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ESTIMATION OF LIQUEFACTION-INDUCED GROUND SETTLEMENT (CASE STUDIES)

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ABSTRACT

Over the past decade, the focus of liquefaction engineering began to shift towards assessment of the consequences of liquefaction with respect to the seismic performance of engineered structures and facilities, which requires accurate and reliable tools for prediction of ground deformations over the small to moderate range. Promising new predictive tools are evolving. These include simplified, empirical tools as well as sophisticated analytical and constitutive models. Recently, a high quality laboratory testing program consisting of undrained, cyclic simple shear testing on fully-saturated samples of Monterey No. 0/30 sand was completed at U.C. Berkeley. As a result, a new semi-empirical procedure was proposed for predicting post-liquefaction volumetric reconsolidation ground settlements in essentially level ground ($\alpha \approx 0$ conditions). This new procedure also includes modification for predicting liquefaction-induced ground settlement in sloping or near free-face ground ($\alpha \neq 0$ conditions). The new procedure was shown to perform well for a suite of field performance case histories with small-to-moderate ground settlements, comparing with existing semi-empirical engineering tools for estimating liquefaction-induced ground deformations.

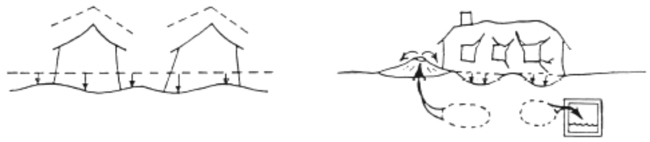
INTRODUCTION

Liquefaction-associated ground settlements and displacements are a major cause of damage in earthquakes. Since the initiation of modern geotechnical earthquake engineering, most liquefaction related research has been dedicated primarily to assessment of liquefaction susceptibility and “triggering” analysis, while relatively fewer studies have focused on liquefaction-induced ground deformations. This stemmed in part from a widely held belief that soil liquefaction inevitably leads to catastrophic failures, and thus the best strategy is to prevent liquefaction from occurring at all. This concept has proved inaccurate. Numerous laboratory and field studies show that liquefaction-induced, uncontrolled flow-type failure occurs only within extremely loose sands (e.g.: $D_r \leq 35\%$), while medium dense to dense sands tend to experience only limited shear deformations before dilation begins to reduce pore pressure and the soil begins to regain strength and stiffness. Because sands with extremely low density are not commonly encountered, flow-type failures are much less frequently observed than small-to-moderate ground deformations. As a result, small-to-moderate, liquefaction-induced ground deformation and the companying damage are increasingly gaining attention from the earthquake engineering community.

Current state-of-art probabilistic and deterministic liquefaction triggering analysis procedures (e.g.: Seed et al. 2001) are capable of predicting the occurrence (or non-occurrence) of soil liquefaction with satisfactory accuracy. Unfortunately, these tools do not directly provide any information regarding expected liquefaction-induced ground deformations. For instance, Yoshida and Ito (1999) investigated the field performance of the Port Island in the 1995 Hyogoken-Nambu earthquake. They noted that while liquefaction occurred at both improved and unimproved ground, the sites that were located on improved ground suffered significantly less deformation and damage than the sites on unimproved ground. This case demonstrates that liquefaction triggering analysis alone is of very limited value in assessing field liquefaction performance.

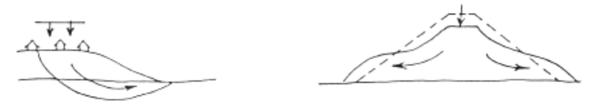
BACKGROUND

Liquefaction-induced ground settlement is of great engineering significance. There are many mechanisms that can result in liquefaction-induced ground settlements, as shown in Fig. 1. Most of these involve vertical settlements as a result of deviatoric ground deformation, but Fig. 1(a) illustrates purely volumetric reconsolidation settlement in level or near level ground. This mechanism of liquefaction-induced settlement is mainly attributed to the densification of sandy and/or silty deposits resulting from the dissipation of excess pore water pressures. During the past decades, a number of laboratory testing programs have been conducted during the past decades to investigate seismically-induced volumetric change characteristics of saturated sandy soils prior to and after liquefaction. Some representative studies are listed in Table 1.



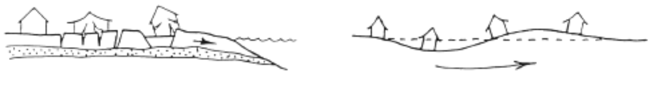
(a) Ground Loss Due to Cyclic Densification and/or Volumetric Reconsolidation

(b) Secondary Ground Loss Due to Erosion of "Boil" Ejecta



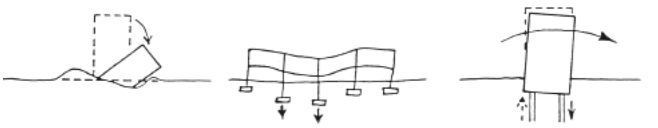
(c) Global Rotational or Translational Site Displacement

(d) "Slumping" or Limited Shear Deformations



(e) Lateral Spreading and Resultant Pull-Apart Grabens

(f) Localized Lateral Soil Movement



(g) Full Bearing Failure

(h) Partial Bearing Failure or Limited "Punching"

(i) Foundation Settlements Due to Ground Softening Exacerbated by Inertial "Rocking"

Fig. 1. Schematic illustration of liquefaction-induced ground vertical displace-ment mechanisms (Seed et al., 2001)

These studies revealed that among a number of factors (e.g.: particle size and shape, confining stress level, etc.) that could potentially affect the volumetric reconsolidation strain within a sand, the excess pore water pressure level and the prior shear strain amplitude are the most influential.

Prior to the onset of liquefaction, the reconsolidation volumetric strain ($\varepsilon_{v,r}$) is well correlated (approximately linearly) with maximum or residual pore water pressure ratio up to 90 percent of initial effective vertical stress (Lee and Albaisa, 1974). This correlation quickly diminishes as the excess water pressure approaches the initial effective vertical stress and essentially terminates when the excess pore pressure ratio reaches 1.0, which is typically regarded as the initiation of liquefaction.

Post-liquefaction volumetric reconsolidation strain within a sand has been found to be correlated with the maximum shear strain γ_{max},(Tatsuoka et al., 1984). Nagase and Ishihara (1988) also showed that correlations between $\varepsilon_{v,r}$ and γ_{max} are independent of the strain path that a soil follows prior to reaching γ_{max}. More recently, Shamoto et al. (1996) proposed that the relative volumetric reconsolidation of sands can be uniquely correlated with γ_{max} over a wide range of γ_{max} from 0.02 to 10 percent and a wide range of relative density.

Table 1. Laboratory studies of reconsolidation volumetric strain in saturated sands due to cyclic loading

Sand	Testing method	Initial effective stress, kPa	Relative density, %	Reference
Monterey sand	Cyclic triaxial, Isotropic consol.	104~414	30, 50, 75, 85	Lee and Albaisa (1974)
Monterey sand	Uni-, bi-directional DCSS, Ko consol.	40~180	35, 45, 60, 80	Kammerer et al. (2002), Wu et al. (2003)
Toyoura sand	Cyclic triaxial	100	46 – 87	Shamoto et al. (1996)
Toyoura sand	HCT, Ko consol.	< 30	20, 30	Yoshimi et al. (1975)
Sengenya-ma sand	HCT, Ko consol.	49~294	54 – 86	Tatsuoka et al. (1984)
Fuji river sand	Uni and multi-directional DCSS, Isotropic consol.	98~196	47, 73, 93	Nagase and Ishihara (1988)

These studies also show the reconsolidation volumetric strain decreases with increasing value of relative density. In addition, if reconsolidation occurs prior to the initiation of liquefaction, the volumetric strain is relatively small, ranging from less than half to just over 1 percent. Substantially larger volumetric strains up to several percent may develop if reconsolidation occurs after liquefaction triggering. In some physical model tests, maximum reconsolidation volumetric strain of 10 percent or larger was measured. However, it is not clear whether this magnitude of volumetric strain really occurred in the natural sediments.

In the past decade or so, several simplified and/or empirical engineering analytical tools were developed for the purpose of predicting seismically or liquefaction-induced ground deformations. These methods rely on similar kinds of input information such as seismic excitation parameters, topographic parameters, and subsurface geology/geotechnical parameters. Based on the methodologies for analysis of liquefaction-induced ground deformations, these methods can be sorted into one of the three categories: empirical, semi-empirical and numerical methods.

METHODOLOGY

Empirically-based ground deformation analysis methods are typically developed exclusively from field performance case history database compiled for past earthquakes. While recent proposed empirical approaches (e.g.: Bardet et al., 1999; Youd et al., 2002) have improved significantly over those developed in the 1980's, few, with the exception of the Rauch (1997) model, have the capability of predicting liquefaction-induced ground settlement.

Unlike empirically-based analytical approaches, in which various contributing factors are lumped into a single equation, most semi-empirical approaches follow a 3-phase methodology, as shown in Fig. 2. The first step is typically a liquefaction triggering analysis in which the subsurface layers that are expected to liquefy as a result of scenario ground shaking are identified. The following step is to estimate the shear strain and reconsolidation volumetric strain in these liquefied sub-layers. Finally the ground lateral displacement and settlement are calculated on the basis of the estimated strain components. This type of analytical method is commonly developed on the basis of laboratory testing results and then calibrated against field case histories. Representative semi-empirical approaches include the Tokimatsu and Seed (1984), Ishihara and Yoshimine (1992), and Shamoto et al. (1998). Because semi-empirically based methodologies have a solid mechanics basis, they are appealing to both geotechnical researchers and practitioners. They also enjoy a logical and flexible framework, into which new findings or correlations can be readily integrated without having to revamp every individual piece.

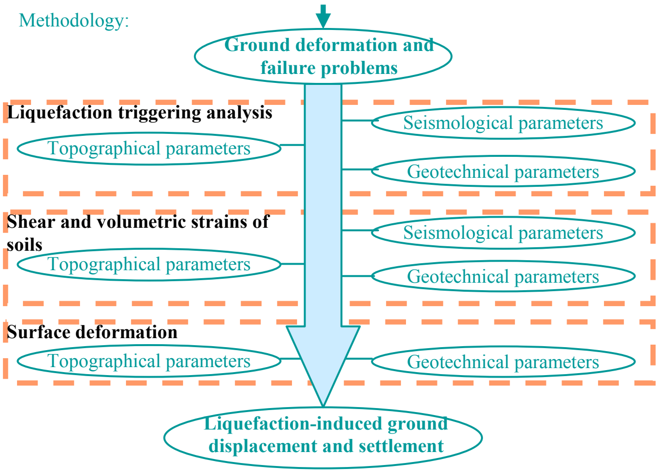


Fig. 2. Components of semi-empirically based methodology

A comprehensive laboratory testing program was recently completed at U.C. Berkeley to study various liquefaction-related issues (Kammerer et al., 2002; Wu, 2002). Uni- and bi-directional, undrained cyclic simple shear tests were performed on fully saturated specimens of Monterey 0/30 sand. After a specimen was brought to liquefaction under undrained, constant cyclic shearing load, the drainage valve was opened and the specimen was reconsolidated to the initial stress state. The reconsolidation volumetric strain data was collected in this testing program. On the basis of this new laboratory testing data set and previous data sets, a new set of correlations between the apparent cyclic shear stress ratio (CSR), the SPT blow count $N_{1,60,CS}$ and the reconsolidation volumetric strain was recently proposed by the authors (Wu, 2003), as shown in Fig. 3.

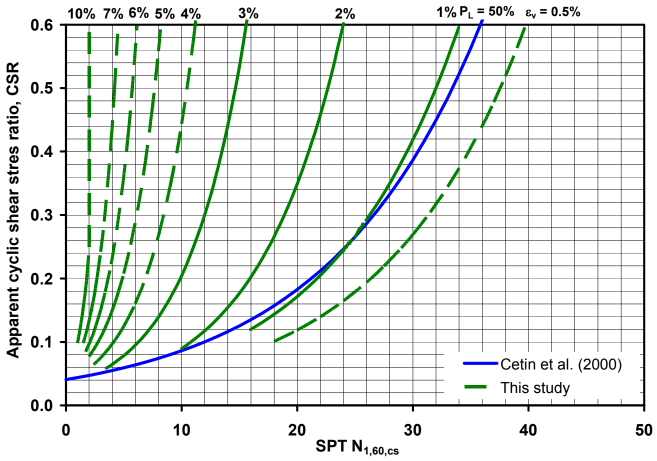


Fig. 3. Recently proposed new correlations between CSR, $N_{1,60,cs}$ and reconsolidation volumetric strain (Wu et al., 2003).

Because little reconsolidation volumetric strain with values of 3% or greater were collected in this testing program, the correlations for larger volumetric strains ($\varepsilon_v \geq 4\%$) were proposed based on extrapolation and careful evaluation of existing correlations and data sets. As a result, they are less well defined and reflect the authors' judgment; these contours are thus plotted with dashed lines, indicating greater uncertainties associated with these curves. Also shown in Fig. 3 is the liquefaction resistance curve with 50% probability of liquefaction (P_l) that was proposed by Cetin et al. (2000).

PROPOSED PROCEDURE FOR ESTIMATING SEISMICALLY-INDUCED GROUND SETTLEMENTS

On the basis of this set of post-liquefaction reconsolidation volumetric strain correlations, a new semi-empirical analytical procedure is developed to estimate seismically-induced ground settlement in nearly level ground. This new procedure is also based on the recently published SPT-based probabilistic liquefaction triggering analysis (Cetin et al., 2000; Seed et al., 2001). This state-of-art liquefaction triggering analysis tool not only provides an accurate estimation of probability of liquefaction, but also introduces some significant updates to previous tools, including a new nonlinear shear mass participation factor (R_d) and a new fines correction factor (C_{FINES}).

The new procedure consists of following steps:

1. Evaluate liquefaction susceptibility for each saturated soil layer or sub-layer. For each layer or sub-layer of liquefiable soil type, develop a representative value of $N_{1,60,CS}$ and $CSR_{eq, M=7.5}$, following the procedures described by Seed et al. (2001).

2. Use the proposed correlations between CSR and $N_{1,60,CS}$ as presented in Fig. 3 to estimate the post-liquefaction reconsolidation volumetric strain of each liquefiable soil layer or sub-layer. If the depth to the layer is relative large, the estimated reconsolidation volumetric strain may be adjusted for effects of vertical effective stress.

3. To calculate volumetric compression of non-saturated sandy layers, follow the Tokimatsu and Seed (1984) procedures.

4. Sum the volumetric changes of all soil layers and sub-layers to get the total estimated ground settlement.

This procedure estimates the ground settlement component induced by volumetric reconsolidation deformation of liquefied soils, and is suitable for level or nearly level ground with negligible static "driving" shear stress. However, the deviatoric-deformation-induced ground settlement component should also be considered when sloping or near free-face ground is involved. To account for the settlement component induced by deviatoric deformation of liquefied soils, the following additional steps are recommended.

5. Increase the ground settlement estimation calculated in step 4 by an amount equal to 10 to 20 percent of the observed lateral ground displacement, with a mean value of 15 percent. If no observed lateral ground displacement is available, use estimated ("predicted") ground lateral displacement instead. The liquefaction-induced lateral ground displacements may be estimated through empirical approaches, such as Bardet et al. (1999) or Youd et al. (2002).

6. If the estimated lateral ground displacement is smaller than 0.3 m (~1 ft), the influence of the deviatoric deformation is insignificant and the additional ground settlement component associated with lateral ground displacement should be neglected (taken as zero). Conversely, this modification should not be applied if the estimated ground lateral displacement is larger than 1.5 m, since this magnitude of lateral ground displacement would likely alter (or violate) the fundamental mechanism of vertical ground displacement for the new proposed procedure, as large lateral displacements tend to rupture the ground and produce "blocky" movements and the ground settlements, including tilting and local block rotations, quickly become difficult to predict.

The parameters required in the proposed procedure are listed in Table 2. Some parameters (e.g.: fines content) may be estimated when not readily available in analysis.

Table 2. Required parameters of the proposed procedure

Factor	**Parameter**
Seismic excitation	M_w, PGA, etc.
Topography	Level or gentle sloping ground ($\alpha \sim 0$)
Subsurface conditions	SPT N values or equivalent N values, Fines content (FC), GWT depth, soil densities, thickness of layers

FIELD CASE HISTORIES STUDIES

This new procedure has been used to predicate the settlements of liquefied sandy deposits representing case histories from a number of earthquakes. The predicted ground settlements were then compared with observed values. In the present study, a total of 14 liquefaction cases from 7 earthquakes were selected, and a total of 57 field observations of liquefaction-induced ground settlement were included in the database. These cases are listed in Table 3, along with the references that were cited in this study.

Table 3. Liquefaction-induced ground settlement case histories

Earthquake	**Location**	**Reference**
1944 Tohnankai	Komei City	Kishida, 1966; Lee and Albaisa, 1974; Cetin et al., 2000
1964 Niigata	Niigata City	Yamada, 1966; Ishihara and Yoshimine, 1992; Hamada, 1992; Cetin et al., 2000; Bardet et al. 2002
1968 Tokachioki	Hachinohe City	Ohsaki, 1970; Tokimatsu and Seed, 1984; Cetin et al., 2000
1978 Miyagiken-Oki	Arahama City	Tohno and Yasuda, 1981; Tokimatsu and Seed, 1984; Cetin et al. 2000
1989 Loma Prieta	Moss Landing, Miller Farm, Treasure Island, Marina District, South of Market, East Bay	Kayen, 1992, 1998; O'Rourke et al. 1992; Ishihara, 1993; De Alba et al. 1994; Holzer et al.1994; Bennett and Tinsley, 1995; Boulanger et al., 1997; Pease and O'Rourke, 1998; Power et al., 1998; Rollins and McHood, 1998; Mejia, 1998; Cetin et al., 2000

1994 Northridge	San Fernando Valley	Bennette et al., 1998; Holzer et al.,1999; Cetin et al., 2000;
1995 Hyogoken-Nambu	Port Island, Rokko Island, Kobe Port, Naruohama Island	Tokimatsu et al., 1996; Yasuda et al., 1996, Hamada et al., 1996; Shibata et al., 1996; Ishihara et al., 1996; Akamoto and Miyake, 1996; Kazama et al., 1998; Shamoto et al., 1998; Bardet et al., 2002..

Because the proposed procedure does not calculate the deviatoric ground settlement component, which could be significant for sites that are near free faces or on steep slopes, most of the selected sites in these field performance case histories are located on relatively level ground and are at least 30 meters (~90ft) away from the nearest free face. However, a few exceptions, such as the Moss Landing case, were included due to their unusually high quality ground settlement and borehole data, in spite of their proximity of waterfront.

For each case presented in Table 3, representative SPT borehole logs were collected and entered into a spreadsheet program to calculate the ground settlement. The estimated ground settlement was then paired with the observed (measured) ground settlement and plotted in Fig. 4(a). In this ground settlement case history database, each site has between 1 to 14 pairs of settlements. In cases where multiple SPT boreholes are spatially distributed close to each other, calculations of ground settlement were carried out independently for each borehole profile, and the estimated ground settlements are then averaged to get a single estimation of ground settlement.

Similar calculations were exercised using the Ishihara and Yoshimine (1992), the Tokimatsu and Seed (1984), and the Shamoto et al. (1998) procedures. The volumetric strain correlations for these procedures are presented in Fig. 3(b), (c) and (d). For the Ishihara and Yoshimine procedure, the values of CSR and $N_{1,60,cs}$ are the same as those used for this new procedure because the Ishihara and Yoshimine procedure is based on the factor of safety against liquefaction, and thus is insensitive to the choice of CSR and N-values as long as they are compatible. For the Tokimatsu and Seed, and the Shamoto et al. procedures, the recent NCEER recommendations (Youd et al., 2002), including fines content adjustment, were followed to compute CSR and $(N_1)_{60,CS}$. It was necessary, however, to convert $(N_1)_{60}$ into $(N_1)_{72}$ before applying fines content adjustment to get N_a in the Shamoto et al. procedure. It should be noted that neither the original Tokimatsu and Seed method nor the original Ishihara and Yoshimine method provide fines adjustments. Therefore, these analyses represent the use of "Modified" Tokimatsu and Seed and "Modified" Ishihara and Yoshimine approaches, as fines adjustments were made to all N-values. Details of these selected field case histories and the calculations are published in a separated report (Wu et al. 2003).

For some cases in which the observed lateral ground displacements were larger than 0.5m, the estimated (predicted) ground settlements were expected to be on the low side. This is because larger ground lateral displacement is frequently accompanied by complimentary deviatorically-induced vertical deformation that is not considered in these semi-empirical methods.

The performance of this proposed semi-empirical ground settlement estimation method and those of the three existing methods: "Modified" Ishihara and Yoshimine (1992), "Modified" Tokimatsu and Seed (1984), and Shamoto et al. (1998) may be qualitatively evaluated by examining Fig. 4. Overall, these four methods perform satisfactorily against the 57 field liquefaction-induced ground settlement observations. Most predictions by the four methods fall between 50 and 200 percent of the observed values, indicating good agreement between the predictions and the observations. It seems that Ishihara and Yoshimine approach tends to be over-estimating slightly, while Tokimatsu and Seed approach tends to be under-estimating slightly.

The performances of these four methods may be better evaluated by statistical methods. For evaluation purposes, two statistics are calculated for the estimations produced by each method: the mean residual and the mean standard error. The residual, e_i, is defined as

$$e_i = Estimation_i - Observation_i \tag{1}$$

and the mean residual is

$$\text{Mean residual} = \frac{\Sigma e_i}{N} \tag{2}$$

Similarly, the mean standard error is defined as

$$\text{Mean standard error} = \sqrt{\frac{\Sigma e_i^2}{N}} \tag{3}$$

Residuals show the deviation of estimations from the observations. The mean residual is an index for measuring the bias of estimations. A positive mean residual indicates overestimation and vice versa. The mean standard error is an index for measuring the degree of scattering. The larger a mean standard error, the more scattered the estimations are.

Table 4 presents the mean residual and the mean standard error for each method evaluated in the present study, which seems to suggest that:

Table 4. Performance of the proposed new procedure and existing approaches

Procedure	Mean residual, $\frac{\Sigma e_i}{N}$	Mean standard error, $\sqrt{\frac{\Sigma e_i^2}{N}}$
This study	0.002	0.099
Ishihara and Yoshimine (1992)	0.026	0.121
Tokimatsu and Seed (1984)	-0.011	0.108
Shamoto et al. (1998)	0.011	0.111
Average of the four methods	0.007	0.103

(1) All four methods have relatively small mean residuals and mean standard errors, which indicate they perform reasonably well against this database.

(2) Among the four methods, the new proposed method yields the smallest absolute mean residual and the smallest mean standard error. This shows that the new proposed method has the least bias and the smallest scattering of the estimations, and thus has the best performance in this group of four.

(3) The modified Ishihara and Yoshimine (1992) method yields the largest positive mean residual, which suggests that the Ishihara and Yoshimine (1992) method tends to overestimate. Shamoto et al. (1998) method similarly tends to overestimate, but to a lesser degree.

(4) If the predictions of the four methods are averaged for each individual case and compared to the observations, the resulting mean residual is rather small, indicating the biases may be largely cancelled out by averaging estimations from these four methods. The scatter of estimations, however, is only marginally improved by the averaging technique.

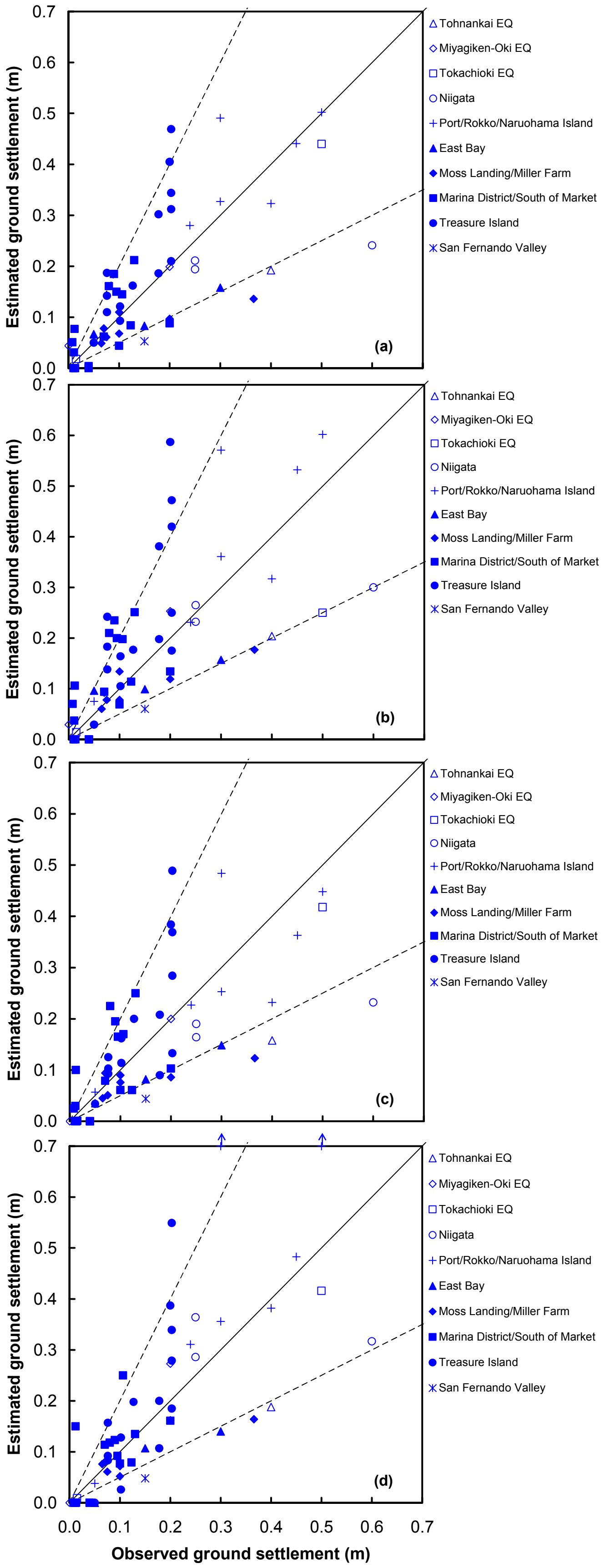


Fig. 4. Comparison between predicted and observed ground settlements in case histories: (a) the new proposed correlations, (b) "Modified" Ishihara and Yoshimine (1992), (c) "Modified" Tokimatsu and Seed (1984), (d) Shamoto et al. (1998)

CONCLUSION

An extensive liquefaction field performance case history study was conducted to assess the applicability and reliability of the proposed new procedure for evaluating liquefaction-induced volumetric reconsolidation ground settlements in level or nearly level ground. It was found that most of the ground settlements predicted by the proposed procedure fall between 50 to 200 percent of the observed field settlements, rendering the proposed analysis methodology a useful engineering tool.

Two of the previously existing ground settlement estimation procedures, namely the Tokimatsu and Seed (1984) and the Ishihara and Yoshimine (1992) approaches, lack formal methods for dealing with variable fines content. By adopting the most recent NCEER recommendations for the fines content adjustment for the Tokimatsu and Seed approach, and adopting the liquefaction triggering relationship and fines content adjustment by Seed et al. (2001) for the Ishihara and Yoshimine approach, these two (modified) approaches perform nearly as well as the other two procedures that have built-in fines content adjustments (the Shamoto et al. method and this new procedure).

Among the four candidate procedures, the new proposed procedure yields predictions of smallest overall average bias and slightly lower variance than the other three. This new procedure also enjoys the additional advantage of being directly compatible with the recent probabilistically-based liquefaction triggering analysis methodology proposed by Cetin et al. (2000).

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