STUDY ON THE MECHANISM OF THE LIQUEFACTION-INDUCED DIFFERENTIAL SETTLEMENT OF TIMBER HOUSES OCCURRED DURING THE 2000 TOTTORIKEN-SEIBU EARTHQUAKE

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ABSTRACT :

The 2000 Tottoriken-seibu earthquake with a magnitude of 7.3 occurred in west Japan on September 6, 2000. In a housing development, named Abehikona, more than 100 timber houses settled and tilted due to liquefaction. No severe cracks were observed on the walls of the settled houses. 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. After the earthquake, angles of inclination of the settled houses were measured. The maximum angle of tilting and the maximum differential settlement in Abehikona housing development were 37.5/1000 and 33 cm, respectively 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. According to measured inclination of the houses at Abehikona, there was a tendency that two adjacent houses tilt towards the inside of the houses. The authors carried out several analyses by ALID/win, to demonstrate the effect of several factors, such as distance between adjacent houses, groundwater level, depth of liquefaction layer, F_L, R_L, on the differential settlement. In the analyses the ground at Abehikona housing lot was modeled. Analyzed results showed that differential settlement is influenced by the above mentioned factors.

KEYWORDS: Liquefaction, Timber house, Differential settlement, Sandy soil

1. 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 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 (Yasuda, Hitomi, and Hashimoto, 2004). Moreover, several analyses were carried out to demonstrate the factors affected to the differential settlement.

2. LIQUEFCTION-INDUCED DAMAGE AT ABEHIKONA HOUSING DEVELOPEMENT

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 earthquake. Photo 1 and 2 show the settled houses and boiled sands in Abehikona housing development during the 2000 Tottoriken-seibu earthquake. More than 100 houses settled and tilted though 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.

As more than 100 houses settled and tilted due to liquefaction, angles of inclination of the settled houses were measured after the earthquake. In the measuring, the corner of smallest settlement, Corner "A" in Fig. 2, was selected

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

Photo 2. Boiled sands in Abehikona development

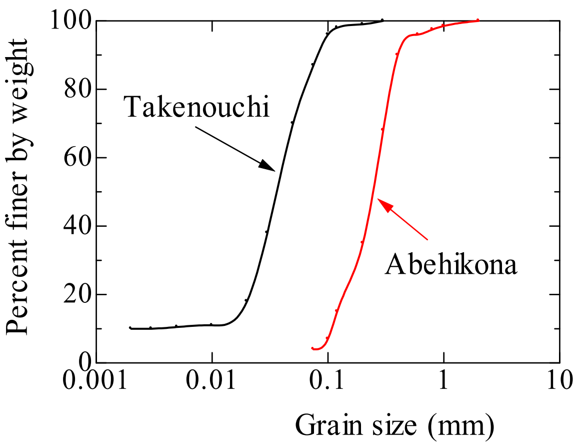


Figure 1. Grain size distribution curves of boiled sands in Abehikona housing development and Takenouchi industrial *park*

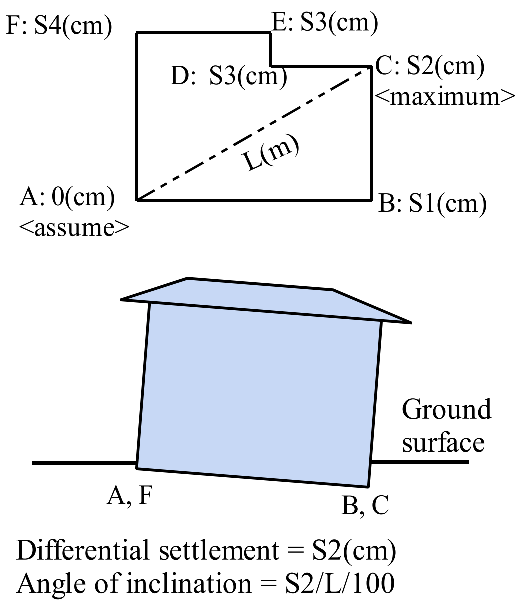


Figure 2. Definition of differential settlement and angle of tilting of houses

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.2, 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 3 shows distribution of the rank of angle of inclination in Abehikona housing development. Heavily tilted houses distributed mainly in northeast zone. Observed sites of sand boils are also shown in Fig.3. 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.

Figure 3 Distribution of the rank for angle of inclination of houses in Abehikona housing development

In the heavily tilted houses, inhabitants felt giddy and nausea, and could not live in their 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 4 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 5 compares the judgment and the angle of inclination. The 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.

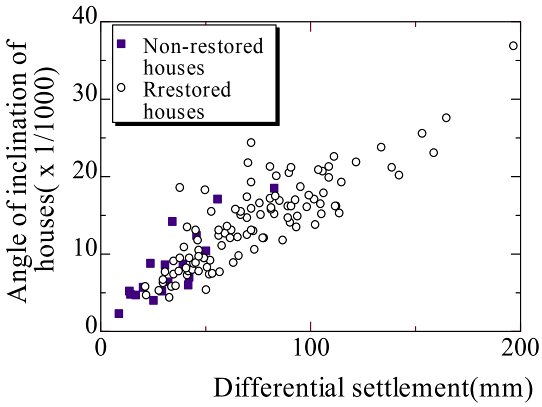


Figure 4 Angle of inclination of restored and non-restored houses

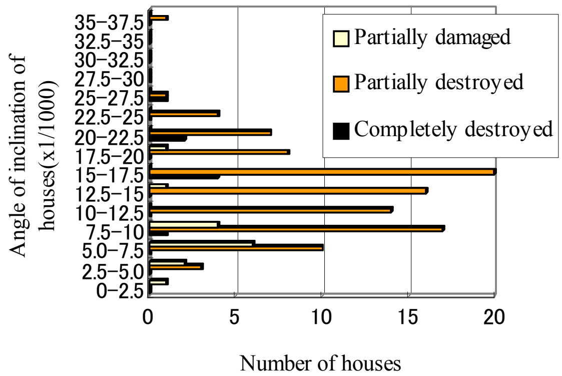


Figure 5 Comparison of degree of damage of houses and their angles of inclination

Photo 3 Two apartments tilted outside in Adapazari during 1999 Kocaeli earthquake

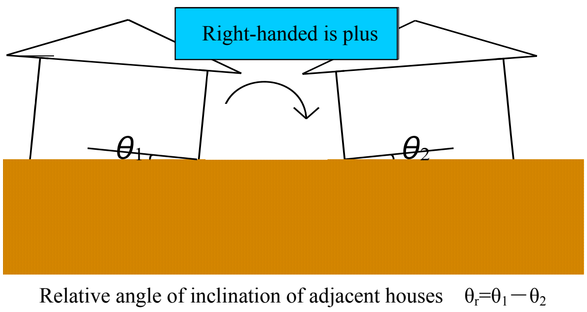


Figure 6 Definition of relative angle of inclination of adjacent houses

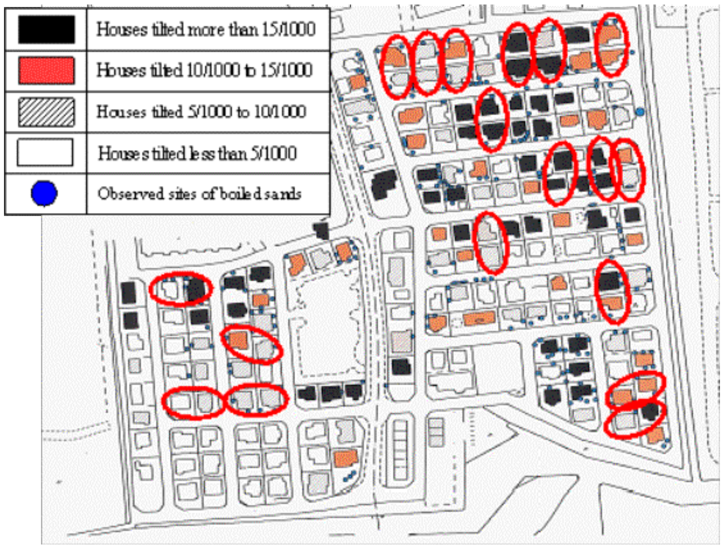


Figure 7 Selected 18 sets of adjacent houses

3. EFFECT OF DISTANCE BETWEEN ADJACENT TWO HOUSES

Two adjacent houses shown in Photo1 settled and inclined towards the inside of the houses. On the contrary, two buildings, shown in Photo 3 settled and tilted outside in Adapazari during the 1999 Turkey Kocaeli earthquake. These houses and building were almost symmetric and had no eccentric weight. Therefore, it seems that the weights of two adjacent houses affect the angle of inclination. Then relationship between two adjacent houses and inclination of houses were investigated. In the investigation, relative angle of inclination of adjacent houses $\theta_r = \theta_1 - \theta_2$ was defined as shown in Fig.6. If two house inclined towards the inside of the houses, θ_r was defined as positive. Then 18 sets of adjacent houses shown in Fig.7 were selected because no house exists outside of the sets and the effect of two houses must be clear. Figure 8 shows the relationship between distance of adjacent houses and relative angle of inclination. Four points in the figure have special condition that ground water table is too shallow. Then if four pints are neglected, it can be said that the relative angle of inclination decreased with distance of adhjacent houses.

Similar investigation was carried out on the buildings settled during the 1964 Niigata earthquake. Two data sets are plotted on Fig.9. As shown in the figure, relative angle of inclination is about 1 to 3 degrees if the distance is narrow as 1 to 5m. And the relative angle deceased with the distance up to almost 7m. At this distance, the relative angle was negative. Then the relative angle increased with the distance to become zero.

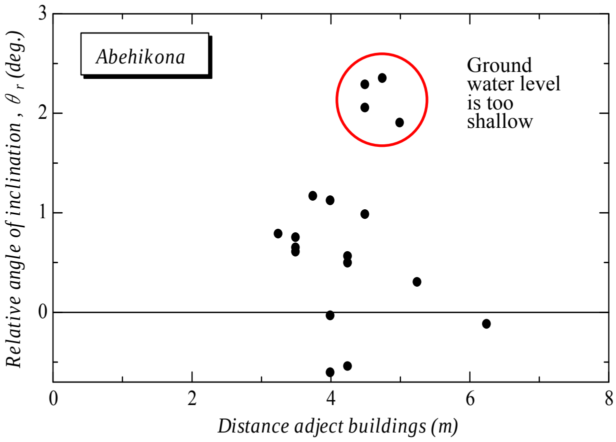


Figure 8 Relationship between distance of adjacent houses and relative angle of inclination at Abehikona housing lot

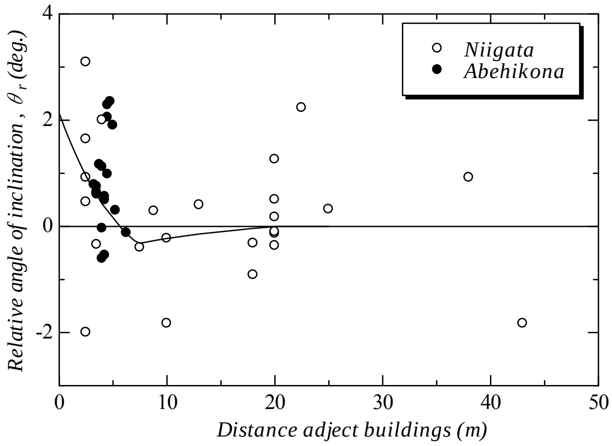


Figure 9 Relationship between distance of adjacent houses and relative angle of inclination at Abehikona and Niigata City

4. ANALYSES FOR LIQUEFACTION-INDUCED DIFFERENTIAL SETTLEMENT

In addition to the case study on the actual settlement of hoses at Abehikona housing development, several analyses were carried out to demonstrate the factors which affect to liquefaction-induced differential settlement of houses. Soil condition, seismic condition and dimension of houses for Basic Model Case (Case2-0) were assumed as same conditions at Abehikona housing development, as follows:

1) Depth of liquefiable layer: GL-1.5m to -10m
2) Fines content of the liquefiable layer: 7.2 %
3) Liquefaction strength ratio (undrained cyclic stress ratio) R_L: 0.225
4) Safety factor against liquefaction, F_L=0.8
5) Dimension of a house: 10 m wide, 6 m height, 2 stories, 7.848kN/m^2
6) Distance between adjacent two houses: 1m

Then, several factors were changed to demonstrate their effect on differential settlement as follows:

a) Distance of adjacent houses: 1m to 15m
b) Depth of ground water table: 0m to GL-6.5m
c) Depth of the bottom of liquefiable layer: GL-2.5m to GL-15m
d) Safety factor against liquefaction, F_L: 0.5 to 1.0
e) Liquefaction strength ratio (undrained cyclic stress ratio) R_L:

In the analyses, a computer code ALID (Yasuda et al., 1999) was used. Figure 10 shows the deformation of the Basic Model Case (Case 2-0). As show in the figure, two houses settled and inclined inside. Average settlement of the houses was about 150mm. And relative angle of inclination was about 1.2 degree. These values are similar as the actual settlement and inclination.

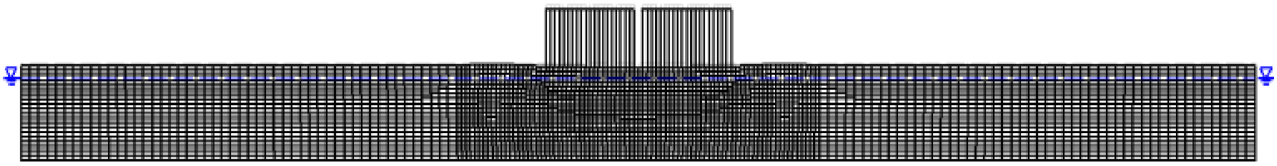
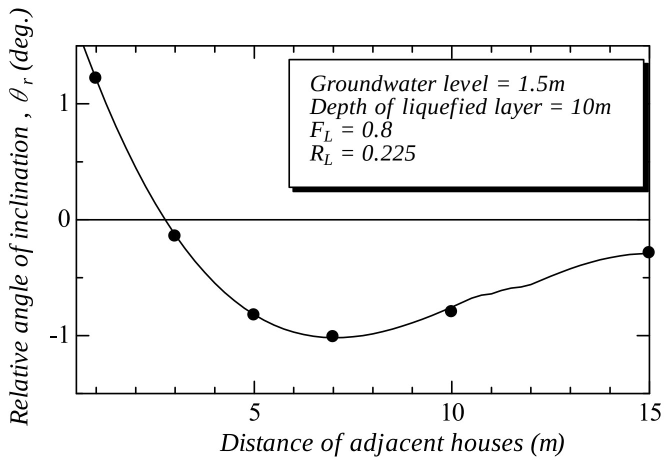
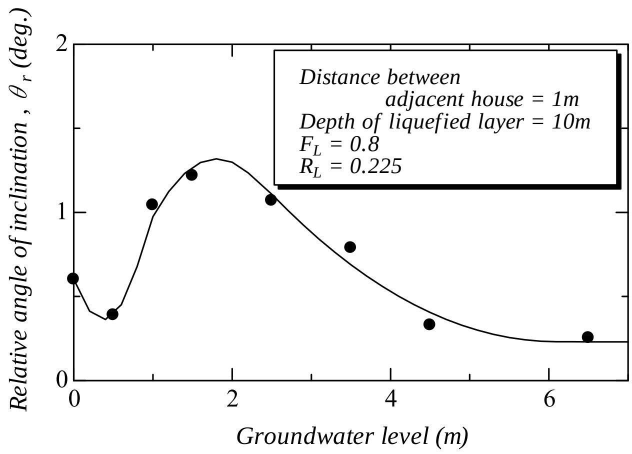


Figure 10 Deformation of the Basic Model Case (Case 2-0)

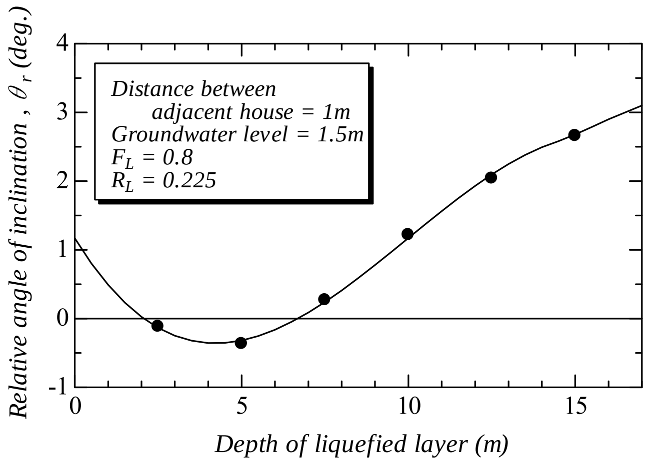
Figures 11 to 15 show relationships between relative angle of inclination and distance of adjacent houses, depth of groundwater table, depth of liquefied layer, F_L, and R_L, respectively. If the distance of adjacent houses is narrow less than 3m, two adjacent houses tilted towards the inside of the houses. On the contrary, two adjacent houses tilted outside if the distance is 3 to 15m. This relationship is similar as the actual relationship shown in Fig.9. Effect of depth of water table to relative angle of inclination was complex. Relative angle of inclination decreased with the depth of liquefied layer up to GL-5m, then increased. And, relative angle of inclination increased with the decrease of F_L and R_L.



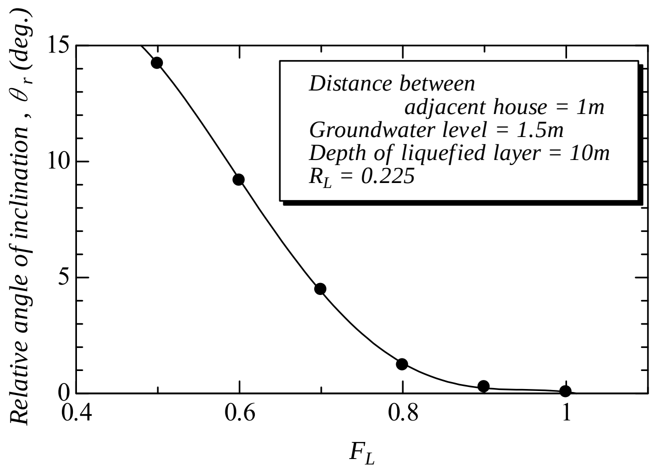
Figures 11 Relationships between relative angle of inclination and distance of adjacent houses



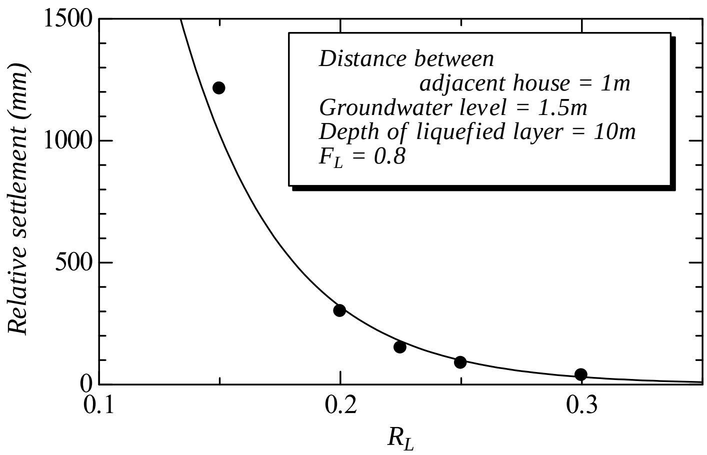
Figures 12 Relationships between relative angle of inclination and depth of groundwater table



Figures 13 Relationships between relative angle of inclination and depth of liquefied layer



Figures 14 Relationships between relative angle of inclination and F_L



Figures 15 Relationships between relative angle of inclination and R_L,

5. CONCLUSIONS

The authors conducted detailed study on the liquefaction-induced differential settlement of residential timber houses during the 2000 Tottoriken-seibu earthquake. Moreover several analyses were conducted on the differential settlement. The following conclusions were derived through these studies:

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. Distance between adjacent houses, groundwater level, depth of liquefaction layer, F_L, R_L, affects the liquefaction-induced differential settlement.

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