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# A simplified procedure to estimate liquefaction-induced settlements of buildings

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ABSTRACT: A simplified procedure was proposed to approximately estimate liquefaction-induced settlements of buildings with rigid shallow foundation founded on horizontally stratified deposit, in which key controlling factors such as building, soil, and earthquake conditions are appropriately taken into account. Building settlements and tilting observed in a series of tests made under various controlled conditions in centrifuge liquefaction tests were used to check the potential effectiveness of the proposed method. The settlements and tilting estimated by the proposed method were found to be consistent with the observed ones, irrespective of building, soil and earthquake conditions, suggesting its potential effectiveness.

## 1 INTRODUCTION

Soil liquefaction that occurred during recent earthquakes (2011 Christchurch, 2011 Tohoku, and 2016 Kumamoto earthquakes) still caused excessive settlement and titling not only of many residential wooden houses but also of low-rise reinforced concrete (RC) buildings founded on shallow foundations. Despite many earthquake reconnaissance and laboratory studies regarding the settlements of buildings with shallow foundation on liquefaction-prone soils (e.g., Yoshimi and Tokimatsu 1977; Santio et al, 2004; Dashti et al, 2010; Tokimatsu et al, 2013), relative importance of key parameters controlling the problems have not been thoroughly understood to date. In addition, there exists no reliable and yet simple method to estimate both liquefaction-induced building settlement and tilting. The objective of this paper is therefore to review and examine key parameters affecting not only settlement but also tilting of buildings with shallow foundations founded on liquefiable soils based on centrifuge experiments and to explore the possibility to estimate liquefaction-induced building settlement and tilting observed in centrifuge tests in a simple manner.

## 2 TEST APPARATUS AND PROCEDURES IN CENTRIFUGE EXPERIMENTS

The tests were conducted using two laminar boxes of different sizes and subjected to different centrifugal accelerations. Most of the tests were run with the container shown in Figure 1 under a centrifugal acceleration of 50 g. Some were carried out with a larger container under 25 g. The tests with a scaling factor of 25 simulated proto-type configurations, while those with a scaling factor of 50 was a half scale model of the prototype model.

Sixteen tests conducted by Tokimatsu et al. (2013, 2017) and Hino et al. (2015) were used in this study, in which 8 different building models together with 9 different ground models were used. Except for Test E run with one building, two buildings were laid on liquefiable sand deposits, with different soil, building, and input ground motion characteristics to study the important parameter controlling the problem. Only one building each is used for Tests H to P, because drainpipes, which are not the subject of this paper, were installed around the periphery of the other building.

The eight building models have different foundation width, contact pressure, height of gravity center, and load eccentricity ratio. The two letters of building ID in turn reflect the contact

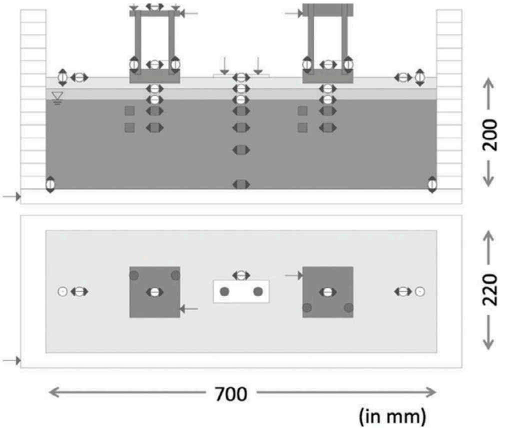


Figure 1. Test setup

pressure (2: $20kN/m^2$; 5: $50kN/m^2$; 7: $70kN/m^2$; and 9: $90kN/m^2$) and foundation width and eccentricity ratio (S: 4.5m and 0.04; L: 9.0m and 0.04; L': 8.0m and 0.04; and E: 4.5m and 0.10). The natural periods of building were 0.3–0.4 s for 2S, 2L and 2L'; 0.15 s for 5S and 5E; 0.2 s for 7S and 7L; 0.25s for 9S. The embedded depths of foundation were 0.50m for Tests A to G, 0.15m for Tests H to N, and 0.25m for Tests O and P.

The nine ground models have different groundwater table and different stratification of soil density. The first letter of Soil Model ID reflects groundwater table (1: 1m; 2: 2m, 3: 2.5m; and 4: 4.0m), with the rest (one to three letters) representing the variation of relative density (L: 50%; M: 60–65%; and D: 90%) with depth below the groundwater table.

An artificial ground motion called "Rinkai" (Tokimatsu et al, 2013; Hino et al, 2015) was used as an input motion in the longitudinal direction of the laminar box. The outputs from the installed sensors were recorded until the excess pore pressure in the ground had dissipated completely. This shaking and observation process was repeated until the outputs became out of scale. The peak input accelerations were adjusted to 4.0 $m/s^2$ for the first flight, 2.0 $m/s^2$ for the second flight, and 4.0 $m/s^2$ thereafter, for tests A to N. For tests O, peak input accelerations were 4 $m/s^2$ for the first three flights and $7m/s^2$ thereafter. In contrast, accelerations were 7 $m/s^2$ for the first two flights and 8 $m/s^2$ thereafter for test P. This paper discusses the results from first three flights. The detail description of test apparatus and procedure were described elsewhere (Tokimatsu et al., 2017).

## 3 EFFECTS OF BUILDING, SOIL AND GROUND MOTION CONDITIONS

### 3.1 *Effects of building contact pressure*

Figure 2 shows the liquefaction-induced absolute and relative building settlements, and tilting angles during the first flight of buildings with different contact pressures but with the same

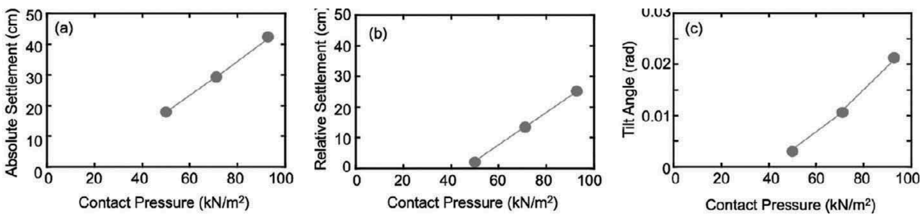


Figure 2. Effects of contact pressure a on absolute and relative settlement and tilt angle in the first flight with a ground water table of 2.5 m

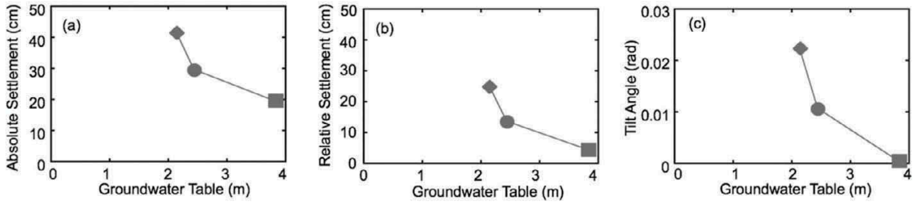


Figure 3. Effects of groundwater table on absolute and relative settlements and tilting angle of in the first flights with building models 7S

eccentric ratio of 0.04, which were founded on the same model ground (3L2) with a groundwater table of 2.5 m and a relative density of 50 %. The figure confirms that, under the same ground and earthquake conditions, the absolute and relative settlements, and tilting angle of building tend to increase with increasing contact pressure.

### 3.2 *Effects of groundwater table*

Figure 3 compares the liquefaction-induced absolute and relative settlements, and tilting angles during the first flights of building models 7S founded on soil models having the same initial relative density of 50 % but with different initial groundwater tables. The figure suggests that the absolute settlement, relative settlement, and tilt angle of building tend to decrease with increasing groundwater table depth. In specific, when groundwater table is as deep as 4 m below the ground surface, the relative settlement and tilting angle of the model building becomes negligibly small even though the building has suffered absolute settlement arising from soil liquefaction. This infers that the building settled along with the ground in this case.

### 3.3 *Effects of ground shaking intensity and preshaking history*

Figure 4 compares the liquefaction-induced absolute and relative settlements, and tilting angles of building during the first flight shown in Figure 3 with those during the second and third flights. The extent of settlement and tilting from the second flight (2 m/s$^2$) were lower than those observed in the first and third flights (4 m/s$^2$), suggesting the effects of the input acceleration intensity. In addition, the settlement and tilting caused by the third flight were lower as compare to the first flight, suggesting the effects of soil densification following soil liquefaction during the preceding two flights. Despite soil densification, the tilt angles caused by the third flight are comparable to those of the first flight. This suggests that the reduction in groundwater table depth caused by the preceding might have stronger effects on building tilt.

### 3.4 *Relation between building settlement and tilting*

Figure 5(a) and (b) show the relations of observed building tilts with relative building settlements and with those normalized with respect to building width from all flights, respectively. Although the data in both figures are scattered, Figure 5(b) shows a better trend in which the

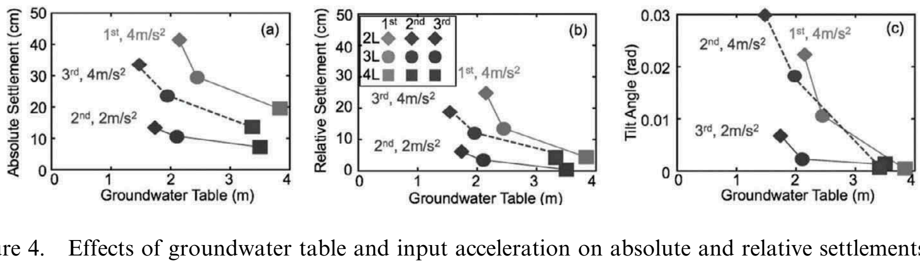


Figure 4. Effects of groundwater table and input acceleration on absolute and relative settlements and tilt angle in the first, second and third flights with buildings 7S

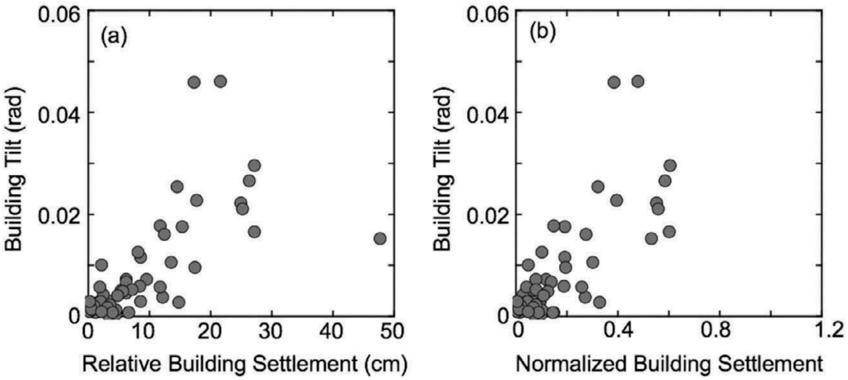


Figure 5. Relation of observed building tilts with relative building settlements and normalized relative building settlements

observed building tilt angle increases with increasing normalized relative building settlement as approximately defined as:

$$\theta \approx \beta S/B \tag{1}$$

in which θ= building tilt angle (rad), $S$ = building relative settlement with respect to the ground surface, $B$ = foundation width and $\beta$ = 0.25-1.0 with an average value of 0.5.

## 4 A SIMPLIFIED METHOD TO ESTIMATE LIQUEFACTION-INDUCED BUILDING SETTLEMENT AND TILTING

Liquefaction-induced settlements of buildings and earth structures have been approximately estimated by equivalent linear approaches, based on theory of elasticity together with equivalent modulus of liquefied soils (Ishii and Tokimatsu, 1988; Yasuda et al, 2017). Based on the study by Steinbrenner (1934), the relative settlement of building with rigid foundation with respect to the level ground, hereby called index for liquefaction-induced relative building settlement, $I_{LBS}$, due to soil liquefaction of a layer having a finite thickness (Figure 6), the deformation modulus of which has decreased from the initial value, $E_{ok}$, to $E_k$ ($E_{ok}$ □ $E_k$), may be approximated as

$$I_{LBS} = a\left\{\frac{I_S(H_1,\nu_1)}{E_1} + \sum_{k=2}^{n}\frac{I_S(H_k,\nu_k) - I_S(H_{k-1},\nu_k)}{E_k}\right\}qB \tag{2}$$

in which $q$ = foundation contact pressure, $B$ = foundation width, $H_k$ = depth from the ground surface to the bottom of the k-th layer, $E_k$ = deformation modulus of the k-th layer, $\nu_k$ = Poisson's ratio of the k-th layer, a = constant to convert the corner settlement of flexible foundation into the average settlement of rigid foundation, and $I_s(H_k, \nu_k)$ is given as:

$$I_S(H_k,\nu_k) = \left(1-\nu_k{}^2\right)F_{1k} + \left(1-\nu_k-2\nu_k{}^2\right)F_{2k} \tag{3}$$

in which $F_{1k}$ and $F_{2k}$ are given as:

$$F_{1k} = \frac{1}{\pi}\left[\ln\frac{\left(1+\sqrt{l^2+1}\right)\sqrt{l^2+d_k{}^2}}{l\left(1+\sqrt{l^2+d_k{}^2+1}\right)} + \ln\frac{\left(1+\sqrt{l^2+1}\right)\sqrt{1+d_k{}^2}}{l+\sqrt{l^2+d_k{}^2+1}}\right] \tag{4}$$

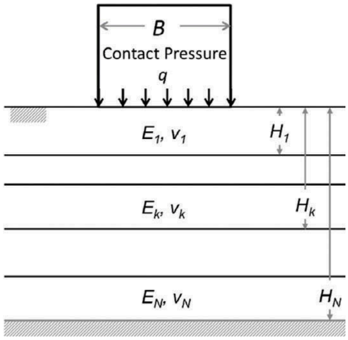


Figure 6. Analytical model to estimate liquefaction-induced building settlement relative to the ground surface

$$F_{2k} = \frac{d_k}{2\pi}\tan^{-1}\frac{l}{d_k\sqrt{l^2 + d_k{}^2 + 1}} \tag{5}$$

in which $l$ = ratio between foundation length and width ($L/B$), $L$ = foundation length, $d_k$ $=H_k/B$.

The degraded deformation modulus, $E_k$, which controls building settlement relative to the ground surface, depends on such factors as the SPT N-value (relative density), and the factor of safety against soil liquefaction in terms of number of cycles (or shear strain), and thus may be defined as:

$$E_k = \alpha E_{ok} \tag{6}$$

in which $E_{ok}$ = initial deformation modulus approximated as:

$$E_{ok} = 10N_k \ (MPa) \tag{7}$$

in which $N_k$ = SPT N-value of the k-th layer and $\alpha$ may be approximately given as:

$$\alpha = \ 0.15 \ (FS_{Nk} > 1) \tag{8}$$

$$\alpha = FS_{Nk}10^{0.05N_k - 2.95} \ (FS_{Nk} \leq 1) \tag{9}$$

in which $FS_N$ = factor of safety against liquefaction in terms of number of cycles. The value of varies from 0.0007 for $N$ = 10 and $FS_N$ = 0.2 to 0.03 for $N$=25 and $FS_N$ = 1, being consistent with the field observation (Tokimatsu et al, 2017).

The Poisson's ratio of the k-th layer, $\nu_k$, is assigned a value of 0.5 for liquefied soils and 0.3 for non-liquefied soils.

Similarly, from Equation 1, the liquefaction-induced tilt angle of building with rigid shallow foundation, hereby called index for liquefaction-induced building tilt, $I_{LBT}$, may be approximated as:

$$I_{LBT} = \ 0.5\frac{I_{LBS}}{B} \tag{10}$$

## 5 EFFECTIVENESS OF PROPOSED METHOD FOR CENTRIFUGE EXPERIMENTS

In order to examine the potential effectiveness of the proposed method, an attempt was made to estimate liquefaction-induced building settlement and tilting observed in centrifuge tests

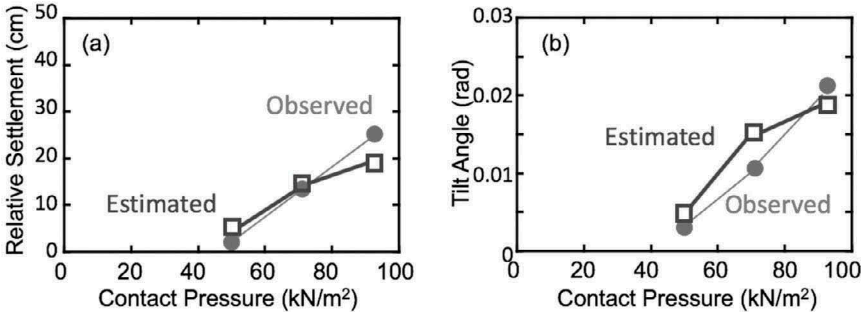


Figure 7. Comparison of estimated settlement and tilting indices with those observed during the first flight of buildings with different contact pressures

using Equations 2 and 10. To estimate the two indices of liquefaction-induced relative building settlement and tilting in the centrifuge experiments, the SPT N-value used in Equation 7 was assumed based on the following:

$$N_k = \sigma'_{vk}(D_r/160)^2 \tag{11}$$

in which $\sigma'_v$ = effective vertical stress of the k-th layer in kN/m$^2$ and $D_r$ = relative density of the k-th layer in %.

Figure 7 compares the estimated settlement and tilting indices (open symbols) with those observed (solid symbols) during the first flight of buildings with different contact pressures but with the same eccentric ratio of 0.04 and founded on the same model ground (3L2) that had a groundwater table of 2.5 m and the relative density of 50%. The estimated values are in fairly good agreement with the observed ones, suggesting that the proposed method can appropriately take into account the effects of foundation contact pressure.

Figure 8 compares the estimated settlement and tilting indices (open symbols) with those observed (solid symbols) during the first flight of building models 7S founded on soil models having the same relative density of 50% but with different groundwater tables. The estimated values are in fairly good agreement with the observed ones, suggesting that the proposed method can appropriately take into account the effects of groundwater table.

Figures 9 and 10 compare the estimated settlement and tilting indices (open symbols) during the second and third flights with the observed ones (solid symbols) during first to third flights. The estimated values can simulate well the significant features observed, i.e., the settlement and tilting from the second flight (2 m/s$^2$) were smaller than those in the first and third flights (4 m/s$^2$), and the settlement caused by the third flight were smaller than those in the first flight. The fairly good agreement in trend between the computed and observed ones

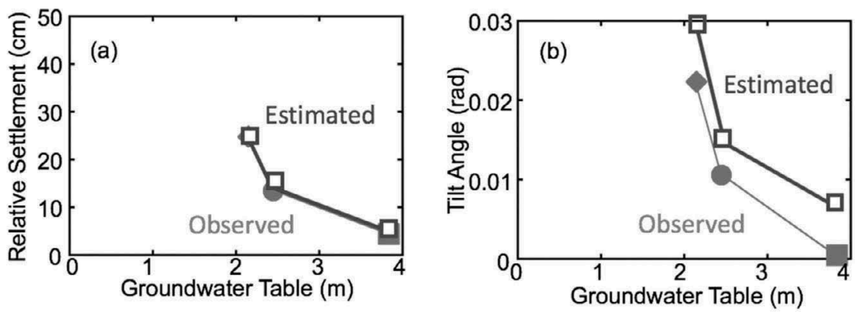


Figure 8. Comparison of estimated settlement and tilting indices with those observed during the first flight of building with different groundwater tables

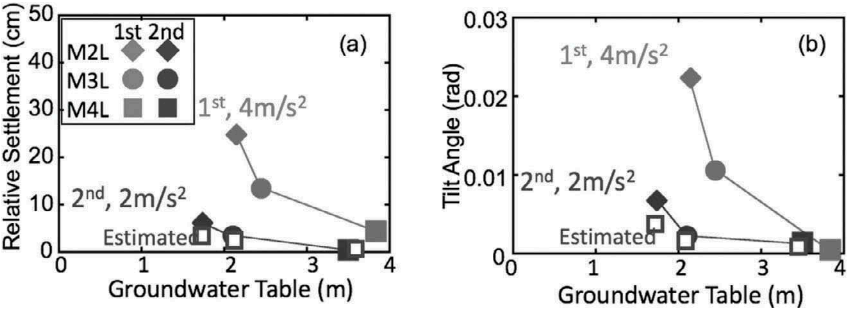


Figure 9. Comparison of estimated settlement and tilting indices with those observed during the second

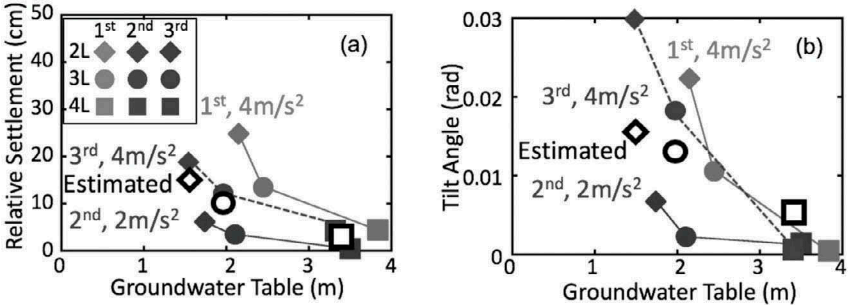


Figure 10. Comparison of estimated settlement and tilting indices with those observed during the second flight of building with different groundwater tables

suggests that the proposed method can also appropriately take into account the effects of ground motion intensity and pre-shearing history.

flight of building with different groundwater tables

Figure 11(a) compares the liquefaction-induced building settlement index computed for the all test cases with the observed ones. There is a good agreement between the two, conforming that the proposed method can simulate well the observed building settlements in the centrifuge experiment and showing promise for field cases. Similarly, Figure 11(b) compares the liquefaction-induced building tilt index computed for the all test cases with the observed ones. There is a fairly good agreement between the two, suggesting that the proposed method can estimate reasonably well the observed building tilt in the centrifuge experiments.

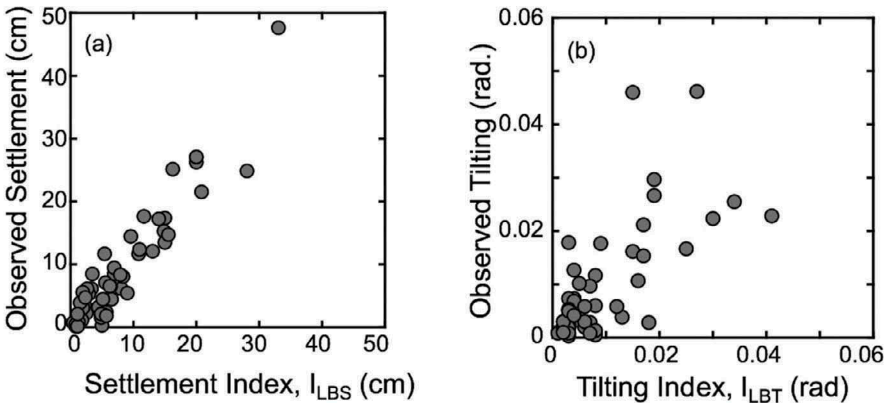


Figure 11. Comparison of estimated settlement and tilting indices with those observed in all tests

Although the liquefied layer cannot behave like an elastic material and the proposed method does not take into account the overturning moment imposed on the foundation from its superstructure, the fairly good agreement described above suggests a possibility that the liquefaction-induced settlement and tilting of building with rigid shallow foundation would be roughly evaluated by the proposed method. It is of course that further studies including verification to field case histories are badly needed to confirm its effectiveness.

## 6 CONCLUDING REMARKS

The liquefaction-induced absolute and relative settlements and tilt angle of building with rigid shallow foundation in the centrifuge experiment tend to increase with increasing contact pressure, and intensity of input motion as well as with decreasing groundwater table. The liquefaction-induced tilt angle of building in the centrifuge experiment tends to increase with increasing non-dimensional settlement normalized in terms of foundation width.

The two indices, i.e., the indexes for liquefaction-induced relative building settlement and the building tilt, proposed in this presentation are promising in roughly evaluating liquefaction-induced settlement and tilting of buildings with rigid shallow foundations. Further studies including verification to field case histories are, however, definitely needed to confirm its usefulness in practice.

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