

Residual Deformation Analyses to Demonstrate the Effect of Thin Steel Sheet Piles on Liquefaction-Induced Penetration Settlement of Wooden Houses

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ABSTRACT

Liquefaction-induced damage to wooden houses occurred in a wide area due to the Great East Japan Earthquake of March 11, 2011. About 27,000 houses settled and tilted in many residential areas. Machines for current countermeasures are too big to use in residential areas. The authors have developed a new countermeasure, enclosing new or existing wooden houses with thin steel sheet piles using a small machine. The effectiveness of this countermeasure was studied by conducting large 1-G shaking table tests on ¼ scale model houses. To establish a design method, several residual deformation analyses have been conducted under various thicknesses of the liquefied layer, depths of thin steel sheet piles, depths of the groundwater table and lateral boundaries, focusing on the penetration settlement and tilting of wooden houses. Analyzed results showed that the penetration settlement of houses decreases with the depth of the sheet piles and the depth of the water table.

Introduction

The 2011 Great East Japan Earthquake, with a magnitude of $M_w=9.0$, occurred in the Pacific Ocean about 130 km off the northeast coast of Japan's main island on March 11, 2011. According to the Ministry of Land, Infrastructure, and Transport, about 27,000 houses were damaged due to soil liquefaction caused by this earthquake. About half of the damaged houses are located in the Tokyo Bay area. The total area of liquefied zones in the Tokyo Bay area, from Shinkiba in Tokyo through Urayasu, Ichikawa and Narashino cities to Chiba City, was about 42km² (Yasuda et al., 2012, Yasuda, 2014). The most seriously damaged area was Urayasu City, where about 85% of the city area liquefied and 8,469 wooden houses were damaged, as shown in Table 1. Figure 1 shows typical liquefaction-induced damage to wooden houses in Urayasu City. Large penetration settlement and tilting of wooden houses occurred in many residential areas. Two houses or four houses close to each other tilted toward each other. Many kinds of remediation methods for liquefaction have been developed in Japan since the 1964 Niigata Earthquake. However, in the design of wooden houses, liquefaction had not been considered. This is the main reason such a large number of houses were damaged. Soon after the 2011 Great East Japan Earthquake, efforts to modify current liquefaction countermeasures for individual new or existing houses started. Remediation measures for individual houses must be economical

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and applicable to a narrow space. Normal soil improvement methods, such as sand compaction piles and deep mixing, are economical but not easy to apply in a narrow area. The authors proposed a new measure, enclosing the foundation soil of a house with thin steel sheet-piles, and confirmed its applicability to houses by large-scale shaking table tests (Kaneko et al., 2014). In addition several residual deformation analyses under different thicknesses of liquefied layers, depths of thin steel sheet piles, depths of the groundwater table and lateral boundaries were conducted to establish a design method.

Table 1: Number of houses damaged by liquefaction in Urayasu City.

Grade of damage	Number of damaged house
Completely	10
Large-scale partially destroyed	1,509
Partially destroyed	2,102
Partially injured	4,848
No damage	963
Total	9,432



Figure 1: Settled and tilted houses in Urayasu City.

Outline of Sheet-Pile Enclosing Method

In the sheet-pile enclosing method, sheet piles are installed around the foundation of a house and connected to the foundation, as schematically shown in Figure 2. A house probably settles for two reasons: i) the lateral flow of liquefied foundation ground due to a decrease of the shear modulus of the liquefied layer, as shown in Figure 3 (a), and ii) the densification of the liquefied layer due to the dissipation of excess pore water pressure. When a liquefied layer is of uniform thickness and the upper non-liquefied layer is thin, houses penetrate into the ground, often at an angle, due to the lateral flow of the liquefied layer. On the contrary, if the ground under a house is enclosed by sheet piles to the depth of the bottom of the liquefied layer, as shown in Figure 3 (b), the house does not settle because the soil under the house, even though liquefied, cannot flow laterally. If the sheet piles are installed to a depth of the middle of the liquefied layer, as shown in Figure 3 (c), small penetration settlement of a house is induced because the lower liquefied soil flows laterally. However the penetration settlement of the house is minor and it can

be controlled to allowable levels by adjusting the depth of the sheet piles. The impact of enclosing the foundation soil of a house with sheet piles on settlement if the foundation ground beneath the house liquefies had been studied by one of the authors and his colleagues, who conducted small-scale shaking table tests on model houses before the 2011 Great East Japan Earthquake. Immediately after the earthquake, the applicability of this method to actual houses was discussed, and additional small-scale and large-scale shaking table tests were conducted. Subsequently, this method was applied to a newly constructed house and to existing warehouses. In addition, the effect of the depth of the sheet piles and the depth of the water table on the settlement of a house enclosed by sheet piles was analyzed.

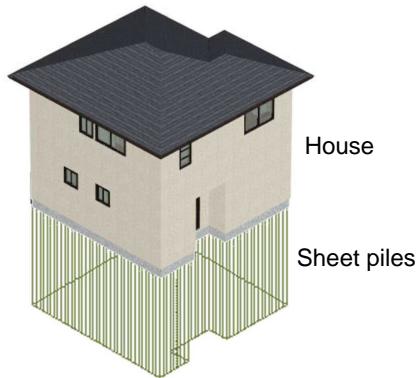


Figure 2: Schematic diagram of sheet-pile enclosing method.

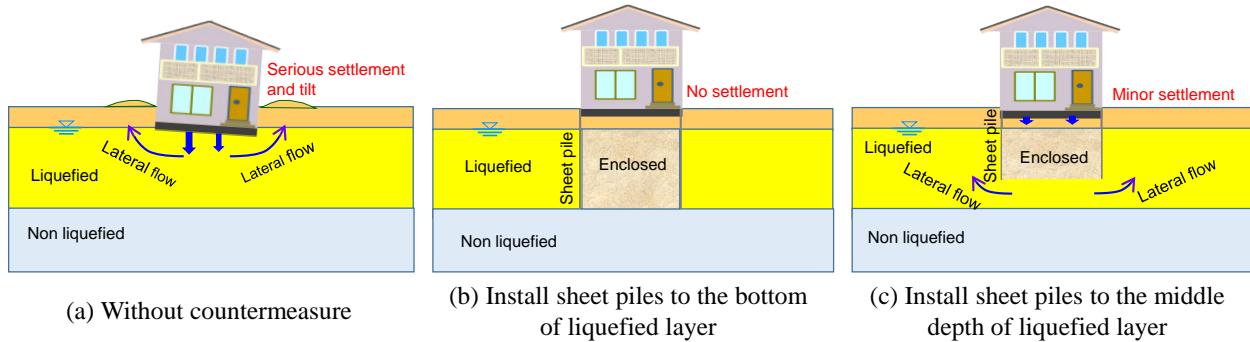


Figure 3: Effect of enclosing by sheet piles on the penetrate settlement and tilt of a house.

Method and Conditions of Analyses

The liquefaction-induced deformation of structures can be estimated by empirical methods, static analyses (residual deformation method), and dynamic analyses. In this study, a static method called ALID (Yasuda et al. 1999) was used to analyze the liquefaction-induced settlement of a wooden house because this method is simpler than dynamic analyses. Figure 4 shows a schematic diagram of stress-strain curves of an intact soil and a liquefied soil. Shear strain increases with very low shear stress up to a resistance transformation point, after which, shear stress increases rapidly with shear strain, following a decrease in pore water pressure. Based on these relationships, the “ALID/Win” computer code was developed. The ALID method is a static finite element method applied in two steps. First, the deformation of the ground before an earthquake is calculated using the stress-strain relationships of unliquefied soils. Second, the

additional deformation of the ground due to liquefaction is calculated using the stress-strain relationship of liquefied soils. Deformation of the ground due to the dissipation of excess pore pressure is also considered. Many cyclic torsional tests were conducted to obtain the stress-strain curves of liquefied sands and softened clays, and a unified relationship between the shear modulus of the liquefied soil G_1 , the effective confining pressure σ'_c , the undrained cyclic strength ratio (liquefaction strength ratio) R_L , and the safety factor against liquefaction F_L , was proposed (see Figure 5). (Yasuda et al. 2004)

The two models shown in Figures 6 (a) and 6 (b), a house on flat liquefied ground and a house on liquefied ground with an adjacent underground wall that prevents horizontal displacement of the ground, were analyzed. In the first model, analyses were conducted under several depths of the water table, thicknesses of the liquefied layer, and depths of the sheet piles, as shown in Table 2. In the second model, analyses were conducted for four distances between the house and the underground wall. The thickness of the liquefied layer and the depth of the water table were fixed as 15.0 m and GL-1.0m, respectively, in the second model. Nodal points at the left boundary in the second model were assumed to be fixed in the horizontal direction and free in the vertical direction to simulate the displacement of the ground adjacent to the underground wall. The overburden pressure of the house was assumed to be 10.0 kN/m². The unit weight of the soil layer, the undrained cyclic strength ratio, and other soil parameters were assumed as shown in Table 3. The safety factor against liquefaction was estimated by the JRA (Japan Road Association) method under the maximum surface acceleration of 200 gals.

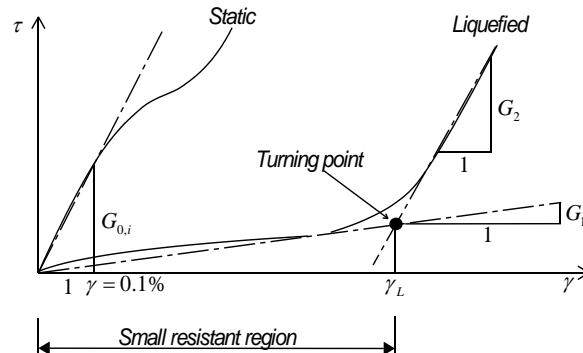


Figure 4: Schematic diagram of stress-strain curve of liquefied soil.

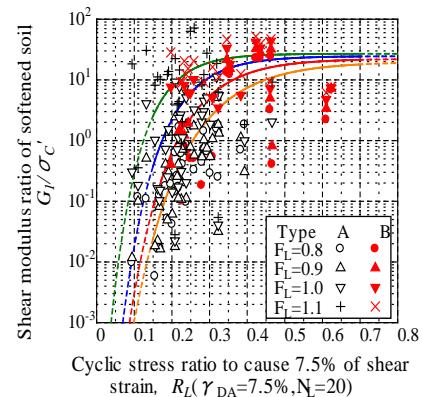


Figure 5: Relationship between G_1/σ'_c and R_L for $F_L=0.8, 0.9, 1.0$ and 1.1 (Yasuda et al. 2004).

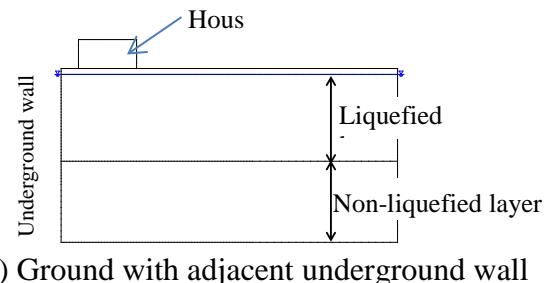
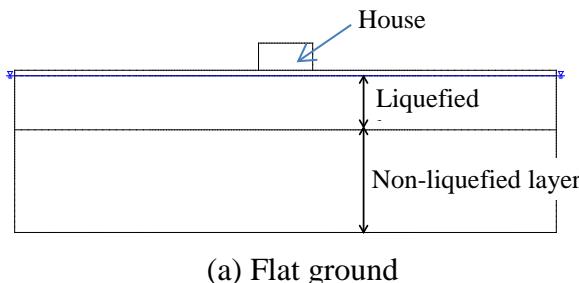


Figure 6: Analyzed models

Table 2: Analyzed condition for the first model.

Depth of water table	GL-1.0m, GL-1.5m, GL-2.0m
Thickness of liquefied layer	5.0m, 10.0m, 15.0m
Depth of sheet piles	(1) Without sheet pile (2) 1m, 2m, 2.5m, 4m for thickness of liquefied layer = 5m (3) 2m, 4m, 5m, 6m for thickness of liquefied layer = 10m (4) 5m, 7.5m, 9m for thickness of liquefied layer = 15m

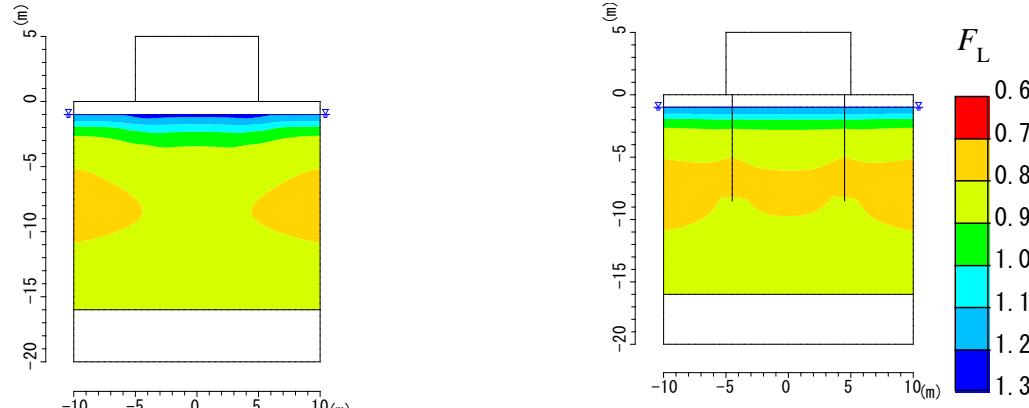
Table 3: Soil properties

Soil parameter	Soil layer		
	Upper than water table	Liquefied	Non-liquefied
Shear modulus at low stain, G_0 (kN/m ²)	2105.26	2105.26	2105.26
Poisson' ratio, ν	0.33	0.33	0.33
Unit weight, γ_t (kN/m ³)	16.0	18.0	17.5
Cohesion, c (kN/m ²)	0.0	0.0	0.0
Internal angle, Φ (deg.)	24.07	22.80	22.09
Liquefaction strength, R_L	-	0.27	-
Fines content, F_C (%)	-	32.96	-

Analyzed Results

Figures 7 (a) and 7 (b) show the distribution of the safety factor against liquefaction F_L for the model without countermeasure and for the model enclosed by sheet piles to the middle depth of the liquefied layer, respectively. The estimated F_L under the house is 1.0 to 0.7 in both cases. Therefore, in this analysis, liquefaction occurs under the house even though the ground is enclosed by sheet piles. Figures 8 (a) and 8 (b) show the displacements of the nodal points of finite elements due to liquefaction in the models shown in Figures 7 (a) and 7 (b). In the model without countermeasure, the ground under the house flows in the lateral direction, resulting in the large settlement of the house. On the contrary, the lateral flow of the upper ground under the house is prevented by the sheet piles in the second model, but small settlement occurs due to the lateral flow of the ground below the sheet piles. Figures 9 (a) and 9 (b) show relationships between the depth of the sheet piles, the depth of the water table, and the penetration settlement of the house for two thicknesses of the liquefied layer. The definition of the penetration settlement is illustrated in Figure 10. The penetration settlement decreases with an increase in the depth of the sheet piles and with an increase in the depth of the water table. There is almost no penetration settlement if the depth of sheet piles is about 4 m to 5 m, and the settlement of the surrounding ground is greater than the settlement of a house if the depth of the sheet piles is greater than about 4 m to 5 m. Thus, an appropriate depth for the sheet piles was considered to be

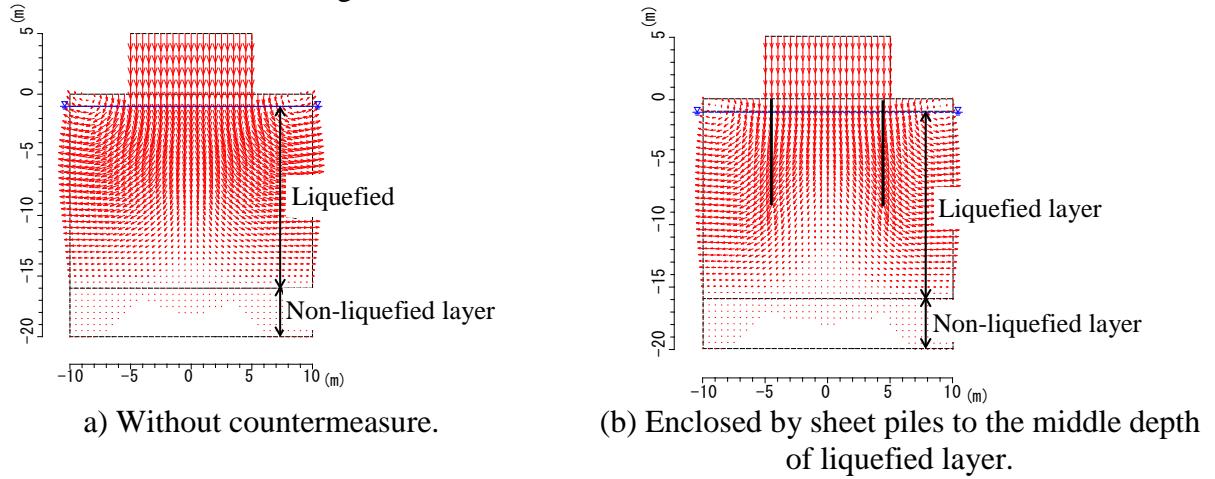
about 4 m to 5 m in these cases.



a) Without countermeasure.

(b) Enclosed by sheet piles to the middle depth of liquefied layer.

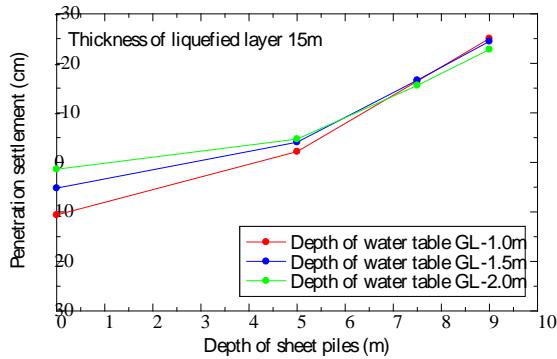
Figure 7: Distribution of the estimated F_L .



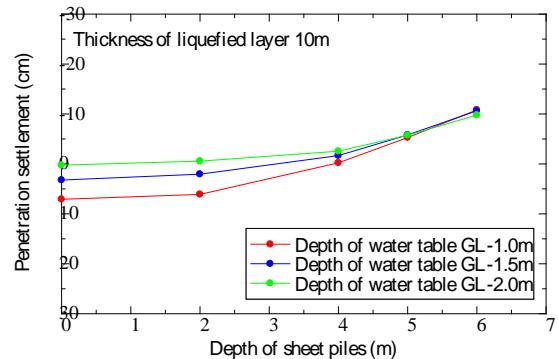
a) Without countermeasure.

(b) Enclosed by sheet piles to the middle depth of liquefied layer.

Figure 8: Displacements of the nodal points of finite elements.



(a) Thickness of liquefied layer: 15m.



(b) Thickness of liquefied layer: 10m

Figure 9: Relationships among the depth of sheet piles, the depth of water table and the

penetration settlement of the house.

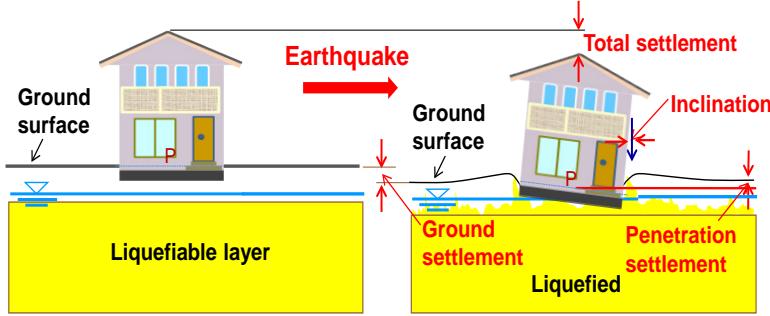


Figure 10: Definition of penetration settlement of a house.

Figures 11 (a) and 11 (b) show the displacements of the nodal points of finite elements due to liquefaction for the model with an adjacent underground wall at the left boundary of the ground. If the distance between the house and the underground wall is 1 m, as shown in Figure 11 (a), the soil under the house flows outside the wall, resulting in the inward inclination of the house. On the contrary, the soil under the house flows to both sides and the house tilts slightly to the opposite side if the distance is 5 m, as shown in Figure 11 (b). Figure 12 shows the relationship between the distance from the house to the underground wall and the inclination of the house. If the distance is less than about 2.5 m, the inclination of the house increases with a decrease in the distance.

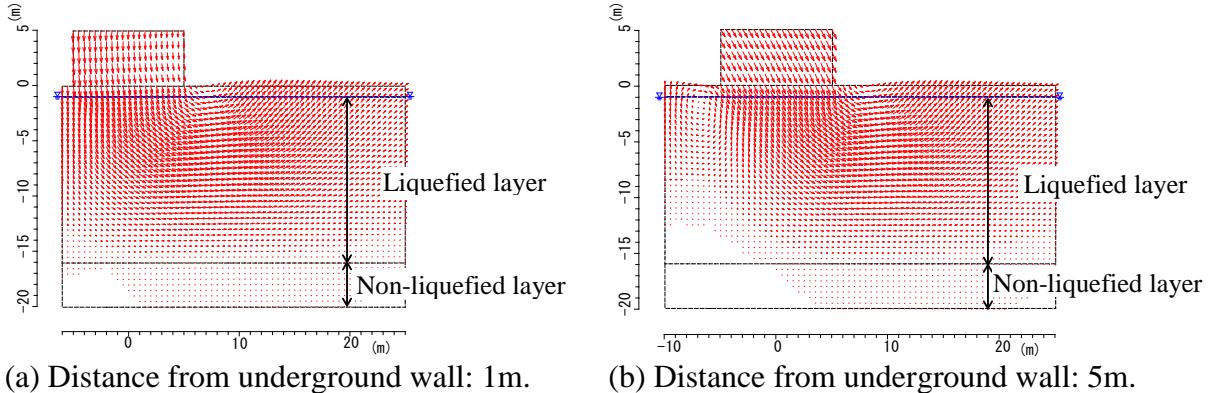


Figure 11: Displacements of the nodal points of finite elements.

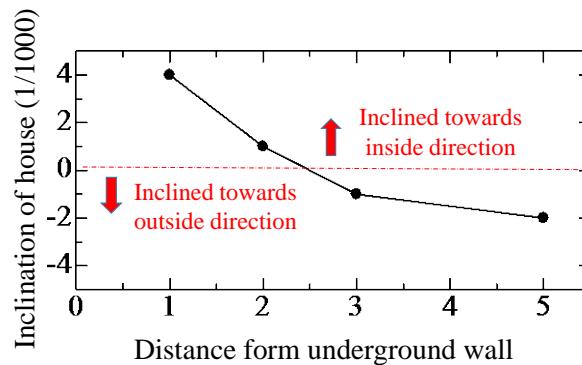


Figure 12: Relationship between the distance from a house to an underground wall and the

inclination of the houses

Conclusions

Several residual deformation analyses were conducted to demonstrate the effectiveness of a new countermeasure, enclosing new or existing wooden houses with thin steel sheet piles, and the following conclusions were derived.

- In the model without a countermeasure, the ground under the house flowed in the lateral direction due to liquefaction, resulting in the large settlement of the house. On the contrary, in the model with sheet piles, the lateral flow of the upper ground under the house was prevented by the sheet piles, and only small settlement occurred due to the lateral flow of the ground below the sheet piles.
- The liquefaction-induced settlement of the house treated by sheet piles decreased with an increase in the depth of the sheet piles and an increase in the depth of the water table.
- Houses close to underground walls settled and tilted due to liquefaction. The inclination of the houses increased as the distance between the houses and the underground walls decreased.

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