SHAKING TABLE TESTS AND ANALYSES ON THE EVALUATION OF APPROPRIATE DENSIFICATION AREA AGAINST SOIL LIQUFACTION

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ABSTRACT :

Among the countermeasures against liquefaction, densification methods by sand compaction piles, stone columns et al., have been widely used because of their high reliability. In the design of densification methods, it is necessary to decide the area to be improved. In 1978, a method to decide the area was introduced in the code for oil tanks in Japan. After that, several methods were proposed. However, the areas for improvement estimated by the proposed methods are quite different. Moreover, the definition of damaged and undamaged structures is not clear. More rational methods to evaluate liquefaction-induced damage to structures should be developed. An appropriate way must be to introduce performance-based design based on allowable settlement of structures.

Then the authors conducted shaking table tests and analyses under several conditions on different areas and densities for improvement. Two models were selected for the tests and analyses. The first model was an old LP gas tank which settled about 64 cm on average and the second model was an apartment house which settled about 10 cm during the 1995 Kobe earthquake. Both structures were settled due to liquefaction though some area of foundation grounds had been improved by densification methods. Shaking table tests were carried out under several conditions of soil compaction area. Test results showed settlements decreased with the increase of the compaction area. An analytical code "ALID" was used to estimate the settlement of the tank and the house. Analyzed settlements of the tank and the house were similar as the settlements obtained by shaking table tests.

KEYWORDS: Liquefaction, Countermeasure, Performance-based design, Settlement, Tank

1. INTRODUCTION

Current countermeasures against liquefaction are classified into two categories (JGS, 1998): i) improve the liquefiable soil to prevent liquefaction, ii) strengthen structures to prevent their collapse if the ground should be liquefied. In the first category, ground is improved to increase liquefaction strength by the following factors: ① high density, ②not-liquefiable grain size, ③stable skeleton or ④low saturation. Other methods to prevent liquefaction are: ⑤immediate dissipation of increased excess pore pressure, ⑥reduction of shear stress by increasing confining pressure, ⑦reduction of shear stress by building an underground wall. Appropriate countermeasures in the second category differ by the type of structure. In the countermeasures, the additional pile method has been applied to bridge foundations, but other methods have been applied to only a few structures.

Among the measures, the sand compaction method has been most widely used because of its high reliability. In the original method, a casing was pushed down and pulled up by a vibrating hammer. Therefore, the method could not be applied at sites with neighboring structures because of the strong vibration. However, a new method to push down and pull up the casings by static rotating force was developed recently. This "non-vibratory sand compaction pile method" has been applied near existing structures.

Design methods to prevent liquefaction has been developed and confirmed. However, it is necessary to decide the area to be improved. In 1978, a method to decide the area was introduced in the code for oil tanks in Japan.

The method was derived from damaged and undamaged structures during the 1964 Niigata earthquake, under which ground had been improved partially or fully, respectively. After that, several methods were proposed based on shaking table tests and analyses. The areas for improvement estimated by the proposed methods are quite different. Moreover, the definition of damaged and undamaged structures is not clear. More rational methods to evaluate liquefaction-induced damage to structures should be developed. An appropriate way must be to introduce performance-based design. More study is necessary for rational design of the area to be improved. Then the authors conducted several shaking table tests and analyses to demonstrate appropriate densification area.

2. SELECION OF MODELES FOR SHAKING TABLE TESTS AND ANALYSES

Two models were selected for the tests and analyses. The first model was an old LP gas tank in MC Terminal Tank Yard in Kobe. The tank yard was located on an artificially reclaimed land. Filled soil is loose gravelly sand with a thickness of 17m to 18m. Alluvial sandy or clayey soils are underlaid. Many tanks and related facilities had been constructed before the 1995 Kobe earthquake. Of them the tank TA-102 of 20,000 kl in capacity was constructed on compacted ground with raft foundation. Compaction method was Vibro-floatation method. Compacted depth was 7m from the ground surface, 5m wider than the tank. SPT *N*-value before and after the compaction were 8 and 10, respectively. Liquefaction and liquefaction-induced ground flow occurred during the 1995 Kobe earthquake in the tank yard. The TA-102 tank settled about 64 cm on average compare with surrounding ground and tilted 1.25 %, due to liquefaction as shown in Photo 1. It is estimated that the compacted area and/or density was not enough to prevent liquefaction and liquefaction-induced settlement.

Photo 1 Damage to tanks during the 1995 Kobe earthquake

The second model was apartment houses at Naruo in Nishinomiya City. The apartment houses were constructed on an artificially reclaimed land with raft foundation. Loose sand layer is deposited from the ground surface to the depth of 8 to 10m. Soft clayey layer is underlaid. Before the construction of the houses, foundation grounds were compacted by sand compaction pile method. Compacted depths were 4 to 7m. And, the zones 1/2 to 1/4 of the compacted depth wider than the houses were compacted. SPT *N*-value of the compacted ground was about 20. Liquefaction occurred in the housing lot during the 1995 Kobe earthquake. Though the foundation grounds were compacted, 5 apartment houses were settled and tilted. Inclinations of the tilted houses were 1/60 to 1/75. And the average settlement was about 10 cm compare with surrounding ground.

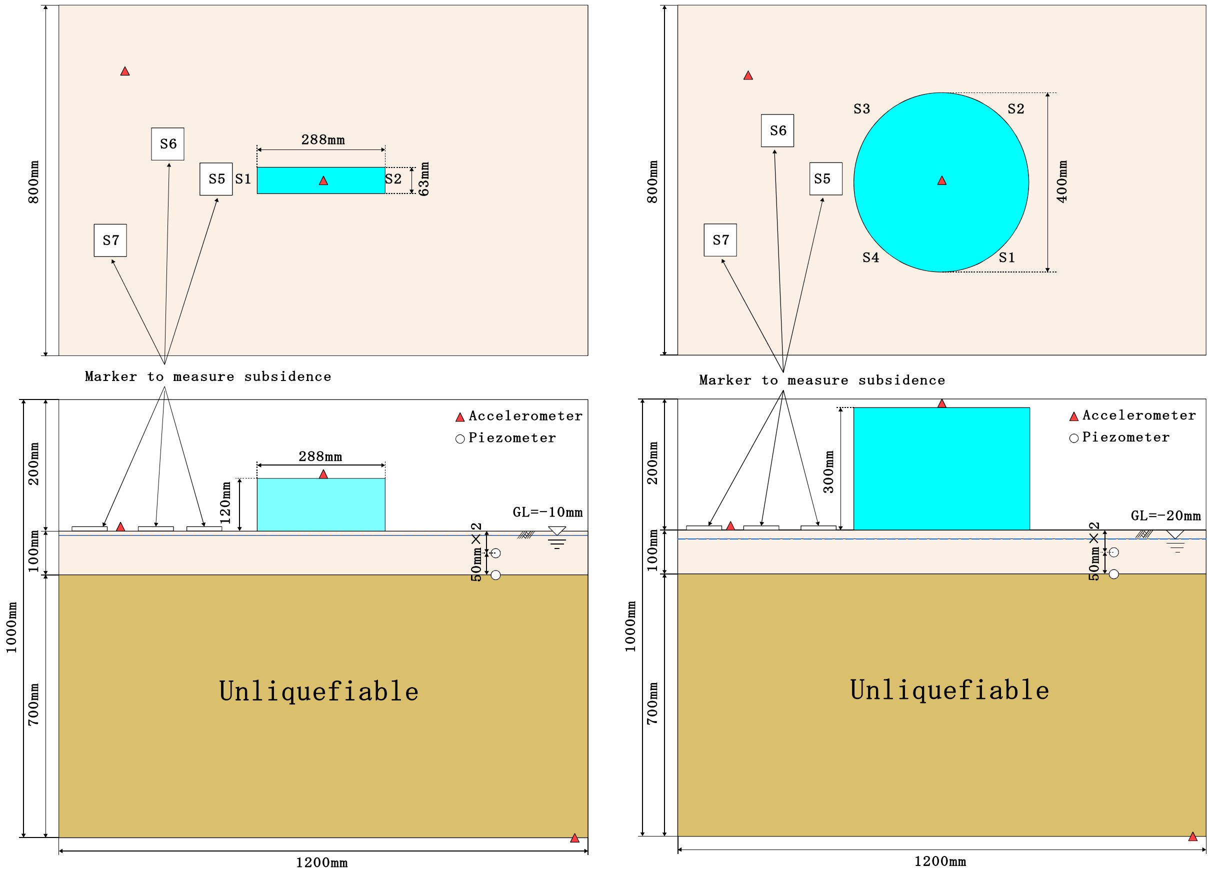

Figure 1 Model for house and tank

Table 1 Test condition

Case	Compacted area		Relative density (%)		Soil compaction area ratio, Ar	Remarks
	Inside to outside of tank	Under tank、*D*	Inside of tank	Outside of tank		
2-1	0～0cm	0cm	—		1.00	Un improved
2-2	-5～5cm	7cm	58.0	48.5	1.054	Actual improve
2-3	-5～6.7cm	10cm	71.0	63.5	1.225	Improved by code for oil tanks
2-4	-5～0cm	6cm	71.0	63.5	1.070	Improved under tank only
2-5	-5～6.7cm	10m	90.0	85.0	1.418	Enough improved

3. SHAKING TABLE TESTS

Shaking table tests were carried out on the models of the TA-102 tank and the apartment house. A laminar shear box with 120cm wide, 80cm thick and 80cm depth was used. Figure 1 shows locations of the model tank, the model house, model grounds and sensors. Scale of the models was 1/100 compare with actual structures. An acceleration wave recorded at Kobe Port Island during the 1995 Kobe earthquake was used for the input motion of shaking. Time scale of the wave was arranged to cause the same settlements as actual settlements.

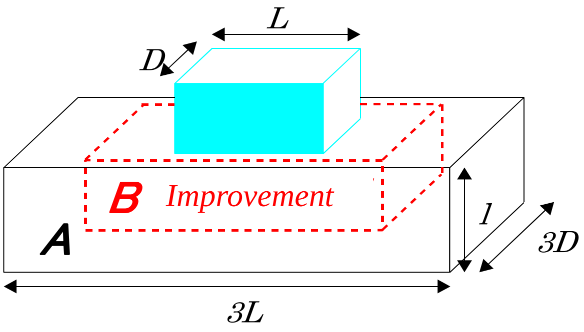

Figure 2 Definition of soil compaction area ratio, Ar

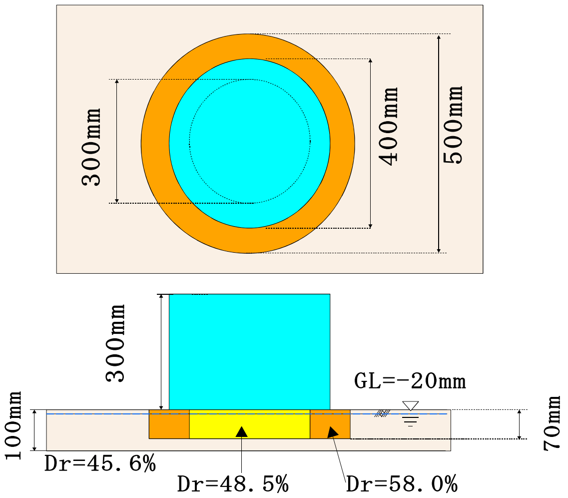

Figure 3 Inner and outer compaction zones

Several areas for compaction were selected to demonstrate the effect of the area on liquefaction-induced settlement of the models. Table 1 shows the conditions of areas for compaction for the model tank. The area for Case 2-2 is the actual compacted area. The ground for Case 2-1 is unimproved ground. The compacted areas for Case 2-3, 2-4 and 2-5 were larger than the actual compacted area. In the table, soil compaction area ratio, Ar is defined as follows:

$$A_r = \frac{B \times D_{r2} + (A - B) \times D_{r1}}{A \times D_{r1}} \tag{3.1}$$

where, *A*: volume of ground which affects to the settlement of the structure
B: volume of compacted ground
D_{r1}: relative density of unimproved ground
D_{r2}: relative density of compacted ground

It is not easy to decide the zone which affects to the settlement of the structure, A. In this study, as shown in Figure 2, depth of the zone was assumed to the bottom of liquefied layer. Length and width of the zone were assumed to three times of those of the model structures. Moreover, the outer and inner zones in the Table 1 were defined as shown in Figure 3. In Japan, it is common to compact with different densities in two zones. Then different densities were selected for the two zones.

Figures 4 and 5 show relationships between Ar and relative settlement of the model tank and the model house, respectively. The relative settlement is defined as follows:

$$\textit{Relative settlement} = \textit{Absolute settlement of structure} - \textit{settlement of surrounding ground} \tag{3.2}$$

As shown in Figs.5 and 6, relative settlements decreased with the increase of Ar. As shown in Eq.3.1, effect of the area and the density of the compacted zone can be considered in the soil compaction area ratio, Ar. Therefore it seems that the liquefaction-induced settlement of structures can be evaluated by Ar.

4. ANALYSES

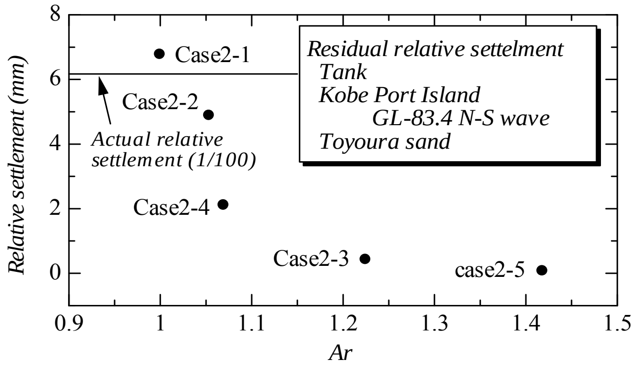

Figure 4 Relationships between Ar and relative settlement of the model tank by shaking table tests

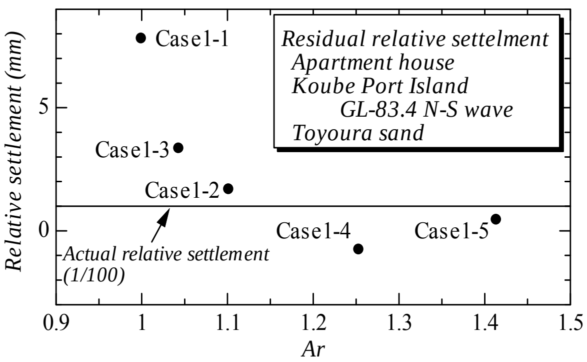

Figure 5 Relationships between Ar and relative settlement of the model apartment house by shaking table tests

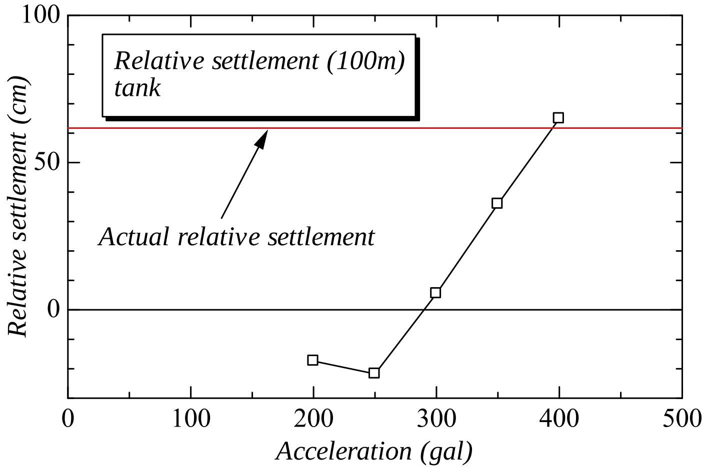

Figure 6 Relationship between the analyzed settlement of the TA-102 tank and the maximum surface acceleration.

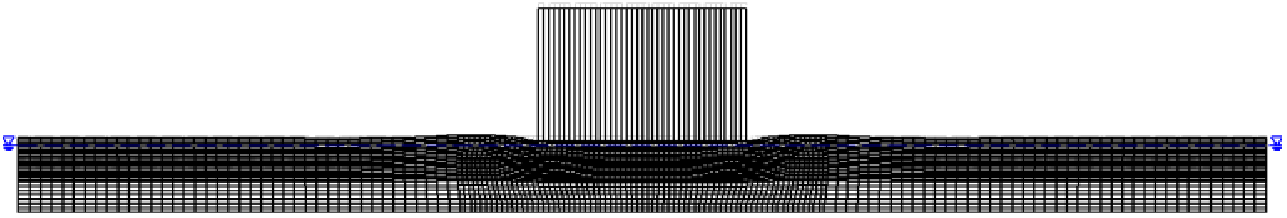

Figure 7 Analyzed deformations of tank and ground (Case 2-2)

Several analyses were carried out by a computer code ALID (Yasuda et al., 1999). Models for the analyses were the TA-102 tank and the apartment house as same as the shaking table tests. However, actual dimensions of the grounds and structures were assumed. Conditions for soil compaction area were similar as the shaking table tests In the analysis by ALID, safety factor against liquefaction, F_L must be assumed. The F_L can be estimated from SPT *N*-value, fines content and the maximum surface acceleration, A_{max}. Then, in the first step, analyses were conducted under several grade of acceleration for both models. Figure 6 shows relationship between the

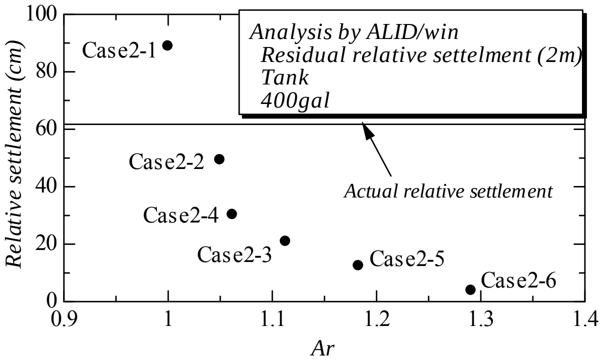

Figure 8 Relationships between Ar and relative settlement of the TA-102 tank by analyses

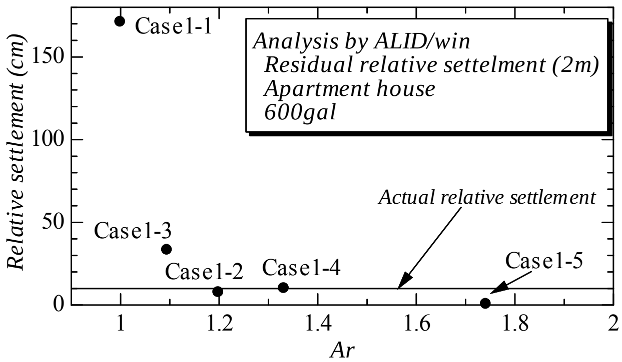

Figure 9 Relationships between Ar and relative settlement of the apartment house by analyses

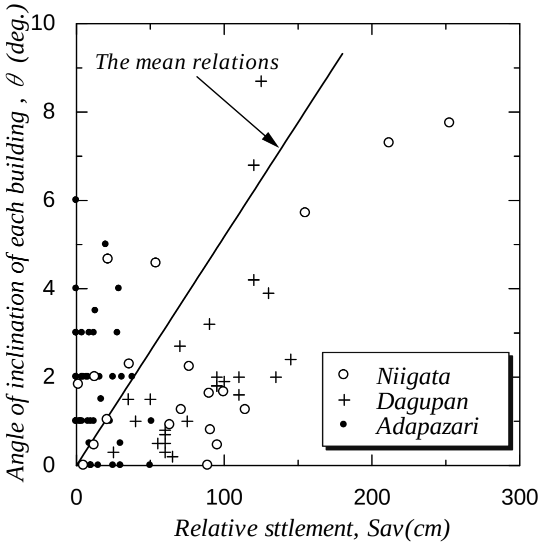

Figure 10 Relationship between relative settlement of buildings and angle of inclination of each building during the 1964 Niigata, the 1990 Philippines Luzon and the 1999 Turkey Kocaeli earthquakes

settlement of the TA-102 tank thus analyzed and the maximum surface acceleration. As the actual settlement of the TA-102 tank during the Kobe earthquake was 64 cm, mentioned above, appropriate A_{max} for the analyses under different soil compaction area ratio was judged as 400 Gals according to Fig.6. Appropriate maximum surface acceleration for the analyses of the apartment house was judged as 600 Gals based on the same procedure for the tank.

Figure 7 shows an analyzed deformation of the tank and the ground for actual soil compaction area ratio. Figures 8 and 9 show relationships between Ar and relative settlement of the model tank and the model house, respectively. The relative settlements decreased with the increase of Ar as same as shaking table tests.

Figure 10 shows relationship between relative settlement of buildings and angle of inclination of each building during the 1964 Niigata, the 1990 Philippines Luzon and the 1999 Turkey Kocaeli earthquakes (Yasuda et al., 2001). Though the data are scattered, it can be said that inclination increases with relative settlement. As mentioned above, settlement and inclination of TA-102 tank were about 64 cm and 1.25 %, respectively. In Japan the allowable inclination of LP gas tanks is 1 %. Then it is estimated that allowable settlement of the tank must be about 51 cm. Area for Case 2-3 was designed by the code for oil tanks. The estimated settlement for

Case 2-3 was 21cm as shown in Fig.8. Therefore, based on these analyses, it can be said that the improving area evaluated by the code for oil tanks is overestimated.

5. CONCLUSIONS

Several shaking table tests and analyses were conducted under several conditions on different areas and densities for improvement to demonstrate the relationship between soil compaction area and liquefaction-induced settlement of structures. The following conclusions were derived through these tests and analyses.

1. Liquefaction-induced settlement of structures decreased with the increase of soil compaction area ratio.

2. It is appropriate to design compaction area based on the settlement of structures.

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