A Detailed Study on the Liquefaction-Induced Settlement of Timber Houses During the 2000 Tottoriken-Seibu Earthquake

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A DETAILED STUDY ON THE LIQUEFACTION-INDUCED SETTLEMENT OF TIMBER HOUSES DURING THE 2000 TOTTORIKEN-SEIBU EARTHQUAKE

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ABATRACT

More than 100 timber houses settled and tilted due to liquefaction at a housing development during the 2000 Tottoriken-seibu earthquake in Japan. Among the damaged houses, 47 houses tilted more than 15/1000. Heavily tilted houses were necessary to restore to become horizontal after the earthquake, though several houses, that tilted slightly, were not necessary to restore. The authors studied the boundary of the angle of the restored and non-restored houses. According to the study by the authors, the critical angle of tilting to restore houses was about 10/1000. The authors studied soil conditions also, and found that groundwater level was shallower than about 1.7 m in the damaged zone. This implies that small structures such as timber houses have no damage due to liquefaction if the groundwater level or the bottom of surface non-liquefiable layer is deeper that about 1.7 m.

INTRODUCTION

The 2000 Tottoriken-seibu earthquake with a magnitude of 7.3 occurred in west Japan on September 6, 2000. Epicenter of the earthquake was located in a mountain area. There are several artificially reclaimed lands and alluvial plains in and around Yonago and Sakaiminato cities, shown in Fig.1 which are located about 20 to 40 km north from the epicenter. Liquefaction occurred at several sites in the reclaimed lands and the alluvial lands. Timer houses and small factories settled and tilted, roads were waved, dikes settled and buried pipes were damaged.

The authors visited the liquefied sites several times after the earthquake and conducted detailed investigations in a housing development, named Abehikona where about 100 timber houses settled and tilted due to liquefaction. Damages to houses and factories in two areas: Abehikona and Takenouchi were introduced at first, then results of the detailed investigation in Abehikona was introduced in this paper.

BRIEF EXPLANATION OF LIQUEFCTION-INDUCED DAMAGE IN TWO SITES

In Yonago City, liquefaction occurred in two newly developed housing developments: Abehikona housing development and Tomimasu housing development, and caused severe settlement

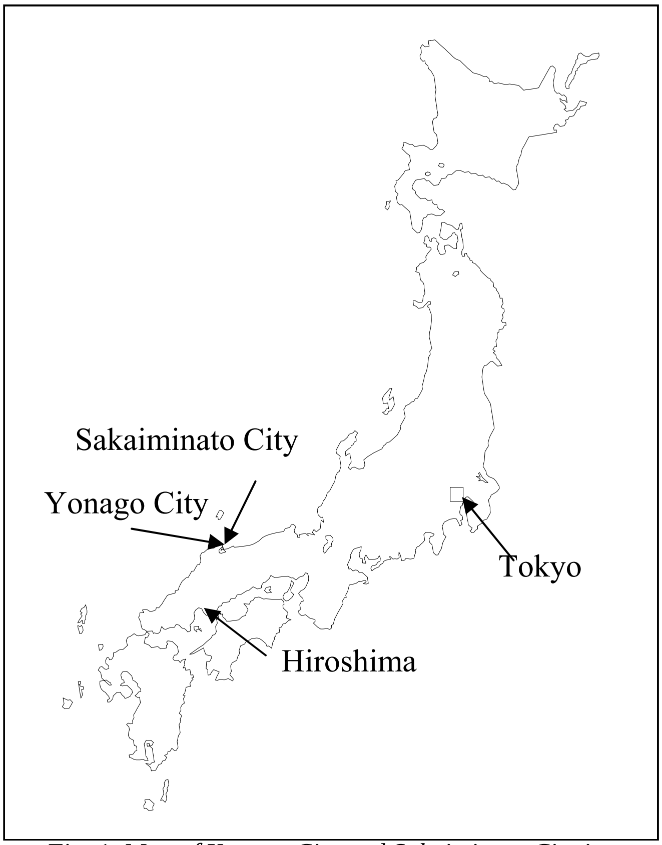

Fig. 1. Map of Yonago City and Sakaiminato City in Japan

Photo 1. Settled and tilted houses due to liquefaction in Abehikona development

Photo 2. Boiled sands in Abehikona development

and tilting of residential houses. Photo 1 and 2 show the settled houses and boiled sands in Abehikona housing development. More than 100 houses settled and tilted in Abehikona housing development as shown in Photo 1. No severe cracks were observed on the walls of the settled houses. Figure 1 shows grain-size distribution curve of the boiled sand. The boiled sand was clean middle sand. This housing development was constructed by filling mainly granite-origin sand. Reclaimed and alluvial sand layers are deposited from the ground surface to the depth of about 7 m. Alluvial clay layer of about 5 m thick is underlay. SPT *N*-value of the sand is around 10.

In Sakaiminato City, liquefaction occurred in a newly reclaimed land named Takenouchi Industrial Park, and brought severe damages to industrial facilities. Photo 3 shows a big sand boil in an industry. The ground was subsided about 30 cm shown in Photo 4 in the industry. River revetment near the industry tilted

Photo 3. A big sand boil at an industry in Takenouchi industrial park

Photo 4. Ground subsidence at an industry in Takenouchi industrial park

Photo 5. Liquefaction-induced flow toward a small river

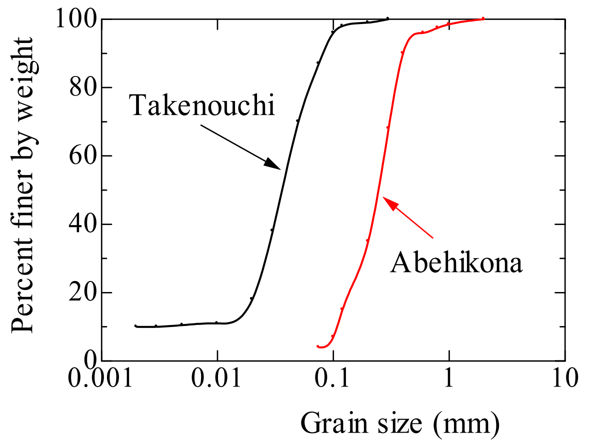

Fig. 2. Grain size distribution curves of boiled sands in Abehikona housing development and Takenouchi industrial park

towards the small river due to liquefaction-induced flow as shown in Photo 5. Boiled soil was very fine silt as sown in Fig.2. Sand boiling continued for about 8 hours after the earthquake because of low permeability of the liquefied silt. This area was constructed by the soil excavated from a channel near Takenouchi Industrial Park. According a boring data, very loose silt layer with SPT *N*-values of 0 to 3, is deposited from the ground surface to the depth of 11.75 m.

ALLOWABLE ANGLE OF INCLINATION OF HOUSES IN ABEHIKONA HOUSING DEVELOPMENT

Abehikona housing development is located in a reclaimed land facing to Nakaumi inlet. Area of the housing development is almost a square with 360 m x 360 m. Reclamation work started in 1985 and building of houses started from 1991. 169 timber houses with mainly two stories had been constructed before the 2000 Tottoriken-seibu earthqukae. Of them, more than 100 houses settled and tilted due to liquefaction. After the earthquake, angles of inclination of the settled houses were measured. In the measuring, the corner of smallest settlement, Corner "A" in Fig.3, was selected at first. By assuming the settlement at this corner is zero, differential settlements at other corners were measured. Then the most settled corner, Corner "C" in Fig.3, was selected. Differential settlement was defined as the difference between the maximum and minimum settlements. Angle of inclination was defined as the ratio of the differential settlement to the distance between the two corners. The maximum angle of tilting and the maximum differential settlements in Abehikona housing development were 37.5/1000 and 33 cm, respectively.

Angle of inclination was classified into four ranks, (a) more than 15/1000, (b) 10/1000 to 15/1000, (c) 5/1000 to 10/1000 and (d) less than 5/1000. Numbers of houses belong to the four ranks were 47, 30, 39 and 53. Figure 4 shows distribution of the rank of angle of inclination in Abehikona housing development. Heavily tilted houses distributed mainly in northeast zone. Observed sites

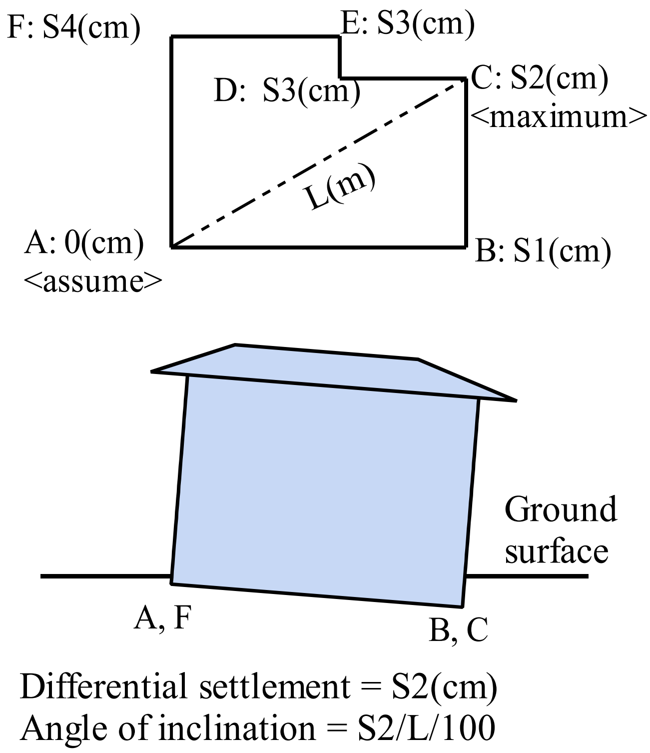

Fig.3. Definition of differential settlement and angle of tilting of houses

of sand boils are also shown in Fig.4. By comparing the angle of inclination and sand boils, it can be seen that sand boils were induced at severely tilted houses. This means that main cause of settlement and tilting of houses was liquefaction.

In the heavily tilted houses, inhabitants felt giddy and nausea, and could not live in the houses after the earthquake, though walls, pillars and windows of the houses had no damage. Then heavily tilted houses had no choice but to restore to become horizontal. In the restore work, superstructures were uplifting by jacks, footings were repaired or reconstructed to become horizontal, then, the superstructures were replaced on the footings. Cost of the restore work for one house was about three to four million Yen (about US$ 25000 to 35000).

On the contrary, slightly tilted houses were not necessary to restore. The authors compared critical angle of inclination whether the restore work was necessary or not. Figure 5 shows relationship between differential settlement and angle of inclination of houses. In this figure, non-restored houses and restored houses were indicated in different symbols, closed square and open circle. It can be seen that the critical angle of inclination to restore was about 5/1000 to 15/1000.

For each house, degree of damage was judged and classified into three degrees, (i) Partially damaged, (ii) Partially destroyed and (iii) Completely destroyed, by government after the earthquake. Figure 6 compares the judgment and the angle of inclination. The

Fig.4. Distribution of the rank for angle of inclination of houses in Abehikona housing development

angle of inclination of completely damaged houses was greater than 7.5/1000. Therefore, it can be said that the allowable angle of inclination of residential houses was about 10/1000.

One of the authors has studied liquefaction-induced settlement of RC buildings during past earthquakes (Yasuda et al., 2001). Figure 7 shows evaluation method for average settlement and angle of inclination. In this study, absolute settlements from the surrounding ground surface at four corners of buildings were measured. Therefore, the average settlement means settlement of the building from the ground surface. Figure 8 shows relationships of the average settlement, Sav (cm) and the angle of inclination, Θ (degree). Though the data are scattered, the following formula was derived:

$$Sav = 20\,\Theta \qquad (1)$$

Allowable angle of inclination of the damaged buildings is not clear. Then, if the allowable inclination is assumed as same as the allowable inclination of the timber houses in Abehikona housing

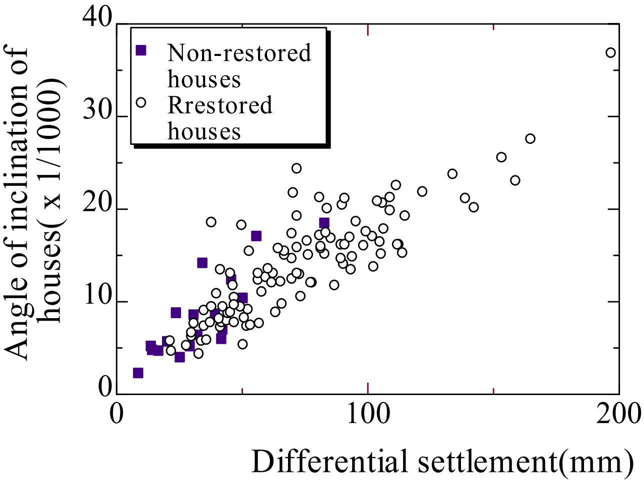

Fig.5. Angle of inclination of restored and non-restored houses

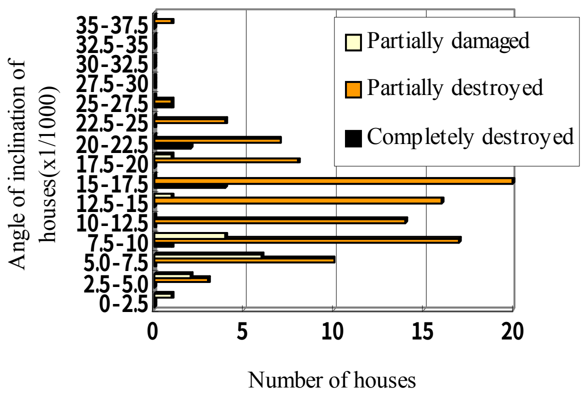

Fig.6. Comparison of degree of damage of houses and their angles of inclination

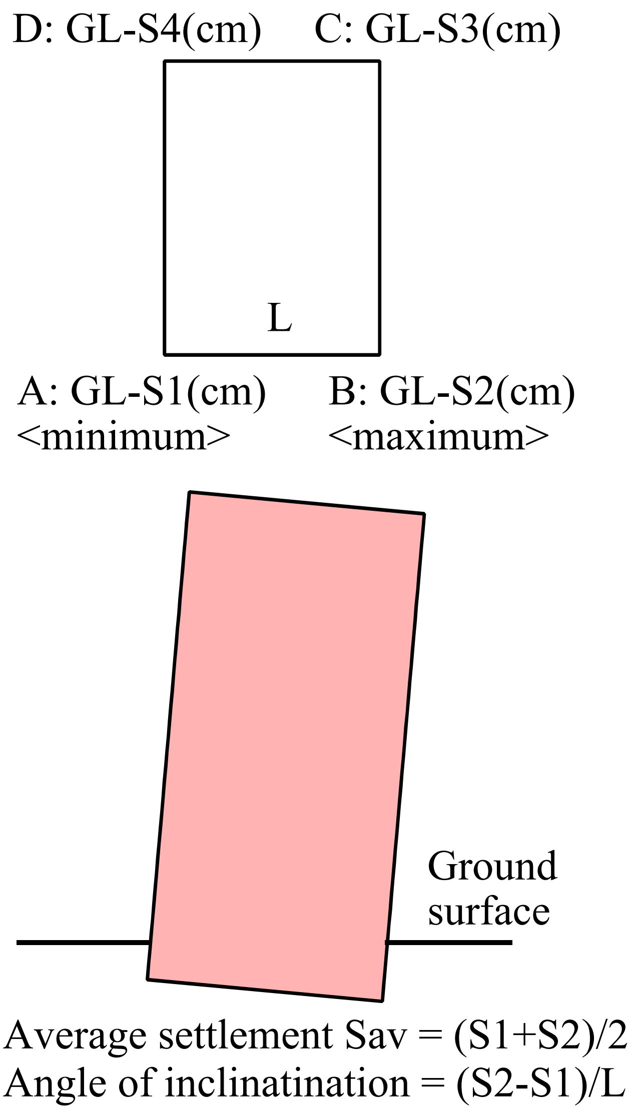

Fig.7. Definition of average settlement and angle of inclination of RC buildings

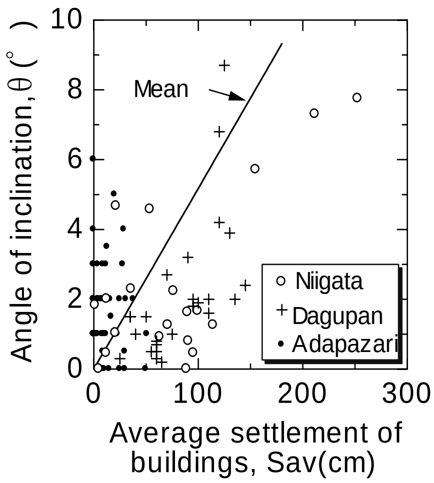

Fig.8. Relationship between average settlement and angle of inclination of RC buildings

development, allowable Θ and Sav becomes 0.6 degrees and 12 cm, respectively. Therefore, it may be said that the allowable average settlement of a RC building from the ground surface may be about 12 cm.

CRITICAL THICKNESS OF UNLIQUEFIABLE LAYER TO COUSE LIQUEFACTION-INDUCED DAMEGE TO HOUSES IN ABEHIKONA HOUSING DEVELOPMENT

As shown in Fig. 4 severely damaged and sand boiled zone was districted at mainly northeast in Abehikona housing development, though the housing area is almost flat. Then detailed survey of the depth of groundwater level was conducted by the authors to demonstrate the reason why the damage was concentrated at this zone. Photo 6 shows a vinyl tube with strainer to measure the groundwater level. Outer diameter of the tube is 13 mm. Four small holes of 3 mm in diameter were drilled and covered by a

Fig.9. Contour line of the depth of groundwater level

mesh as the strainer. Boreholes were excavated at 33 sites to the depth of about 3 m and the vinyl tubes were installed in the boreholes. Depths of groundwater level at the 33 sites were measured on the almost same date but one year after the 2000 Tottoriken-seibu earthquake. Thus seasonal difference of the depth of groundwater level was canceled.

Figure 9 shows contour lines of the depth of groundwater level. It is estimated that the ground surface subsided about 20 cm due to liquefaction base on the differential settlement of pile supported structures as shown in Photo 7. By considering the subsidence of the ground surface, the real depth of groundwater level just before the earthquake was estimated and illustrated on Fig.9. As shown in the figure, depth of groundwater level in Abehikona housing development was shallow as GL-0.8 m to GL-2.1 m in whole area. Especially the depth of groundwater level at northeast zone was shallowest as about GL-1m. Special attention must be paid for

Photo 6. Vinyl tube with strainer to measure depth of groundwater level

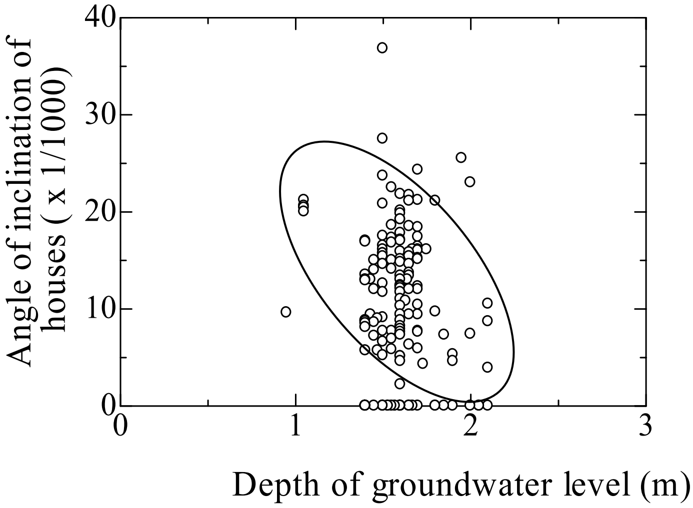

Fig.10. Relationship between depth of ground water level and angle of inclination of houses

Photo 7. Evidence of ground subsidence due to earthquake observed around pile-supported apartment

southeast zone because liquefaction and related damage did not occur in the zone. The reason may be that the zone was treated before constructing houses by surcharge (preloading method) to avoid the settlement of houses due to consolidation of alluvial soft clay.

In Fig.10, the depth of groundwater level is compared with the angle of inclination of houses. Though the data are scattered, angle of inclination decreased with the increase of the depth of groundwater level. As mentioned before, the allowable angle of inclination was about 10/1000. Corresponding depth of groundwater level can be read as about 1.7 m in Fig.10. Therefore, it is estimated that the zones where groundwater level was shallower than GL-1.7 m were severely damaged in Abehkona housing development during the Tottoriken-seibu earthquake. This implies that small structures such as timber houses have no damage due to liquefaction if the groundwater level or the bottom of surface non-liquefiable layer is deeper that about 1.7 m.

CONCLUSIONS

The authors conducted detailed study on the damages of residential timber houses due to liquefaction during the 2000 Tottoriken-seibu earthquake, and the following conclusions were derived:

1. Many houses had to be restored because those houses severely settled and tilted due to liquefaction. The allowable angle of inclination not necessary to restore was about 1/100.

2. Angle of inclination of houses increased with the decrease of the depth of groundwater level. The critical depth corresponding to the allowable angle of inclination was about 1.7 m.

ACKNOWREDGEMENTS

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