Marina District of San Francisco. It was found that most of this settlement was resulted from densification of hydraulic fills that were placed to reclaim the area from San Francisco Bay in the 1890s. The site consisted of about 2m of top fill overlay by 6m of loose sandy fill. A layer of recent bay mud extends from depth of 8m to 30m. The water table is located at about 2m below the ground surface. A maximum acceleration of 0.2g was measured in the vicinity of the Marina District. Figure-9 shows the $(N_1)_{60}$ distribution with depth for the Marina District site (O'Rourke *et al.*, 1991 and Kramer, 1996).

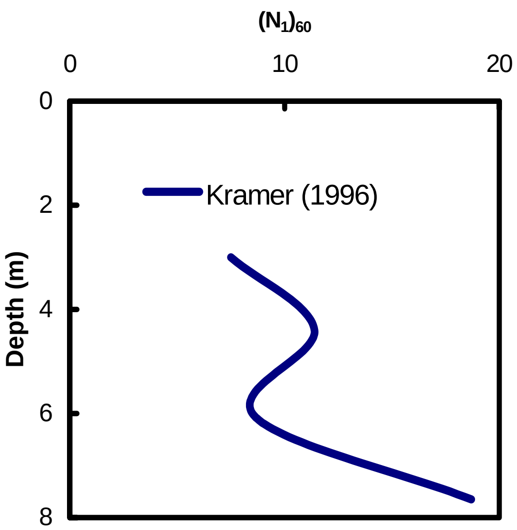

Figure-9. Distribution of $(N_1)_{60}$ with depth.

Figure-10 illustrates the computed cyclic stress ratio (CSR) versus depth using equation (1). The computed cyclic stress ratio (CSR) tends to increase with depth.

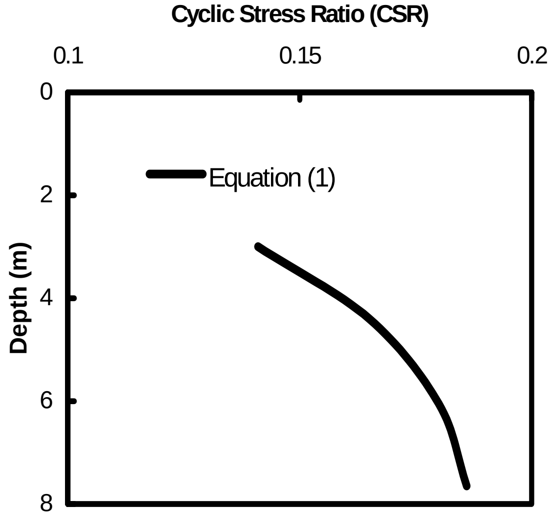

Figure-10. Computed distribution of CSR with depth.

The volumetric strain predicted by Tokimatsu-Seed, Ishihara-Yoshimine (1992) and the present approaches are shown in Figure-11. The Ishihara-Yoshimine approach computes higher volumetric strain than the Tokimatsu-Seed and present approaches with the exception from the depth greater than 7m where a larger volumetric strain is predicted by the present approach. This is because the present approach tends to overestimate slightly the volumetric strain at larger $(N_1)_{60}$ using equation (2).

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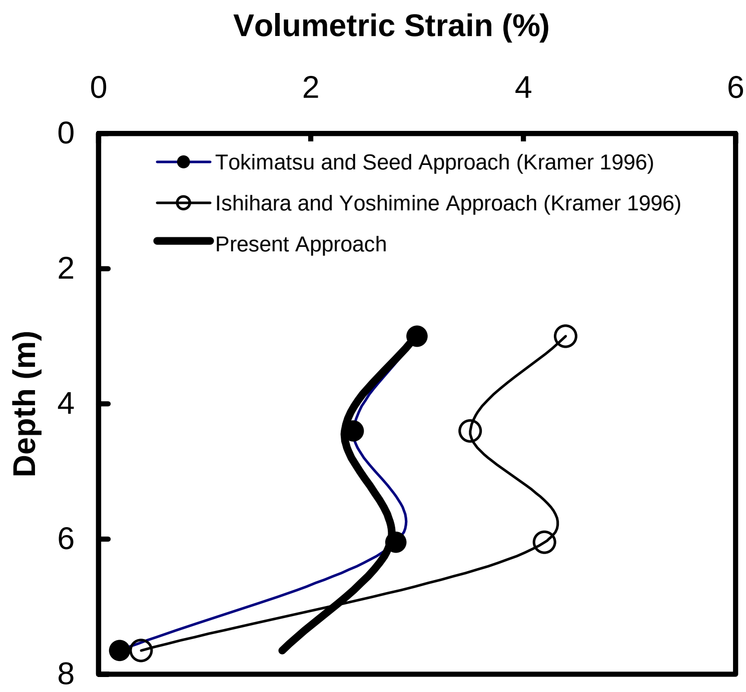

Figure-11. Comparison of computed distributions of volumetric strain with depth.

Figure-12 shows the settlement variation with depth curves predicted by Tokimatsu-Seed, Ishihara-Yoshimine and present approaches. The Ishihara-Yoshimine approach predicts higher settlement than those by Tokimatsu-Seed and present approaches. As expected, the present approach computes larger settlements at the depth greater than 7m due to the larger volumetric strains computed shown in Figure-11.

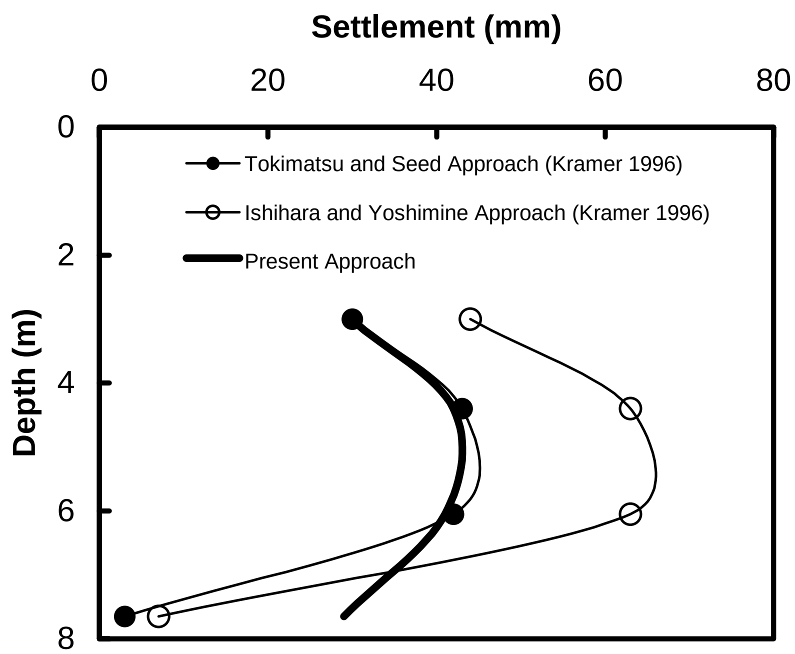

Figure-12. Comparison of computed distributions of settlement with depth.

Figure-13 compares the predicted performance using the Tokimatsu-Seed, Ishihara-Yoshimine (Kramer, 1996) and present approaches with the measured settlement. The Tokimatsu-Seed approach under-predicts while the Ishihara-Yoshimine approach over-predicts the settlements. The settlement predicted by the present approach compares favorably with the measurement. However, all the approaches provide acceptable design prediction.

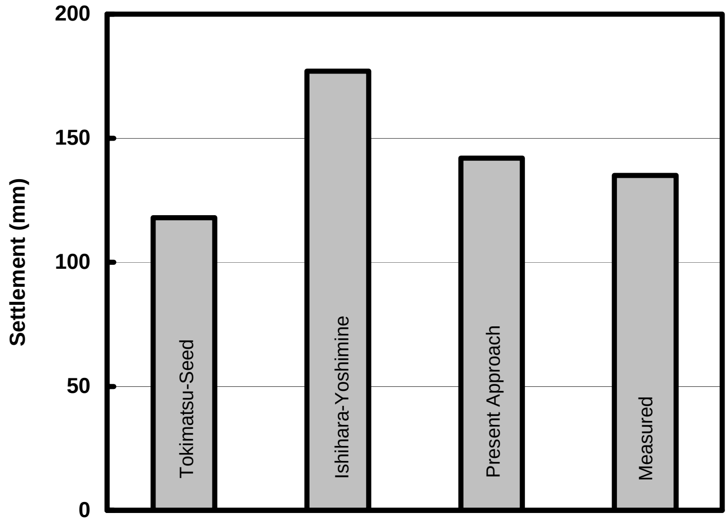

Figure-13. Comparison of computed and measured settlements.

CONCLUSIONS

A simple and practical approach has been presented for the evaluation of liquefaction-induced settlement in saturated sandy soils. The proposed approach does not require the use of charts, tables and diagrams and hence it can be conveniently implemented numerically and allows the expeditious analysis of multi-layered soil profile. The present approach may be able to characterize the liquefaction boundary line that separates liquefaction from non-liquefaction regions. It may provide a simple way to explore the level of risk of liquefaction based on the cyclic stress and SPT values. The computed settlements by the present approach are comparable with those by other published approaches. Reasonably good agreement is obtained between the predicted results by the present approach and the measured results at two sites subjected to liquefaction-induced settlements. The proposed approach is based on the limited data examined. Further validation of the proposed approach using additional field liquefaction data from earthquakes with various magnitudes is warranted.

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