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Effect of Groundwater Depth on Differential Settlement of Wooden Houses during Soil Liquefaction

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ABSTRACT

In the Great Tohoku Earthquake on March 11, 2011, many single-family houses suffered differential settlement due to liquefaction. To investigate the effect of groundwater depth on differential settlement of wooden houses, centrifuge shaking table tests were conducted. The results can be summarized as follows: The relative settlement and tilt angle of the structure decrease as the groundwater depth increases. When the groundwater depth was kept at about 4m below the ground surface, the relative settlement and tilt angle of the tested houses were negligible. However, when the groundwater depth was about 1m below the ground surface, large relative settlement and tilt angle of the tested houses occurred. The tilt angle of structures generally decreased as the factor of safety calculated with respect to equilibrium of vertical force and dynamic overturning moment increased.

Introduction

In the Great Tohoku Earthquake on March 11, 2011, extensive soil liquefaction occurred in reclaimed land of Tokyo Bay and the Tone River basin, and many single-family houses suffered differential settlement. This was especially true in Urayasu city, where about 1/3-1/2 of the wooden houses on reclaimed land tilted more than 1/100 (Tokimatsu et al., 2012). Similar damage also occurred on reclaimed land in the Great Hanshin-Awaji (Kobe) Earthquake on January 17, 1995. Differential settlement of wooden houses due to liquefaction might be related to the thickness of the non-liquefaction surface layer.

Since the 2011 Great Tohoku Earthquake, the demand for inexpensive liquefaction mitigation measures for existing houses has increased. Suzuki et al., (2013) estimated the effects of dewatering and drainage methods as liquefaction mitigation measures for existing structures using centrifuge shaking table tests. The dewatering method lowers the water table, which increases the thickness of the non-liquefiable surface layer and thereby decreases the damage caused by liquefaction. The drainage method advances the dissipation of excess power water pressure, thereby reducing damage caused by soil liquefaction. This paper investigates the effect of groundwater depth on differential settlement of wooden houses and does not include discussion on the effect of drainage method.

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Description of Centrifuge Shaking Table Tests

The shaking table tests were conducted in a centrifuge with accelerations of 50 g and 25 g. Figure 1 shows the test models used in the centrifuge with 50 g and 25 g acceleration. In the shaking table tests the groundwater depth, size of structure, drain pile diameter and spacing, and maximum input acceleration were varied. Two structure models placed on the ground and the drain piles were inserted around the left side model. In this paper, to examine the effects of groundwater depth, the cases without drain piles are discussed.

Table 1 shows the test cases. Each case ID is defined by the experimental condition. The first number indicates the ground water depth in the prototype scale, the letter indicates the structure

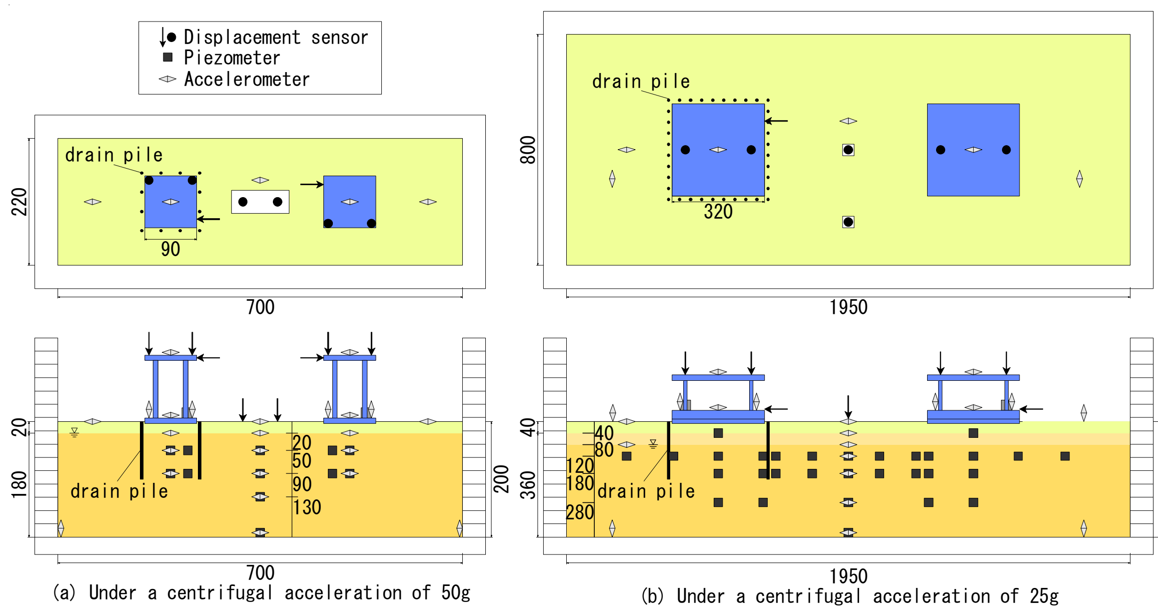


Figure 1. Test setups for centrifuge acceleration of 50g and 25g in model type (unit mm)

Table 1. Test model series

case ID	Groundwater level Model (Prototype)	Structural model	Maximum of input acceleration Model (Prototype)	Centrifugal acceleration
1S-4	20mm (1.0m)	Small	$200m/s^2$ ($4.0m/s^2$)	50g
1S-4*	20mm (1.0m)	Small	$200m/s^2$ ($4.0m/s^2$)	50g
3S-4	50mm (2.5m)	Small	$200m/s^2$ ($4.0m/s^2$)	50g
4S-4	80mm (4.0m)	Small	$200m/s^2$ ($4.0m/s^2$)	50g
1L-4	20mm (1.0m)	Large	$200m/s^2$ ($4.0m/s^2$)	50g
3L-4	50mm (2.5m)	Large	$200m/s^2$ ($4.0m/s^2$)	50g
3L-4*	50mm (2.5m)	Large	$200m/s^2$ ($4.0m/s^2$)	50g
2L-4	80mm (2.0m)	Large	$100m/s^2$ ($4.0m/s^2$)	25g
2L-7	80mm (2.0m)	Large	$175m/s^2$ ($7.0m/s^2$)	25g

dimensions, and the last number indicates the value of the maximum input acceleration in the prototype scale. The cases with an asterisk were conducted twice to confirm reproducibility of the test results.

The laminar box used in the tests with a centrifugal acceleration of 50 g had a length of 700mm, a width of 220mm, and a height of 300mm. The lower 180mm of the box were filled with number 7 silica sand and the upper 20mm were filled with number 8 silica sand. Both sands were air pluviated with a relative density of 50%. The sand was saturated under vacuum using silicon oil with 50 times the viscosity of water. Two structural models, one small and one large, were used in the test. The small structure model had a plan dimension of 90mm×90mm, a height of 118mm, and a weight of 323g. An eccentric mass with a weight of 52g was set on the foundation at a distance of 25mm from the structure's center. The large structure model had a plan dimension of 180mm×180mm, a height of 190mm, and a weight of 1043g. An eccentric mass with a weight of 139g was set on the foundation at a distance of 75mm from the structure's center. The depth of the groundwater was set to 20mm, 50mm, and 80mm (1.0m, 2.5m, and 4.0m in prototype scale) for the small models and 20mm and 50mm (1.0m and 2.5m in prototype scale) for the large models.

The laminar box used in the tests with a centrifugal acceleration of 25g had a length of 1950mm, a width of 800mm, and a height of 800mm. The bottom 360mm of the box were filled with Toyoura sand and the upper 40mm were filled with number 8 silica sand. Both sands were air pluviated with a relative density of 60%. The sand was saturated under vacuum using silicon oil with 25 times the viscosity of water. One large structural model was used in each test. The large structure model had a plan dimension of 320mm×320mm, a height of 170mm, and a weight of 5340g. An eccentric mass with a weight of 860g was set on the foundation at a distance of 120mm from the structure's center. The groundwater depth was set to 50mm (2.0m in prototype scale).

The structural models in all the cases had an average contact ground pressure of 15-18kN/m^2, a natural period of 0.3-05s, and a center of gravity 2.5m above the ground in the prototype scale. These values are similar to those of common single-family houses in Japan. The RINKAI (Structural Safety Committee in Water Front Area, 1992) synthetic earthquake wave was used as the input acceleration. The maximum acceleration was adjusted to 4.0m/s^2 in prototype scale except for case 2L-7 where it was 7.0m/s^2. In the tests, the horizontal and vertical acceleration and displacement in the structures, as well as the excess pore water pressure and the horizontal and vertical acceleration and displacement in the ground were measured. In this paper, the test results are written in prototype scale.

Test Results

Figure 2 shows, from bottom to top, the acceleration series of the input ground motion, at the ground surface, and the superstructure, the excess pore water pressure of the ground below the structure at 4.5m below the ground level, the tilt angle of the superstructure, and the settlement of the superstructure and ground for test 1S-4. Straight line in Figure 2 (c) stands for the initial effective stress, in which the initial overburden pressure from the structure is taken into account based on Boussinesq's formulas. The excess pore water pressure at 4.5m below the ground level

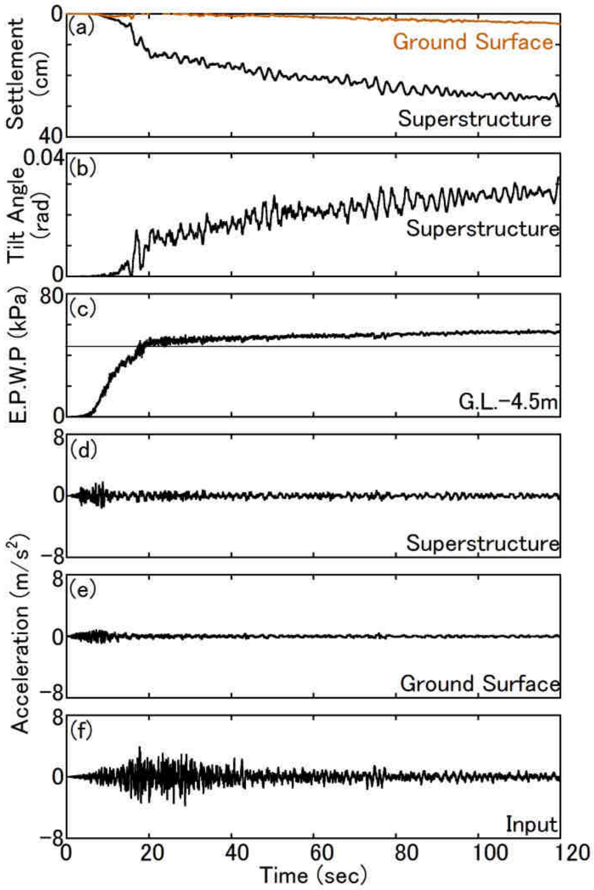


Figure 2. Results of test 1S-4

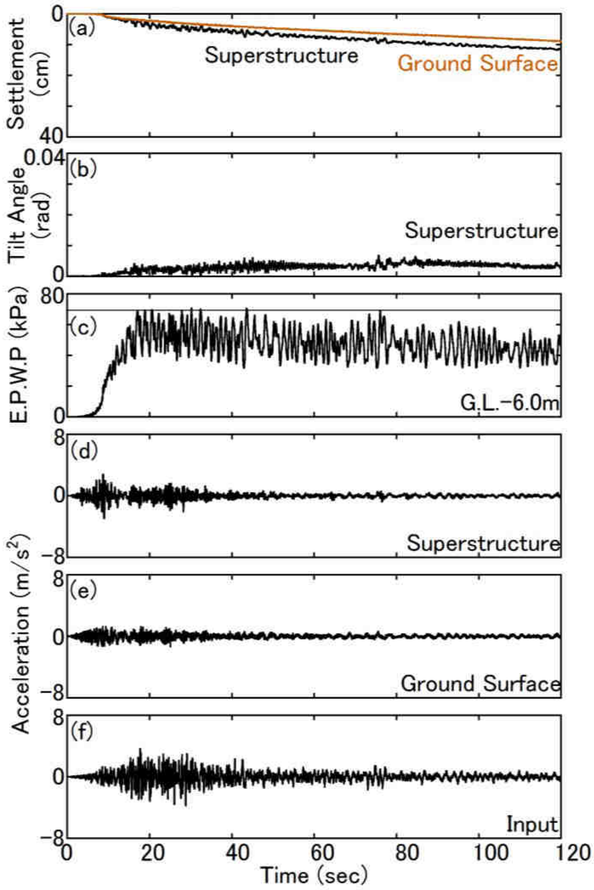


Figure 3. Results of test 4S-4

becomes approximately equal to the initial effective stress, which means that the saturated sand layer liquefies. After liquefaction, the acceleration amplitudes at the superstructure and ground surface are small, the settlement of the structure is larger than that of the ground surface, and the tilt angle of the structure increases.

Figure 3 shows the same data as Figure 2 but for test 4S-4 and for excess pore water pressure measured at 6.0m below the ground level. The excess pore water pressure at 6.0m below the ground level becomes approximately equal to the initial effective stress, which means that the saturated sand layer liquefies. After liquefaction, the acceleration amplitudes at the superstructure and ground surface are small, the settlement of the structure is larger than that of the ground surface and the tilt angle of the structure increases. The acceleration amplitude of 1S-4 shown in Figure 2 is smaller than that of test 4S-4 shown in Figure 3. However the settlement and tilt angle of the structure of 1S-4, which has a groundwater depth of 1.0m, are larger than that of test 4S-4, which has a groundwater depth of 4.0m. The difference between the results of the two tests is due to the difference in the thickness of the non-liquefiable surface layer.

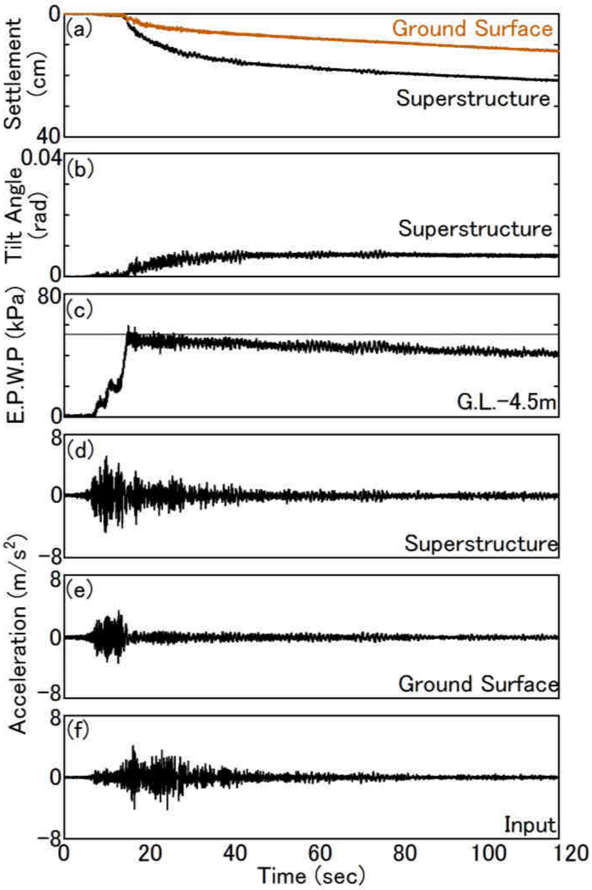


Figure 4. Results of test 2L-4

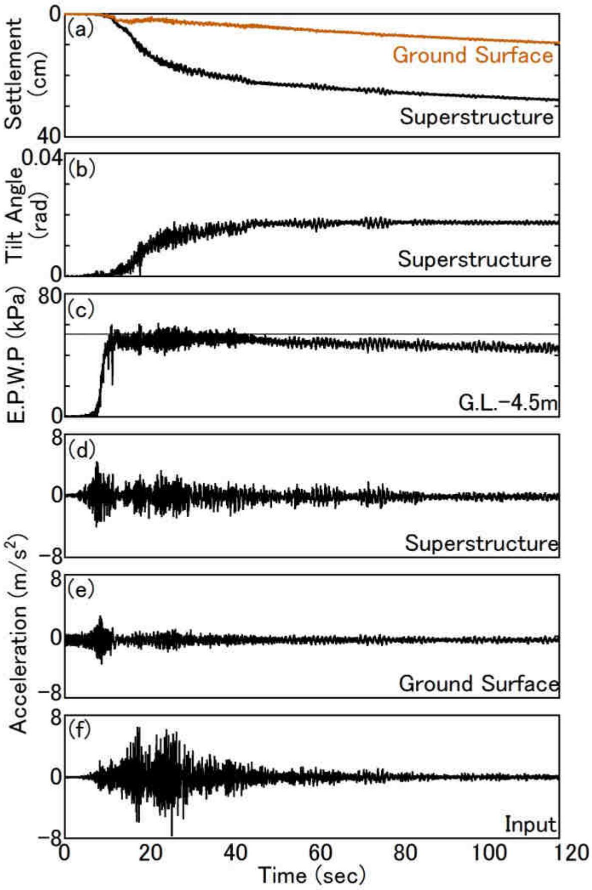


Figure 5. Results of test 2L-7

Figures 4 and 5 show the results of tests 2L-4 and 2L-7 in the same form as Figures 2 and 3. In both tests the excess pore water pressure at 4.5m below the ground level becomes approximately equal to the initial effective stress, which means that the saturated sand layer liquefies. After liquefaction, the acceleration amplitudes at the superstructure and ground surface are small, the settlement of the structure is larger than that of the ground surface and the tilt angle of the structure increases. Figures 4 and 5 show that test 2L-7 has larger acceleration amplitudes at the superstructure and ground surface, and larger settlement and tilt angle of the structure than test 2L-4. The difference in the results is probably caused by the fact that test 2L-7 ($7.0m/s^2$) had a larger input acceleration than test 2L-4 ($4.0m/s^2$).

Effect of Groundwater Depth

To examine the effect of the groundwater depth, Figure 6 shows the relationship between the groundwater depth and the relative settlement and tilt angle of the structure after the dissipation of excess pore water pressures for cases with a maximum input acceleration of $4.0m/s^2$. The relative settlement and tilt angle of the structure decrease as the groundwater depth increases. When the groundwater depth is 4.0m, the relative settlement is almost zero. On the other hand, when the groundwater level is 1.0m, the relative settlement and tilt angle of the structure are very

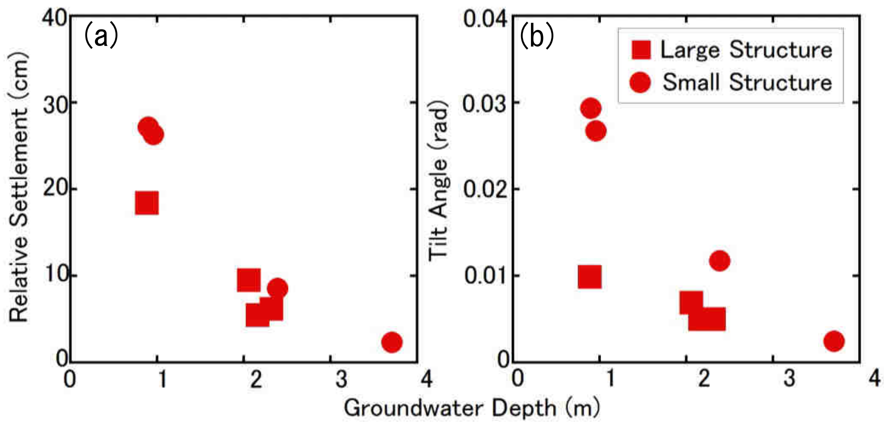


Figure 6. Relationship between groundwater depth and relative settlement and tilt angle

large. The relative settlement and the tilt angle of the small structure model are larger than those of the large structure model. The difference in plan dimension may influence the degree of liquefaction in the ground below the structure.

Estimation of safety factors against tilting

To estimate the degree of the tilt angle, the equilibrium of load and moment acting on the structure is examined. Figure 7 shows the equilibrium of vertical force and rotational moment on a non-liquefiable layer having of a thickness of H. Assuming that only the shear force of the soil above the groundwater level can act against the vertical force and the overturning moment from the structure, the safety factor with respect to the vertical force equilibrium F_{sm} is given as Equation (1)

$$F_{sw} = R_w / L_w \quad (1)$$

where R_w is the resisting force and L_w is the entire vertical force of the structure. R_w and L_w are defined in Equations (2) and (3)

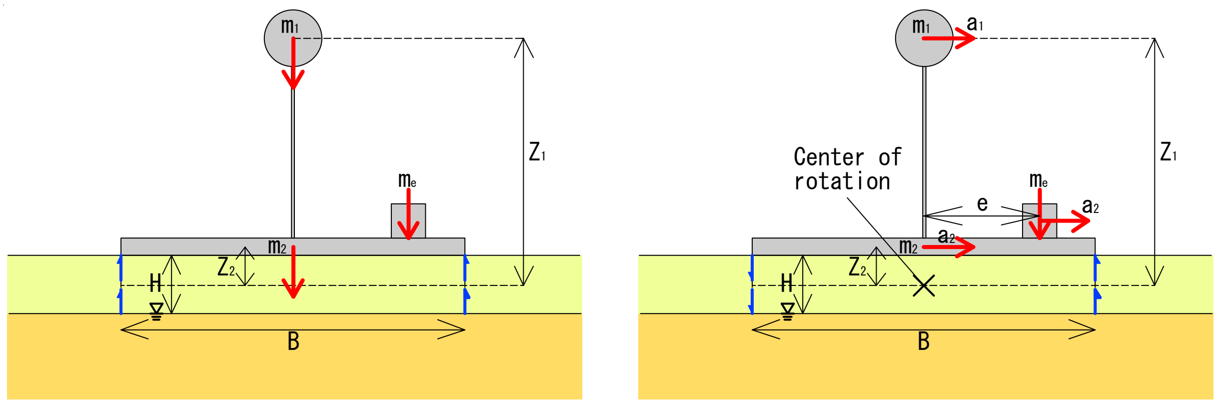
$$R_w = (K \gamma H^2 / 2) \times \tan\theta (B + L) \times 2 \quad (2)$$

$$L_w = (m_1 + m_2 + m_e) g \quad (3)$$

Where K is the coefficient of earth pressure, γ is the unit weight of the non-liquefiable soil, H is the thickness of the surface layer above the groundwater level, θ is the internal friction angle of the non-liquefiable soil, B is the width of the structure, L is the length of the structure, m_1, m_2 and m_e are the masses of the superstructure, foundation and eccentric mass, g is the acceleration of gravity.

The safety factor with respect to the moment equilibrium F_{sm} is given as Equation (4)

$$F_{sm} = R_m / L_m \quad (4)$$



(a) Equilibrium of vertical force (b) Equilibrium of rotational moment

Figure 7. Equilibrium of vertical force and rotational moment

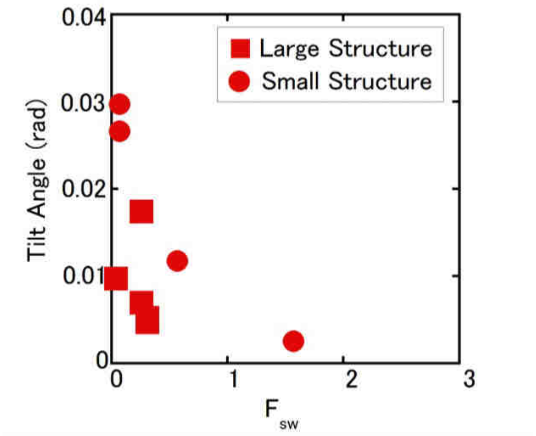


Figure 8. Relationship between the factor of safety calculated with respect to equilibrium of vertical force and the tilt angle of the tested structures

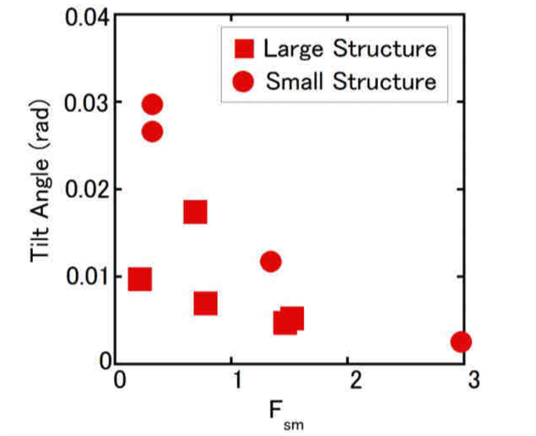


Figure 9. Relationship between the factor of safety calculated with respect to equilibrium of overturning moment and the tilt angle of the tested structures

where R_m is the resisting moment and L_m is the maximum overturning moment after liquefaction. R_m and L_m are defined in Equations (5) and (6)

$$R_m = (K \gamma H^2 / 2) \tan\theta (B / 2 + L) B \quad (5)$$

$$L_m = m_1 a_1 z_1 + (m_2 + m_e) a_2 z_2 + m_e g e \quad (6)$$

Where a_1 and a_2 are the maximum accelerations of the superstructure and foundation after liquefaction, z_1 and z_2 are the heights of the center of gravity of superstructure and foundation, and e is the distance between the center of the foundation and the eccentric mass.

Figure 8 shows the relationship between the factor of safety calculated with respect to equilibrium of vertical force and the tilt angle of the structures. The tilt angle of the structures generally decreases as the factor of safety increases. Figure 9 shows the relationship between the factor of safety calculated with respect to equilibrium of overturning moment and the tilt angle of the structures. The tilt angle of the structures generally decreases as the factor of safety increases. This suggests that the vertical force and the dynamic overturning moment could have a significant effect on the tilt angle of structures.

Conclusions

Centrifuge shaking table tests were conducted to investigate the effect of groundwater depth on differential settlement of wooden houses. The conclusions can be summarized as follows:

1) The relative settlement and tilt angle of the structure decrease as the groundwater depth increases.

2) When the groundwater depth was about 4m below the ground surface, the relative settlement and tilt angle of the tested houses was negligible. However, when the groundwater level was about 1m below the ground surface, large relative settlements and tilt angles of the tested houses were observed.

3) The tilt angle of structures generally decreased as the factor of safety calculated with respect to equilibrium of vertical force and dynamic overturning moment increased. This suggested that the vertical force and the dynamic overturning moment could have a significant effect on the tilt angle and relative settlement of structures.

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