Mitigation of Nonuniform Settlement of Structures due to Seismic Liquefaction

Rouzbeh Rasouli[1]; Ikuo Towhata[2]; Hadrien Rattez[3]; and Rolf Vonaesch[4]

Abstract: Limited uniform settlement of a building subject to liquefaction may not affect the living conditions of the residents immediately after an earthquake. However, even some small nonuniform settlement can cause serious disruptions to residents' normal life. Because most residents of inexpensive houses cannot afford expensive retrofitting measures against this problem, different possible countermeasures against seismic nonuniform settlement of buildings are proposed, and their performance is evaluated in this study. The proposed mitigations should be not only technically promising but also economically affordable for residents of private houses. The proposed mitigations are (1) installation of sheet-pile walls around the building's foundation with limited lowering of the groundwater level; (2) installation of diagonal drains under the foundation accompanied by limited lowering of the groundwater level; and (3) limited surface ground improvement. The experimental results showed some differences between the performances of the proposed mitigations in non-uniformly loaded buildings compared with cases of uniformly loaded buildings. It is observed that installation of sheet-pile walls is not a promising countermeasure against tilting of the structures even though it reduces the total settlement. The liquefied sand in the area surrounded by the sheet piles and the building's foundation could easily deform, resulting in tilting of the building. In contrast, installation of drains reduced both settlement and tilting of structure by providing a nonliquefied column of soil under the foundation. Surface ground improvement also reduced both total settlement and tilting of the structure. However, its efficiency in reduction of the uniform settlement was found to be mostly dependent on the length of improvement rather than its depth, whereas the depth of improvement plays an important role in reduction of the tilting. **DOI: 10.1061/(ASCE)GT.1943-5606.0001974.** *© 2018 American Society of Civil Engineers.*

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Introduction

Following a strong earthquake in liquefiable areas, tilting and settlement of structures can cause serious problems in people's live. The 2011 Tohoku earthquake in Japan and 2010–2011 series of earthquakes in New Zealand have provided numerous examples of buildings that suffered from such problems. The extent of liquefaction-induced damages during these earthquakes has been well documented by various researchers and can be referred to for understanding the importance of this issue on individuals' lives as well as its appearance as a national problem for the government when the innumerable cases happen at once nationwide [among all, Towhata et al. (2014), Konagai et al. (2013), and Tokimatsu et al. (2012) discussed Japan's experience and Cubrinovski et al. (2012, 2014) have discussed New Zealand's experience].

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Although both uniform and nonuniform settlements of structures can cause various problems to the people's living conditions, there are a number of differences between the nature of these problems as well as their countermeasures. The very immediate problems due to uniform settlement can be the cutting of lifelines such as water pipes, sewer pipes, and gas pipes. Besides these faults, which can also happen in nonuniform settlement, there are other serious issues that appear in the case of nonuniform settlement of the building. For instance, even 0.5° of tilting can cause intolerable dizziness and sleeping problems to residents of a building, which could make their lives impossible to continue in that building even for a couple of days after an earthquake (JSCA 2011). However, Yasuda et al. (2004) pointed out that people want their houses to be balanced again even in case of 0.06° of titling.

In proposing countermeasures against liquefaction-induced distortion of inexpensive private houses, in addition to the technical issues, economic considerations play important roles. The available technologies for improvement of the ground under existing structures, such as chemical grouting by colloidal silica, are scarcely affordable by people for improvement of the soil under their private building and are mainly used for improvement of infrastructures (e.g., Rasouli et al. 2016a) because it costs about 10 times more than conventional liquefaction countermeasures such as installation of prefabricated drains. Thus, the proposed countermeasure should be both economically reasonable and technically effective. Limited ground improvement under houses or installation of sheet-pile walls around the foundation of houses and diagonal drains under houses' foundation, both accompanied by limited lowering of the groundwater level (GWL), are proposed and examined in this study.

Previous works on these problems were mainly devoted to examining the performance of different countermeasures in prevention

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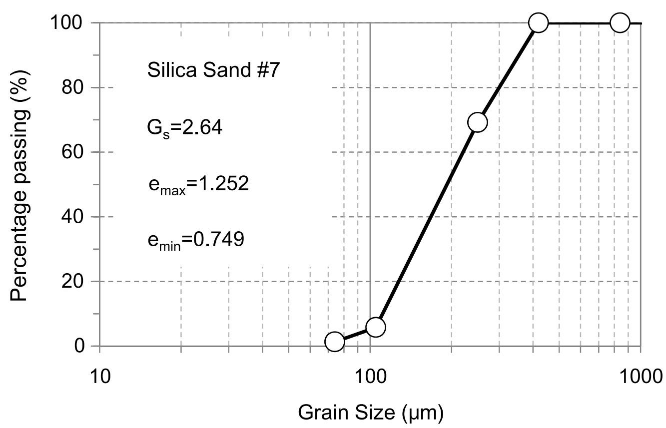
or reduction of uniform settlement of buildings. Rasouli et al. (2014) proved the effectiveness of reinforcement of the ground under houses by installation of vertical sheet piles around the building's foundation in reducing settlement of houses due to liquefaction. Dashti et al. (2010) proposed creation of a rigid soil wall and installation of water barriers around existing structures' foundations. The protective effects of installation of diagonal drains under a building's foundation, accompanied by limited lowering of the groundwater level, were also evaluated by Rasouli et al. (2016b). There are a few previous studies on the nonuniform settlement of buildings. These are mainly limited to the case histories of liquefaction-induced tilting (e.g., Yasuda et al. 2004) or studies on its mechanism and influencing factors and their numerical simulation (Yasuda and Ariyama 2008). The numerous houses damaged during the 2011 Japan and 2010–2011 New Zealand earthquakes triggered studies on the mitigation of the problem as well. For instance, Tani et al. (2014) studied the applicability and efficiency of surface ground improvement on reduction of tilting of a building due to liquefaction.

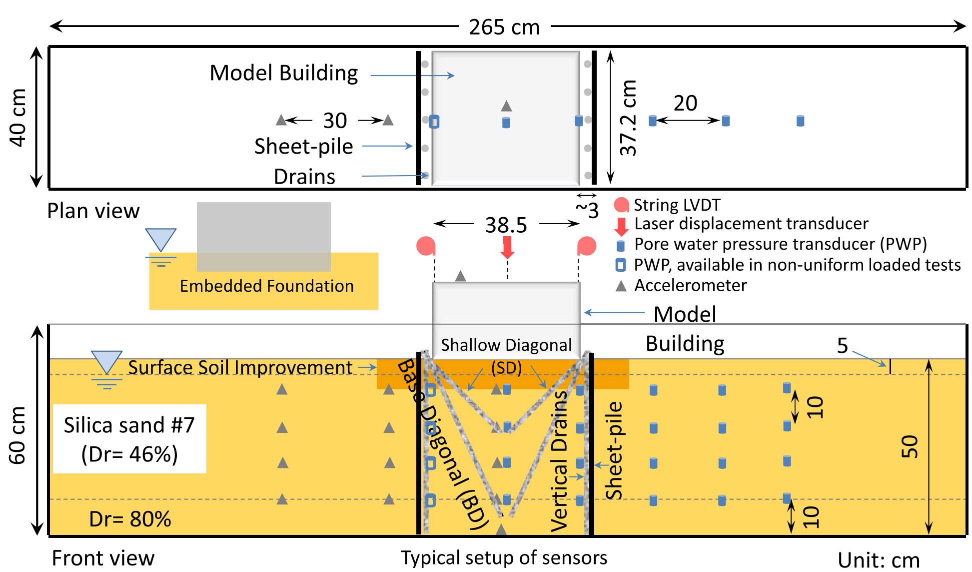
At first glance, it may be assumed that countermeasures that are effective in prevention of uniform settlement of buildings can efficiently reduce their nonuniform settlement as well. However, because of the different loading patterns on the surface of the ground, the performance of the proposed countermeasures is unclear and is therefore studied in this paper.

Setup of 1*g* Model Experiments

The 2 × 3 m shaking table at the University of Tokyo was used for conducting the model experiments in this study. A soil container 2.65 m in length, 0.6 m in height (model ground depth was 0.5 m), and 0.4 m in width was used for the experiments. The walls of the box were made of transparent acryl to observe the deformation of the model ground. To reduce the effects of rigid boundaries, two shock absorbers of 2.5 cm thickness were attached to each end of the box. The model was made of silica sand No. 7. The grain size distribution and properties of this soil are shown in Fig. 1(a). The bottom 10-cm layer of ground was made by air pluviation method and was compacted to reach 80% of relative density. This layer was assumed to be a nonliquefiable layer. The upper four 10-cm layers over the nonliquefiable layer were made by the water pluviation method. Being fully saturated and having a relative density of 46%, these layers were considered liquefiable layers. Beside the transparent walls of the soil container, vertical and horizontal lines of colored sand were installed to observe the deformation of the model



(a)



(b)

Fig. 1. (a) Particle distribution of silica sand No. 7; and (b) schematic diagram of a typical experiment and position of sensors, sheet piles, and drains.

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ground. For making the vertical lines, U-shaped aluminum bars were placed near the transparent wall of the box. After finishing each 10-cm layer of ground, the vertical colored-sand column was made by pouring sand into the U-shaped bar. The aluminum bars were removed after the model ground construction was completed. In case of horizontal lines, the saturated colored sand was gently placed near the transparent wall after finishing each layer. In addition, many accelerometers and pore-water pressure (PWP) transducers were installed to record the behavior of the model ground [Fig. 1(b)].

The GWL was set at surface, −5, and −10 cm from the surface in different cases. In cases of low GWL, a 2-cm gravel layer was placed to prevent water rising into the unsaturated surface layer due to the capillary effect.

The surface structure was modeled by a wooden box filled with sand. This provided a rigid building model that neglects the effects of the building's internal interaction on the effectiveness of the proposed mitigation technics. Ground input acceleration often amplifies with mitigation, and if it is near the fundamental mode of the building, that may affect the performance and results of the proposed countermeasures. The box had surface dimensions of 38.5 cm length and 37.2 cm width, leaving a minor space from the side wall of the soil container. The total load of this model was about 195 N. Among different reasons that may lead to nonuniform settlement of structures during liquefaction, such as a nonuniform liquefiable layer, uneven liquefiable layer, or characteristics of the ground motion and superstructure, the focus in this study is on nonuniform loading on the model ground. In this regard, the building model was divided by a thin piece of wood. One side of the box was loaded to about 122 N and the other side to 73 N (Fig. 2). Considering the bottom of the wooden box as a rigid foundation, the stress distribution on the model ground's surface can be calculated by Eq. (1)

$$q_{l,R} = \frac{Q}{bl}\left(1 \pm \frac{6e}{l}\right) \tag{1}$$

where Q = resultant load of the model building; b = width of the slab; l = length of the slab; and e = eccentricity of the resulting load. The contact pressure at the building base is shown in Fig. 2.

To calculate tilting of model structure, except for Case 5 in which string-type displacement transducers were used, the data recorded by the accelerometer mounted on the model structure were used for all other cases (Fig. 2). When carrying out Case 4, tilting of the building was measured by both the accelerometer and displacement transducers, and it was verified that the tilting of the building model can be measured by both methods. Even though the time history of tilt measured by each of these two methods did not pass through the same exact path, they were reasonably close to each other and resulted in almost equal final tilting (Fig. 2). Time history of the settlement was recorded by means of a laser displacement transducer pointed at the center of the model building's roof.

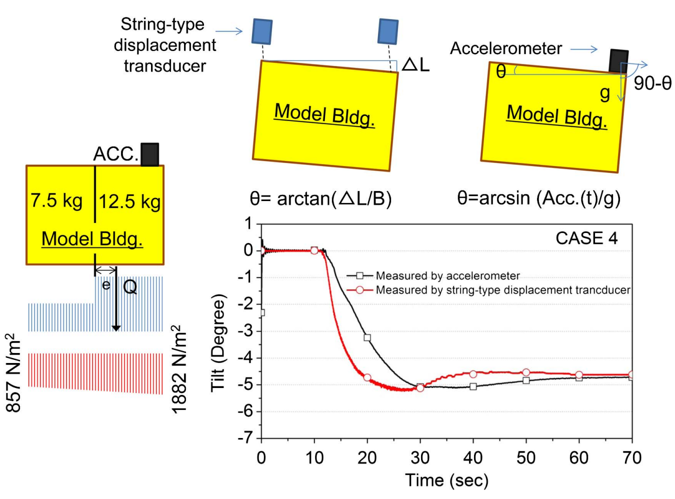

Fig. 2. Schematic illustration of foundation's surface pressure and calculation of tilting of the model structure.

Three mitigations were proposed to reduce tilting of model building due to liquefaction. The first method was installation of sheet-pile walls around the building's foundation. Aluminum plates of 2-mm thickness were utilized for modeling the sheet piles around the foundation. The plates were fixed at the bottom (which represents reaching a nonliquefiable layer) and were constrained from lateral displacement at the top (hinge condition). The flexure rigidity of the plates was $\mathrm{EI} = 47 \times 10^{-3}\ \mathrm{kN} \cdot \mathrm{m}^2/\mathrm{m}$. In the second option, diagonal prefabricated drainage pipes were installed. The drains were modeled by plastic pipes with many holes on them. The holes were covered by small-sized metallic mesh to prevent influx of liquefied sand into the drain. Third, limited surface ground improvement was carried out. Epoxy glue was used as the bonding agent between soil particles to model the improvement of the ground under the model building. More details about the model preparation have been given by Rasouli (2014) and Vonaesch (2014).

All of the experiments were conducted with the same base input motion for comparison. Fig. 3 shows the time history of base shaking in which the sinusoidal waves with the maximum amplitude of $0.3g$ were applied to the model along its longitudinal direction. The Arias intensity of this input motion during its maximum amplitude (15–26s) is $I_a = (\pi/2g)\int_{t=15}^{t=26} a(t)^2 dt$, where $a(t) = \sin(20\pi t)$ and $I_a = 2.5918$. This intensity was discussed by experts to be considered in the future design code after the 2011 earthquake in Japan. Ground-motion characteristics affect the performance of the proposed countermeasures and the extent of damage to the building. Although the nonsymmetric time history of ground motion is one cause of tilting, the present study uses harmonic shaking in order to focus on the effects of nonuniform loading. The scope of this study should be kept in mind when interpreting the experimental results and conclusions.

Relative density of 46% for the liquefiable layers is equivalent to about 60% relative density in the prototype because the low stress level in $1g$ model tests is compensated by this reduction of density (similitude of dilatancy) (Towhata 2008). The frequency of input motion was 10 Hz, and the entire duration of motion was 25 s. Shaking lasted for a long time in order to consider an earthquake of large magnitude and also to reproduce the worst extent of subsidence and tilting. Considering Iai's (1989) law of similitude with a scale factor of 20, these experiments are modeling a scenario

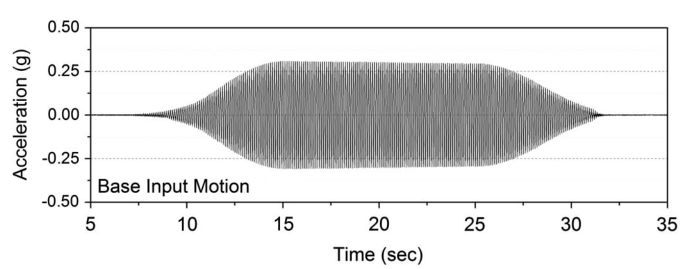

Fig. 3. Base input motion.

Table 1. Law of simulation based on Iai (1989)

Ratio of scale factor, $n = 20$	Iai (1989)	Model	Prototype
Vertical length	n	1	20
Horizontal length	n	1	20
Mass density	1	1	1
Stress and pressure	n	1	20
Shaking time	$n^{3/4}$	1	9.46
Acceleration	1	1	1
EI of pile/width	$n^{7/2}$	1	35,777

where an earthquake of $0.3g$ and 1 Hz frequency strikes a 3-story residential building of 150 t weight founded on a 7.5×7.5 m area for a long duration, as happened during the 2011 earthquake in Japan. The building is supposed to be sited on a 6-m-deep liquefiable layer, overlain on a stiff nonliquefiable layer. The use of water as the pore liquid in the present series of experiments caused underestimates of the performance of drains. The experimental results are reported in this paper so other similitude laws can be taken into account for consideration in future studies. Table 1 summarizes the relationship between model and prototype values based on Iai's (1989) similitude law.

Table 2 presents the program of experiments. Three experiments were conducted as uniformly loaded buildings to serve as control cases (Cases 1–3). Cases 4 and 5 are the control cases for the model building tilting without application of any countermeasures. Cases 6–8 examine the effects of embedment of the foundation on the settlement and tilting. The performance of sheet piles against tilting of structures is examines in Cases 9–13, and the effects of a diagonal drain are studied in Case 14–18. Finally, Cases 19–22 were conducted to observe the effects of limited surface soil improvement on prevention of liquefaction-induced distortion of buildings. The schematic illustration of the application of these countermeasures is provided in Fig. 1(b).

Mechanism of Settlement and Tilting of the Building

Knowing the mechanism and maximum possible settlement of structures during an earthquake gives invaluable insights into prevention of settlement and tilting of the buildings. Fig. 4 shows the time history of settlement of the uniformly loaded model building (defined as displacement of the building from its initial position) without application of any countermeasure. The building experienced less settlement in cases with an embedded foundation compared with the results of corresponding experiments with a surface foundation (compare Case 1 with Case 6 and Case 2 with Case 7). This behavior can be explained by assuming the liquefied sand as a liquid and then calculating the subsidence of the structure in this liquid until the balance of gravity and buoyancy forces are reached. Towhata (2008) suggested that by such consideration of the liquefied sand as liquid, the maximum settlement of river dikes can be estimated by force equilibrium calculations between the gravity and buoyancy forces. The same approach is used in the estimation of the settlement of the model buildings in these experiments. Eq. (2) is used for these estimations

$$S = \frac{m \times g}{\gamma \times L \times w} - E \qquad (2)$$

where $m \times g$ = weight of the building; γ = saturated density of liquefiable soil; L and w = length and width of the surface on which

Table 2. Characteristics of experiments

Case number	Soil	GWL[a] (cm)	Eccentric load	SP[b]	Drains	Embedment	SI[c] (cm)
Case 1	Saturated	0	N/A	N/A	N/A	N/A	N/A
Case 2	Wet[d]/saturated	−5	N/A	N/A	N/A	N/A	N/A
Case 3	Wet/saturated	−10	N/A	N/A	N/A	N/A	N/A
Case 4	Wet/saturated	−5	A[e]	N/A	N/A	N/A	N/A
Case 5	Wet/saturated	−10	A	N/A	N/A	N/A	N/A
Case 6	Saturated	0	N/A	N/A	N/A	A	N/A
Case 7	Wet/saturated	−5	N/A	N/A	N/A	A	N/A
Case 8	Wet/saturated	−5	A	N/A	N/A	A	N/A
Case 9	Wet/saturated	−5	N/A	A	N/A	N/A	N/A
Case 10	Wet/saturated	−10	N/A	A	N/A	N/A	N/A
Case 11	Wet/saturated	−5	A	A	N/A	N/A	N/A
Case 12	Wet/saturated	−5	A	A, short[f]	N/A	N/A	N/A
Case 13	Wet/saturated	−5	N/A	A, short	N/A	N/A	N/A
Case 14	Saturated	0	N/A	N/A	A	N/A	N/A
Case 15	Wet/saturated	−10	N/A	N/A	A	N/A	N/A
Case 16	Wet/saturated	−5	N/A	N/A	A	N/A	N/A
Case 17	Wet/saturated	−10	A	N/A	A	N/A	N/A
Case 18	Wet/saturated	−5	A	N/A	A	N/A	N/A
Case 19	Saturated	0	A	N/A	N/A	N/A	A, $L = 40$[g], $H = 10$[h]
Case 20	Saturated	0	A	N/A	N/A	N/A	A, $L = 50$, $H = 5$
Case 21	Saturated	0	A	N/A	N/A	N/A	A, $L = 60$, $H = 10$
Case 22	Saturated	0	A	N/A	N/A	N/A	A, $L = 80$, $H = 10$

[a]Groundwater level from surface.
[b]Sheet-pile walls.
[c]Surface improvement.
[d]Wet sand near the surface; surface nonliquefiable layer.
[e]A = applied in the experiment.
[f]Short sheet piles not reaching the bottom nonliquefiable layer.
[g]Length of surface improvement.
[h]Height of surface improvement.

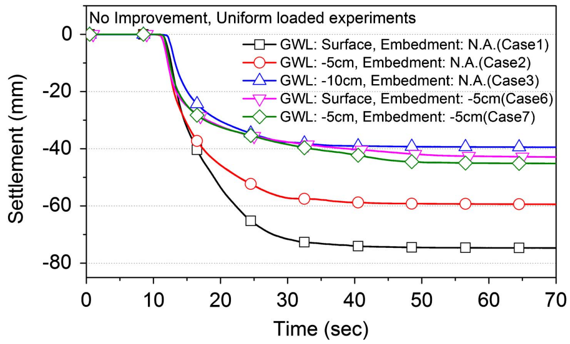

Fig. 4. Time history of settlement of the model building in uniformly loaded experiments without improvement.

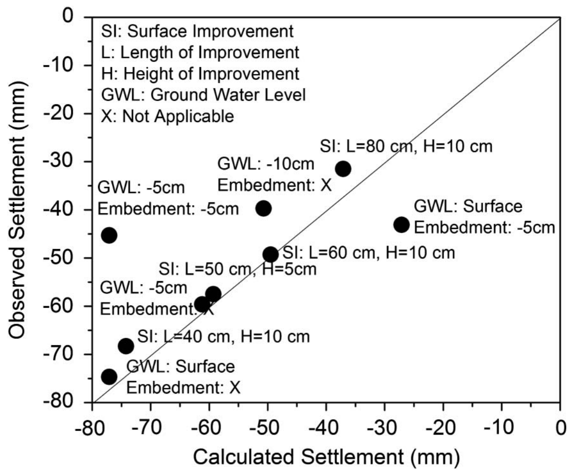

Fig. 5. Comparison between the observed settlement and its estimation based on buoyancy and gravity force equilibrium.

the weight of the building model is acting on the liquefiable ground; and E = embedded part of the foundation under the GWL.

In this study, the duration of shaking was long and its intensity was large enough to assume building models reached their ultimate settlement. The estimated settlement of the model building based on force equilibrium between gravity and buoyancy is compared with the actual observed value in Fig. 5. Cases with no sheet-pile walls and no drains were considered for this comparison. In addition, in cases of surface improvement (SI) where the building's loading was nonuniform, the settlement of the center of the model building (which represents the average of the nonuniform settlement) was considered as the observed settlement. For this calculation, the model building was assumed to be placed on liquid (liquefied soil) and to have sank until the buoyancy force balanced the downward gravity force of the building. Fig. 5 shows that the estimation of the settlement of the building with this approach is consistent with the observed settlement of the building at the end of shaking for cases with no embedded foundation.

In cases with an embedded foundation [Fig. 2(b)] and surface GWL (Case 6), the observed settlement is greater than the estimated settlement (Fig. 5). This inconsistency between the observed and estimated settlement in this case is because in the calculation of the settlement, it was assumed that the soil is basically liquid from the beginning to the end of the test and the buoyancy force is acting on the building even before the shaking. However, in reality, there is no buoyancy force before the shaking and liquefaction of the ground.

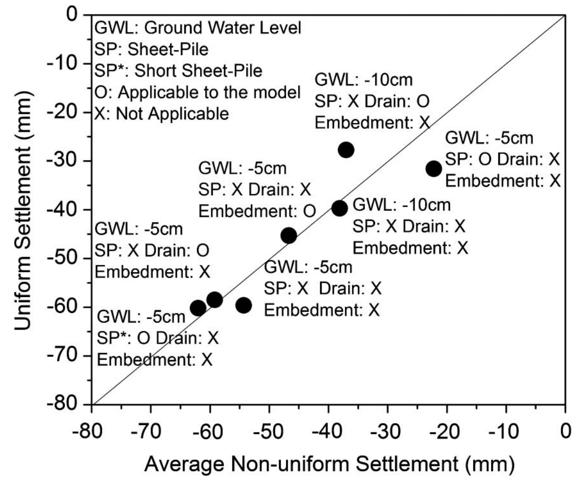

Fig. 6. Comparison between the uniform and averaged nonuniform settlement of buildings in different cases.

The observed settlement in case of embedded foundation and −5 cm GWL (Case 7) was below the estimated value. In the estimation of the settlement of this case, the soil above GWL was assumed not to be liquefied during the shaking; however, after some seconds after the beginning of shaking, the high-pressure groundwater reached the 5-cm surface unsaturated layer, which it liquefied. This caused some additional buoyancy force, which could be the reason for the observed settlement being less than the predication in this case.

Fig. 6 compares the settlement of a uniformly loaded building and averaged settlement of a non-uniformly loaded building with the same conditions and mitigations. The settlement at the center of the model building, which represents the average settlement of the model building in the non-uniformly loaded cases, is plotted in this figure. The figure indicates that the total settlement of the building is very close in uniformly and non-uniformly loaded cases, regardless of the uniformity of the building's surface pressure. The effect of embedment of the foundation is also illustrated in this figure. As discussed previously, by considering the buoyancy force of the liquefied sand when the foundation is embedded in the ground and the groundwater level is at surface, the settlement of the building from its initial position is less than in the case where the foundation is on the surface.

The tilting of the building is dependent on the liquefaction of the underlying soil. As shown in Fig. 7(a), both settlement and tilting of the building took place when the underlying soil liquefied. However, in Case 5 [Fig. 7(b)], the lower GWL stopped the tilting of the building even during shaking, whereas settlement continued. This was probably because of the formation of the force equilibrium between the surface nonliquefied layer and the nonuniform load of the building in Case 5 (−10 cm GWL). However, in Case 4 (−5 cm GWL), the high-pressure GWL reached the surface and softened the entire thin 5-cm nonliquefiable layer at the surface, and such a force equilibrium did not occur.

Evaluation of Possible Mitigations against Tilting of Structures

To date, studies have mainly been devoted to the uniform liquefaction-induced settlement of buildings but the literature lacks studies on nonuniform settlement or tilting of structures due to liquefaction. Rasouli et al. (2015) proposed installation of sheet-pile

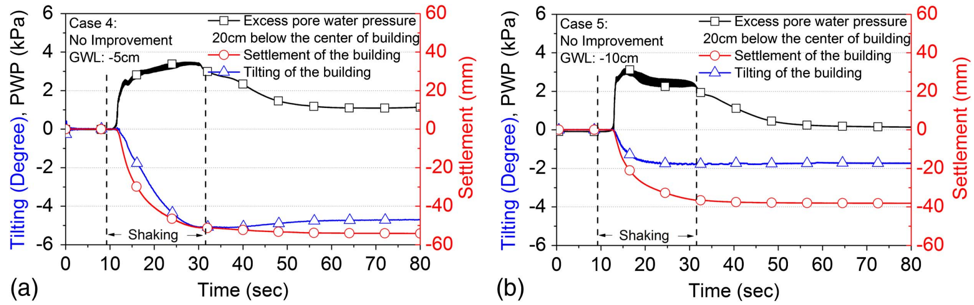

Fig. 7. Relationship between developed excess PWP, tilting, and settlement of building: (a) Case 4, GWL = −5 cm; and (b) Case 5, GWL = −10 cm.

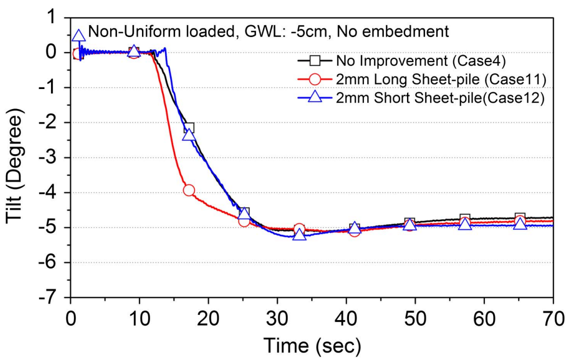

Fig. 8. Time history of model building's tilting in different cases of installation of sheet-pile walls.

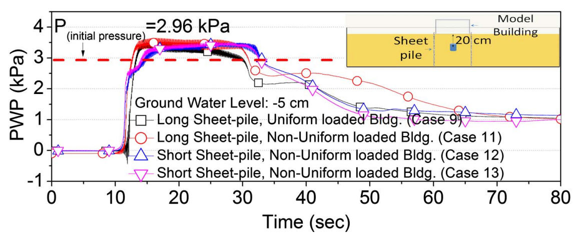

Fig. 9. Development of excess pore-water pressure under the building model, which led to tilting of the structure.

walls accompanied by limited lowering of the GWL as a countermeasure against uniform settlement of a building during liquefaction and concluded that if the sheet piles reach the bottom nonliquefiable layer and are confined from lateral displacement at their tops with limited lowering of GWL at surface, the building's settlement can be prevented. As another countermeasure, Rasouli et al. (2016b) examined the performance of installation of diagonal prefabricated drains with different configurations against the same problem. That study revealed that complete prevention of liquefaction in the column of soil under the building accompanied by limited lowering of GWL will substantially reduce the settlement of the building. In this paper, the performance of the same proposed countermeasures and one other possible mitigation (limited surface improvement) is examined against tilting of buildings.

Installation of Sheet-Pile Walls around the Foundation

Fig. 8 shows time histories of tilting of the model building in different cases with and without installation of sheet-pile walls. In cases with long sheet piles (Case 11), in which the sheet piles reach the bottom nonliquefiable layer, there was an approximately 3-cm gap between the model building's foundation and head of the sheet pile, whereas in the cases with short sheet piles, the head was mechanically fixed to the building's foundation. No recognizable effect of installation of sheet piles can be seen in reduction of tilting in Fig. 8. The building model tilted more or less similarly to the cases with no sheet-pile installation. Such behavior can be attributed to the similar development of the excess pore-water pressure under the model building (Fig. 9) and consequent deformation of the liquefied zone in the constrained liquefied soil surrounded by the sheet piles, bottom of the building's foundation, and bottom nonliquefiable layer (Fig. 10).

When the building was loaded uniformly, the installation of the sheet piles that were fixed at the bottom (which represents reaching the nonliquefiable layer) and constrained at the top (without any mechanical attachment to the building's foundation) decreased settlement by preventing the lateral deformation of the liquefied soil under the building (Rasouli et al. 2015). As discussed previously, the averaged nonuniform settlement of the building is more or less

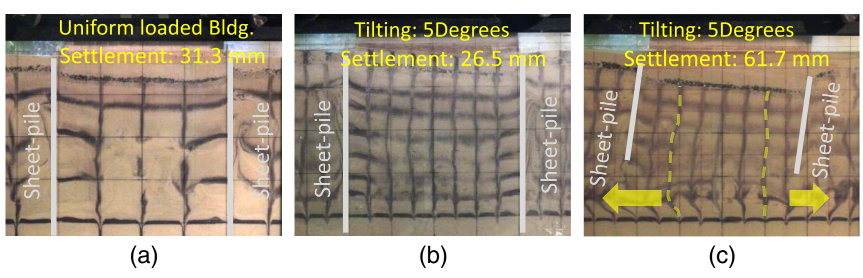

Fig. 10. Deformation of the liquefied sand under the model building in (a) Case 9, with long sheet piles and uniform loading; (b) Case 11, with long sheet piles and nonuniform loading; and (c) Case 12, with short sheet piles and nonuniform loading.

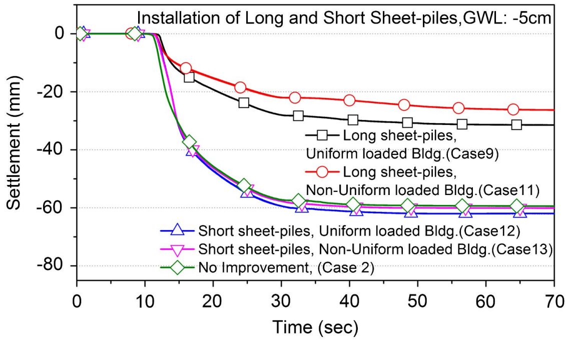

Fig. 11. Time history of settlement of the building in different cases of uniform and nonuniform loading on a building with ground reinforced by sheet piles.

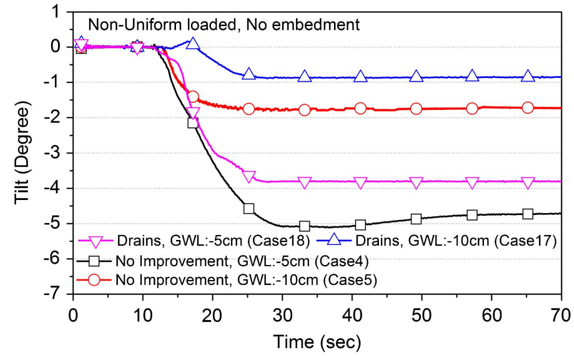

Fig. 13. Time history of model building's tilting in different cases of installation of drains.

equal to uniformly loaded buildings (Fig. 6); however, the considerable deformation of the liquefied soil under the building caused considerable tilting of the non-uniformly loaded building (Fig. 10). Fig. 11 shows that both the uniform and averaged nonuniform settlement of the building are reduced by installation of sheet-pile walls in both uniformly and non-uniformly loaded cases. In cases with short sheet piling, the liquefied sand escaped from the gap between the tip of the sheet pile and bottom nonliquefiable layer, and no recognizable reduction of settlement was observed [Fig. 10(c)]. The reduction in settlement in cases with long sheet piling can be helpful in postquake restoration works, even though this countermeasure failed to reduce the tilting of the building directly. Installation of sheet piles in non-uniformly loaded buildings had no effect on prevention of deformation of the liquefied soil inside the constrained area under the building (Fig. 10). Therefore, the nonuniform load of the building deformed the liquefied soil with no resistance, and the model building tilted similarly.

Installation of Inclined Drains under the Foundation

The protective mechanism of drains is different from that of sheet-pile walls. Drains prevent onset of liquefaction in their effective zone. Rasouli et al. (2016b) showed that complete prevention of the liquefaction under the building (with the priority of the shallower levels) is required to substantially reduce settlement.

Installation of vertical drains around the foundation of the building accompanied by shallow diagonal and based diagonal drains prevented liquefaction under the building model. The nonliquefied column of soil under the building does not easily deform under uniform and nonuniform loading (Fig. 12); consequently, tilting of model building was reduced by installation of drains (Fig. 13). Tilting of the building model was reduced by about 20% and 50% in cases with GWL of −5 and −10 cm, respectively. The settlement and tilting of the building model in these cases were mainly due to the loss of strength of the soil in free-field areas and consequent reduction of confining pressure on the column of soil under building model.

Fig. 14 shows the contours of the maximum excess pore-water pressure ratio. The recorded data by excess PWP transducers were divided by the initial vertical effective stress of the sensors' positions. The maximum value of the time history of the recorded data was used for plotting Fig. 14. This figure shows that installation of drains provided a column of nonliquefied ground under the model building throughout the experiment. This nonliquefied column resists both uniform and nonuniform settlement of the building. This is consistent with the negligible deformation of the column of the soil under the building due to the prevention of liquefaction by the drains (Fig. 12). The settlement of the building was also reduced in nonuniform loading cases (Cases 17 and 18), the same as in uniform loading experiments (Fig. 15). The effect of a surface nonliquefiable layer in reduction of settlement can be recognized by comparison of cases with different GWLs (compare Cases 15 and 16 with Cases 17 and 18). Lowering GWL by 5 cm (GWL from −5 to −10 cm) reduced the settlement by about 40%–50%. The protective effects of lowering GWL can be seen in terms of tilting of the building as well, where lowering of GWL by 5 cm reduced the tilting of the structure by about 60%–70%.

Limited Surface Ground Improvement

The considerable effect of a surface nonliquefiable layer suggests that limited surface ground improvement under the building is a wise alternative countermeasure instead of lowering the GWL of a vast area. In practice and in case of existing structures, application of limited surface ground improvement is possible by creation of miniature injection holes in the first floor of the building. In this series of experiments, epoxy glue was utilized for preparation of the improved-ground model. Fig. 16 shows the unconfined

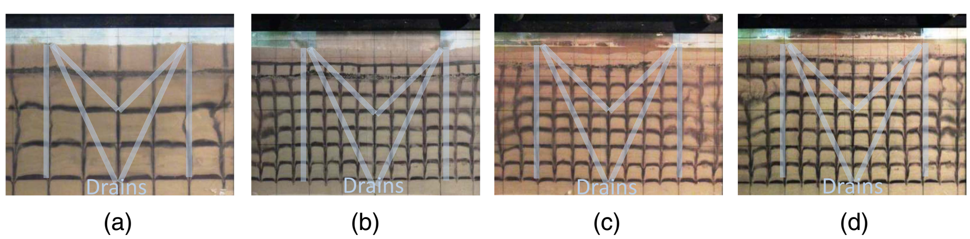

Fig. 12. Prevention of liquefaction and deformation of the ground under the model structure by installation of vertical and diagonal drains under the foundation: (a) Case 15; (b) Case 16; (c) Case 17; and (d) Case 18.

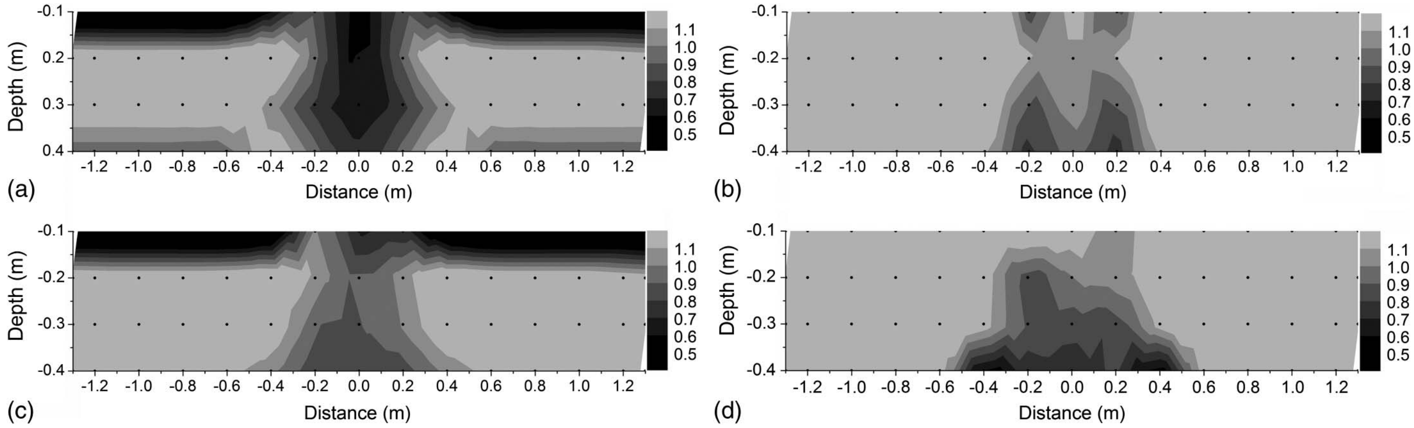

Fig. 14. Contours of maximum excess pore-water pressure ratio: (a) Case 15, with drains, uniform loading, and GWL = −10 cm; (b) Case 16, with drains, uniform loading, and GWL = −5 cm; (c) Case 17, with drains, nonuniform loading, and GWL = −10 cm; and (d) Case 18, with drains, uniform loading, and GWL = −5 cm.

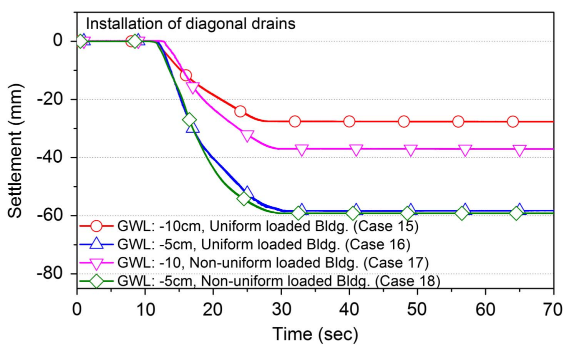

Fig. 15. Time history of model building's settlement in different cases of installation of drains.

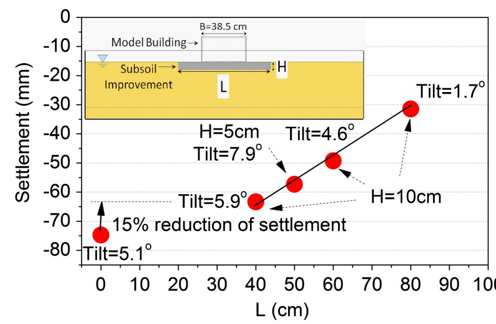

Fig. 17. Linear decrease of settlement by increasing the length of improvement under the building model.

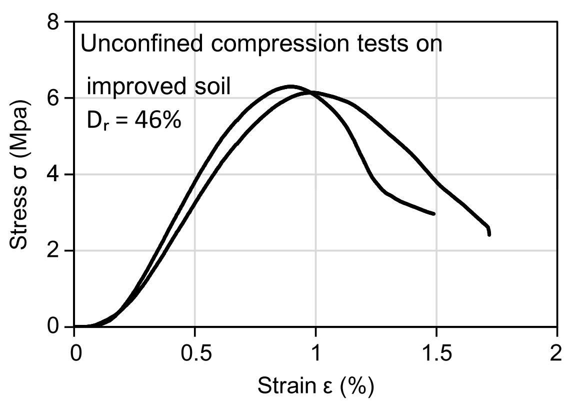

Fig. 16. Unconfined compression strength of soil improved by 5% epoxy glue.

compression strength of the improved soil used for these series of experiments, which was too strong to deform under the stress levels of these series of experiments and therefore models a perfect noncompressible improved soil under the building model. The relative density of the improved soil was kept equal to that in the unimproved-ground model to prevent any displacement of the improved soil block due to buoyancy forces. The effects of depth and length of improvement on settlement and tilting of the model structures are examined in these experiments.

Fig. 17 shows that the settlement of the building model decreased by increasing the length of the improvement, but depth of the improvement had less effect. As discussed in previous sections and illustrated in Fig. 5, the settlement of the model building can be estimated by buoyancy and gravity force equilibrium and is reduced in cases with surface improvement because of the reduction of surface pressure on the liquefied ground by providing a larger area for building's pressure to be acted upon. Similarly, tilting of the structure is also reduced by increasing the length of improvement under the model building (Fig. 18).

Fig. 19 shows that limited rigid improved ground under the building with a length almost twice the length of the model building ($B = 38.5$ cm) decreases the settlement slightly better than the case of dewatering a vast area and providing a compressible nonliquefiable layer under the building (compare rigid-$L = 80$ cm versus compressible-$L = 260$ cm in Fig. 19). It is also observed that the depth (H) of compressible nonliquefiable layer affected the settlement of the building because the settlement increased by almost 50% when the depth of compressible nonliquefiable layer was 50% shallower (compare compressible-$H = 5$ cm versus compressible-$H = 10$ cm in Fig. 19). This occurs because the high-pressure underground water flows into the compressible unimproved layer during liquefaction and loses its strength. However, this loss of strength does not occur in the rigid improved layer. It is understood from Fig. 19 that the depth of the surface nonliquefiable layer is less important in reduction of the settlement when this layer is provided by high-strength soil improvement [e.g., settlement of

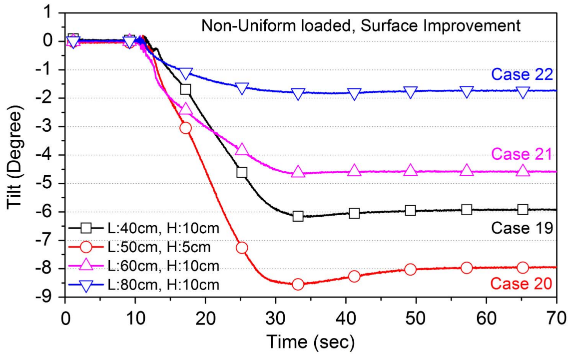

Fig. 18. Effects of the length and compressibility of the surface nonliquefiable layer.

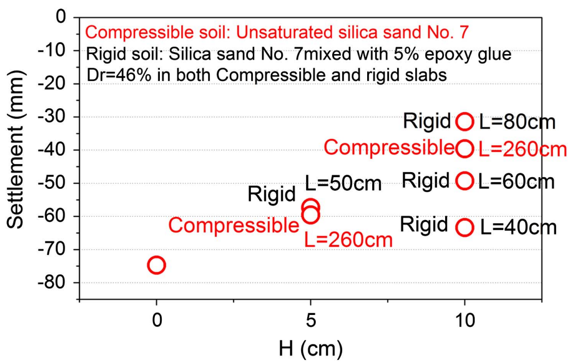

Fig. 19. Time history of building model's tilting in different cases of surface improvement.

the building in case of $L = 50$ cm, which is between the cases of $L = 40$ cm and $L = 60$ cm, regardless of the 50% shallower depth of improvement (H)].

Unlike settlement, the building model's tilting is dependent on the depth of surface improvement. Fig. 18 shows that tilting of the building model in case of $L = 50$ cm and $H = 5$ cm is almost 25% greater than the case of $L = 40$ cm and $H = 10$ cm. This is due to the greater lateral soil pressure acting on the side of the improved block of soil with greater H, even during the liquefaction, which partly counterbalances the nonuniform load of the building model. Furthermore, the tilt of the building in Cases 19 ($L = 40$ cm and $H = 10$ cm) and 20 ($L = 50$ cm and $H = 5$ cm) was more than in the case with no improvement. This is probably due to less interlocking between the smooth foundation of building model and rigid improved soil block, which made it easier for the building model to slide in some inclinations. These points deserve further studies in future.

Concluding Remarks

Performance of three economically reasonable countermeasures against tilting of existing buildings on liquefiable ground was studied by conducting $1g$ shaking-table experiments. The proposed mitigations included (1) installation of sheet-pile walls around the foundation and limited dewatering; (2) installation of diagonal drains under the foundation and limited dewatering; and (3) limited surface ground improvement.

The building was modeled by a rigid box, and the models were shaken by symmetric sinusoidal motion. Although it was found that the characteristics of the building and input ground motion significantly affect the performance of the mitigations and damage to the buildings, the assumptions of this study should be considered when interpreting the results. Based on the scope of this study, the following conclusions can be drawn:

- The settlement of a building in liquefied soil can be estimated by buoyancy–gravity force equilibrium. This mechanism describes the similar settlement of the uniformly loaded and nonuniformly loaded (same total load) buildings and gives insights about possible countermeasures.
- Installation of sheet piles does not reduce tilting of the building directly; this is due to deformation of the liquefied soil in the constrained area between the sheet piles, building foundation, and bottom nonliquefiable layer. However, it would be helpful for postquake restoration works and balancing of the building by reducing settlement of the building. For sheet pile to have a mitigative effect against settlement, their reaching the bottom nonliquefiable layer is essential. Short sheet piling does not reduce either tilting or the settlement of the buildings.
- Unlike sheet-pile walls, installation of drains provided a column of nonliquefied ground under the building, and when it was accompanied by adequate lowering of the GWL, both settlement and tilting of the model building was reduced substantially. Prevention of liquefaction in the whole depth of the soil column under the building is essential for having the best performance.
- Shallow and wide soil improvement under the building can be a good alternative for vast lowering of the GWL. Shallow, strong soil improvement with a length double the building's length is expected to work as well as a vast lowering of the GWL against both tilting and settlement of the building. The depth of improvement is not critical in reduction of the total settlement of the building, but it plays an important role in reduction of tilting.

References

Cubrinovski, M., D. Henderson, and B. Bradley. 2012. "Liquefaction impacts in residential areas in the 2010–2011 Christchurch earthquakes." In *Proc., Int. Symp. on Engineering Lessons Learned from the Giant Earthquake*, 811–824. Tokyo: Japan Association for Earthquake Engineering.

Cubrinovski, M., M. Taylor, D. Henderson, A. Winkley, J. Haskell, B. A. Bradley, M. Hughes, L. Wotherspoon, J. Bray, and T. O'Rourke. 2014. "Key factors in the liquefaction-induced damage to buildings and infrastructure in Christchurch: Preliminary findings." In *Proc., 2014 New Zealand Society for Earthquake Engineering Annual Conf.*, 9. Auckland, New Zealand: New Zealand Society for Earthquake Engineering.

Dashti, S., J. Bray, J. M. PestanaRiemer, and D. Wilson. 2010. "Centrifuge testing to evaluate and mitigate liquefaction-induced building settlement mechanisms." *J. Geotech. Geoenviron. Eng.* 136 (7): 918–929. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000306.

Iai, S. 1989. "Similitude for shaking table tests on soil-structure-fluid model in 1 g gravitational field." *Soils Found.* 29 (1): 105–118. https://doi.org/10.3208/sandf1972.29.105.

JCSA (Japan Structural Consultants Association-Chiba Branch). 2011. "Methods of restoration after liquefaction-induced tilting." [In Japanese.] Accessed October 27, 2015. http://www.jsca-chiba.com/PDF/110617_ekijyoka.pdf.

Konagai, K., T. Kiyota, S. Suyama, T. Asakura, K. Shibuya, and C. Eto. 2013. "Maps of soil subsidence for Tokyo bay shore areas liquefied in the March 11th, 2011 off the Pacific coast of Tohoku earthquake." *Soil Dyn. Earthquake Eng.* 53 (Oct): 240–253. https://doi.org/10.1016/j.soildyn.2013.06.012.

Rasouli, R. 2014. "Experimental study on mitigation of liquefaction-induced settlement of structures with shallow foundation." Ph.D. dissertation, Dept. of Civil Engineering, Univ. of Tokyo.

Rasouli, R., K. Hayashi, and K. Zen. 2016a. "Controlled permeation grouting method for mitigation of liquefaction." *J. Geotech. Geoenviron. Eng.* 142 (11): 04016052. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001532.

Rasouli, R., I. Towhata, and T. Akima. 2016b. "Experimental evaluation of drainage pipes as a mitigation against liquefaction-induced settlement of structures." *J. Geotech. Geoenviron. Eng.* 142 (9): 04016041. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001509.

Rasouli, R., I. Towhata, and T. Hayashida. 2014. "1-g shaking table tests on mitigation of seismic subsidence of structures." In *Proc., 8th Int. Conf. of Physical Modelling in Geotechnics*, 1001–1007. London: Taylor & Francis.

Rasouli, R., I. Towhata, and T. Hayashida. 2015. "Mitigation of seismic settlement of light surface structures by installation of sheet-pile walls around the foundation." *Soil Dyn. Earthquake Eng.* 72: 108–118. https://doi.org/10.1016/j.soildyn.2015.02.010.

Tani, K., K. Matsushita, T. Hashimoto, A. Yamamoto, H. Takeuchi, T. Noda, H. Kiku, J. Obayashi, and T. Kiyota. 2014. "Mitigation of liquefaction-induced damage to residential houses by surface ground improvement and its cost evaluation." *Jpn. Geotech. J.* 9 (4): 533–553. https://doi.org/10.3208/jgs.9.533.

Tokimatsu, K., S. Tamura, H. Suzuki, and K. Katsumata. 2012. "Building damage associated with geotechnical problems in the 2011 Tohoku Pacific earthquake." *Soils Found.* 52 (5): 956–974. https://doi.org/10.1016/j.sandf.2012.11.014.

Towhata, I. 2008. *Geotechnical earthquake engineering*, 520–523. Berlin: Springer.

Towhata, I., et al. 2014. "Liquefaction in the Kanto region during the 2011 off the Pacific coast of Tohoku earthquake." *Soils Found.* 54 (4): 859–873. https://doi.org/10.1016/j.sandf.2014.06.016.

Vonaesch, R. 2014. "Reduction of seismic settlement and tilting of structures using ground improvement: Shaking table experiments." Master's thesis, Dept. of Civil, Environmental and Geomatic Engineering, ETH Zürich.

Yasuda, S., and Y. Ariyama. 2008. "Study on the mechanism of the liquefaction-induced differential settlement of timber houses occurred during the 2000 Tottoriken-Seibu earthquake." In *Proc., 14th World Conf. on the Earthquake Engineering*. Tokyo: International Association for Earthquake Engineering.

Yasuda, S., T. Hitomi, and T. Hashimoto. 2004. "A detailed study on the liquefaction-induced settlement of timber houses during the 2000 Tottoriken-Seibu earthquake." In *Proc., 5th Int. Conf. on Case Histories in Geotechnical Engineering*. Rolla, MI: Missouri Univ. of Science and Technology.