

Proposal of liquefaction countermeasure technique by log piling for residential houses

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Abstract During the 2011 Great East Japan Earthquake in Japan, extreme liquefaction caused extensive damage to residential houses in the Kanto Plain region with the magnitudes of the settlements and tilts larger than that was observed during past earthquakes. This paper deals with a proposal of technique of ground improvement by installing logs into loose sand layer as a countermeasure against soil liquefaction for the residential houses. Small scale shaking table tests in a 1-g gravity field were carried out using some model grounds. It was clarified that the wooden pile could increase the resistance of ground against liquefaction due to the increase of ground density by piling and the dissipation of excess pore water pressure along the surface of piles. As a result, the magnitude of settlements of the house which was set on the improved ground by piling logs became quite small.

Keywords. Liquefaction, countermeasure, shaking table test, log, residential house, global warming

1. Introduction

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking and has caused a lot of ground failures and structural damage during past earthquakes. Therefore various liquefaction countermeasure techniques based on soil improvement are proposed to mitigate the potential of liquefaction by improving the strength, density and drainage characteristics of the soil. From this point of view, if some piles are installed into loose saturated sand layer, it is expected that the characteristics of ground may be changed as the composite ground of sand and piles.

Global warming is one of the most serious problems in this century. Because a tree can store carbon within itself, the utilization of wood in the engineering field for the carbon stock may contribute to the mitigation of global warming. As a way of extending and increasing the usage of wood, the authors consider that wood should be used in the construction project, because a huge amount of materials are used and soft ground scattered in many different locations. However, modern civil engineering constructions seem to be using lesser amount of wood compared to those in the previous times. Therefore the authors consider that one of the most effective ways to utilize wood is installing the wood into the soft ground as a material for ground reinforcement. Generally, one of the major reasons that affect the reliability of wood is decay and insect damage. However, it is reported that decay and insect damage of wood do not occur below the ground water level (Numata et al., 2008). Since the water level in the soft ground is very high, logs can act as a pile or material for ground improvement without having to concern for decay or insect damage of wood.

The Great East Japan Earthquake of March 11, 2011, caused severe damages and loss of life. Damages observed in the Kanto Plain region, which includes the Tokyo Bay and Tone River areas were dominated by the effects of liquefaction-induced ground failures. Liquefaction-induced damages were observed around the northern shorelines of Tokyo Bay and at communities along the Tone River. Liquefaction caused extensive damage to light residential structures in many of these areas with the magnitudes of the settlements and tilts larger than that was observed during past earthquakes. The authors proposed a technique of ground reinforcement by piling logs into loose saturated sand layer as a countermeasure against liquefaction. This technique has advantage to apply for the residential house which has narrow space around structure because

this technique does not need large construction equipment.

In this paper, a series of small scale shaking table tests was conducted in a 1-g gravity field in order to evaluate the performance of this technique in liquefiable sand layers during an earthquake. From the test results, it was confirmed that the ground improvement by piling logs could be treated as one of the countermeasures to restrain the magnitude of settlements and tilts for the residential houses.

2. Structural Damage due to soil liquefaction

Liquefaction during earthquakes induces such damage of existing structures as uplift or settlement, depending on the weight of structure. It is very important to mitigate damage occurring by liquefaction to take some countermeasures against vertical displacement. Liquefaction caused extensive damage to light residential and light commercial structures with the magnitudes of the settlements and tilts during the 2011 Great East Japan Earthquake as shown in Photo 1 taken in Chiba city. Many of these structures were founded on mat-type foundations that limited damage to the superstructures despite the large settlement of 50 cm over and tilt of 5 % over. Photo 2 shows the uplift of manhole in Urayasu city. The uplift of manhole was as much as 1 m and settlement of surrounding pavement was at most 30 cm. Liquefaction-induced damage to utilities caused widespread disruptions for homeowners.

While those of damage were observed in many places, a structure supported by wood piles which was not damaged by soil liquefaction was existed in devastated area during the 2011 Great East Japan Earthquake. Photo 3 shows a sedimentation basin of the Hebita purification plant in Ishinomaki city. Though liquefaction occurred around the structure, the settlement and tilt of the basin was not observed. As a result of site investigation, it is clarified that this basin was constructed in 1969 supported by wood piles. About 900 pine logs measured 15 mm diameter and 3000 mm long were piled at the interval of 900 mm for the foundation of this basin. It seems that this is the evidence that wood pile is applicable to the liquefaction countermeasure technique.



Photo 1 Settlement and tilt of residential house in Chiba city



Photo 2 Uplift of manhole and settlement of pavement in Urayasu city



Photo 3 Sedimentation basin of the Hebata purification plant in Ishinomaki city

2. Retrieving wood piles from ground

Photo 4 shows Kida Bridge across the Asuwa River that flows in Fukui city, Japan. The bridge was completed in December, 2008. It can be seen that there are a lot of head of piles made of wood in the riverbed near piers. These wood piles were used as foundations of the former Kida Bridge which was completed in 1949. It is assumed that they were placed underneath the riverbed through 59 years (Yoshida et al., 2009).

Photo 5 shows the wood pile which was retrieved from Kida Bridge. The length of the pile was about 3.5m and the diameter was about 30cm. It is clarified that the species of wood pile was cryptomeria, that is, Japanese cedar as a result of identification by using an optical microscope. According to the visual observation of wood pile, it is assumed that the top of the pile was stuck up out about 1m from the riverbed, because the area between about 1m from the top had a mark that water scraped the surface of the wood pile. The wood pile was in the gravelly sand and clay layer and the bottom of the pile was assumed to reach sandy silt layer or sand layer by referring to a borehole data near this site.



Photo 4 Former wood pile foundations near Kida Bridge



Photo 5 Wood pile retrieved from Kida Bridge

3. Investigation for soundness of wood piles

3.1 Visual Observation Test

Fig. 1 shows a result of visual judging method of decay level according to JIS K 1571:2004 (Yoshida et al., 2007). Three evaluators of A, B and C observed and judged the decay level referring to the standard shown in this Figure. The positions of riverbed and water level presumed by site investigation are also shown in this Figure. Because the decay level was 1 or less under the riverbed, it is confirmed that wood pile can keep soundness in the soil under the water level.

3.2 Pylodin Penetration Test

Fig. 2 shows a result of the penetration test by using a Pylodin which can examine the level of decay (Yoshida et al., 2007). The Pylodin was a device to compare depths of penetration by a pin stricken with a certain force. If the level of decay is high, the surface of wood become soft and the depth of penetration become large. The standards of decay is considered that the depth of penetration is 30mm or over. The shape of test piece was a discoid by cutting out the wood pile and the thickness of the piece was 10cm. The penetration tests were conducted on two sides of wood piles. One was the side of cut end and the other was the orthogonal side of cut end. Although the values vary widely at the same ground level as shown in Fig. 2, it is clarified that the wood piles keep health because the most of average values were less than 30mm.

3.3 Compression Test

Fig. 3 shows a result of compression test according to JIS Z 2101:1994 (Yoshida et al., 2008). The size of test piece was 30mm square and 60mm in height and they were made by cutting out the discoid which was used for the Pylodin penetration test. The standard compression strength of Japanese cedar and allowable stress used for design of wood pile foundation are also shown in this Figure. It is considered that the test pieces have three to

five times strength of the allowable strength.

Therefore, it is clear that the wood piles made of Japanese cedar that had been buried in soil under the water through 59 years did not decay and still had enough strength as a pile foundation. In the past, the pine has been often used as a material of the wood pile in Japan. Since civil engineers usually use pine for pile now, it is very valuable evidence that Japanese cedar used to be used as a pile foundation and existed in the ground with no decay. On the other hand, some physical damage and minor decay were found on the top part of the piles where the pile was stuck up out from the ground. It means that wood including Japanese cedar can be used as a construction material in the ground under the water level for at least over fifty years. Therefore, civil engineers should consider using wood as a construction material instead of steel, concrete or other artificial chemical materials for the future, under the condition that the wood is in the soil under the water level.

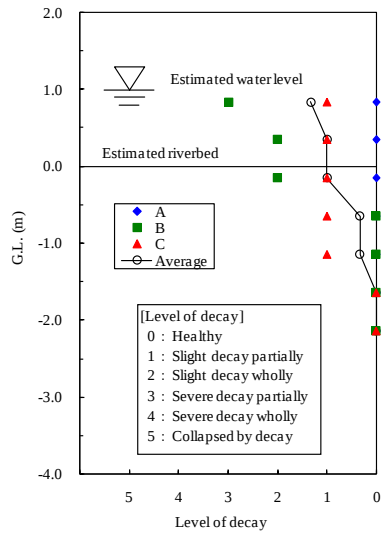


Fig. 1 Results of visual observation test

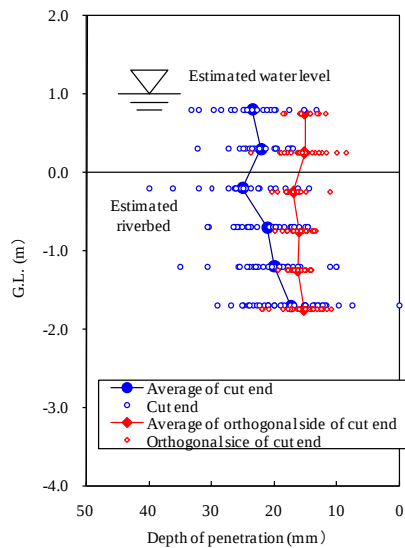


Fig. 2 Results of pylodin penetration test

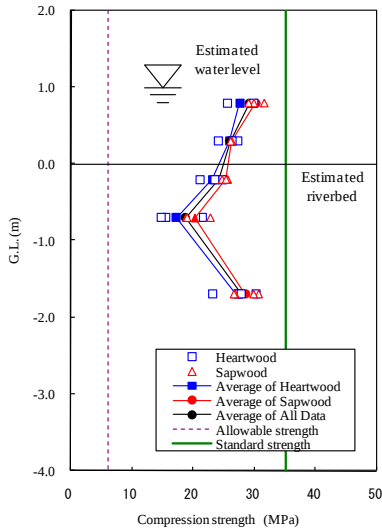


Fig. 3 Results of compression test

4. Shaking table test to clarify effectiveness of installing logs into liquefiable ground

Fig. 4 illustrates cross sections of top and side view of a model ground with locations of transducers (Yoshida et al., 2008). The model ground was set up in a rigid acrylic container that measured 800 mm long, 400 mm wide and 540 mm high. The tests were conducted by using a composite ground which consists of two parts. One was improved area that model of logs made of Japanese cedar got by thinning in Fukui prefecture were installed in loose sand layer which was shown in left side of Fig. 4, the other was unimproved area. The loose liquefiable sand layer was made of silica sand No.7 and the relative density was about 35%. The physical properties of sand are listed in Table 1. The model of log made by scaling down 1/25 of the wood pile of Kida Bridge and measured 12 mm diameter and 220 mm length.

The shaking table tests were conducted as follows: 1) Pore water pressure transducers were installed at the locations as shown in Fig. 4. 2) The container was first filled with water to 300 mm high from the bottom. Then a sieve with a 2 mm mesh was moved back and forth below water surface, pouring wet sand through water to form a uniform sand layer with the thickness of 300 mm. 3) Excess water above the sand layer was soaked up so that the water surface was level with the surface of the sand layer. 4) Accelerometers were installed at the locations as shown in Fig. 4. 5) Thirty six logs were installed into the loose sand layer slowly with an interval 30mm, except the top of log with a length 20mm. 6) No. 5 gravels were laid over the loose sand layer with a thickness 20mm. 7) The model ground was shaken in the horizontal direction with the sinusoidal wave of 100 gal in peak amplitude, 5 Hz in frequency and 5 seconds in duration time as shown in Fig. 5. The pore water pressures and the response accelerations were recorded simultaneously on the data recorder. 8) After the excess pore water pressure had completely dissipated, the vertical displacements of logs and ground surface were measured by a point gauge. 9) The processes of 7) to 8) repeated five times with different amplitude which was from 100 gal to 180 gal at intervals of 20 gal.

Fig. 6 shows time histories of excess pore water pressure ratios located at 100 mm in depth from ground surface after undergoing shaking of 120 gal. In case of unimproved ground, the excess pore water pressure ratio reached 1.0 and the ground completely liquefied. However, in case of improved aground, the maximum value of excess pore water pressure ratio decreased and the velocity of dissipation was extremely fast.

Fig. 7 shows the accumulation of settlement in soil layer. The settlement ratio is defined as a vertical displacement of soil layer divided by initial thickness of the ground, and the residual vertical displacement was accumulated after fifth shaking. The negative value in the Figure means upheaval of ground. Though the settlement became about 60cm after fifth shaking in unimproved ground, the upheaval occurred due to the floatation of logs.

Accumulated vertical displacement of logs at the left, center and right part of improved area after fifth shaking

is shown in Fig. 8. All of the displacement means flotation of logs. It is clear that the flotation occurred since the input acceleration exceeded 140gal. The flotation of logs in the center part enclosed with a lot of logs was less than that in the outer part of improved ground. It seems that the flotation of logs caused the upheaval of ground in the improved area.

It is clarified that the resistance against soil liquefaction increased by installing the logs into the loose sand layer. It is considered that the resistance was caused by the following four effects; 1) replacing the loose sand with logs, 2) densifying the loose sand by installing the log. 3) restraining the shear deformation by fixing the top of logs into gravel layer 4) dissipating the water pressure along the periphery of logs.

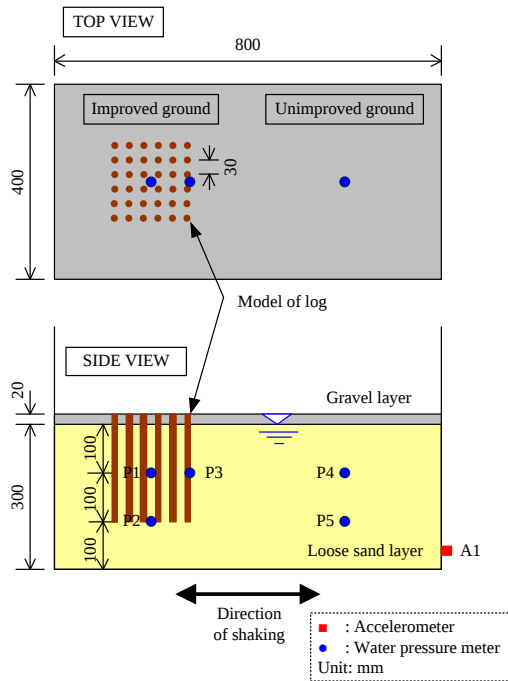


Fig. 4 General view of model ground and transducers

Table 1 Physical properties of sand

Density (g/cm ³)	Average diameter (mm)	Coefficient of permeability (cm)
2.63	0.17	4.79×10^{-3}

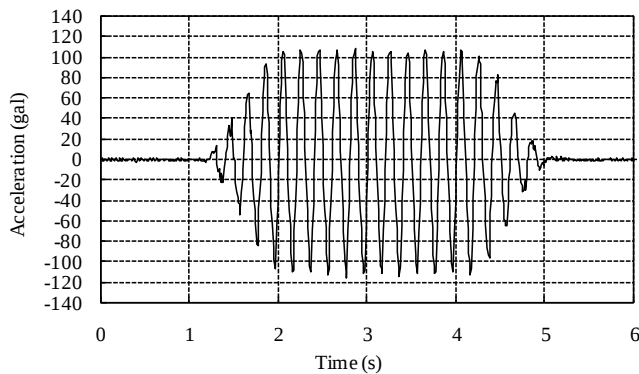


Fig. 5. Time history of input acceleration

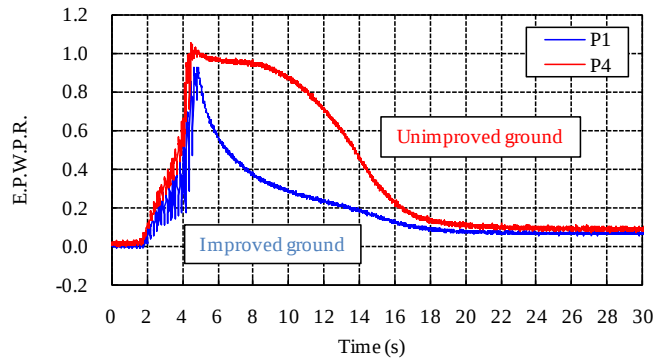


Fig. 6 Time histories of excess pore water pressure ratio

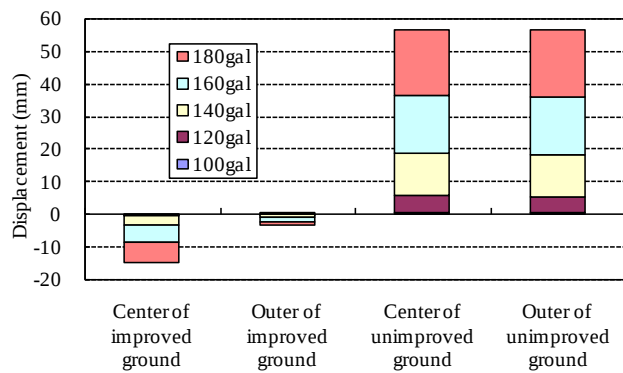


Fig. 7 Vertical displacement of ground surface

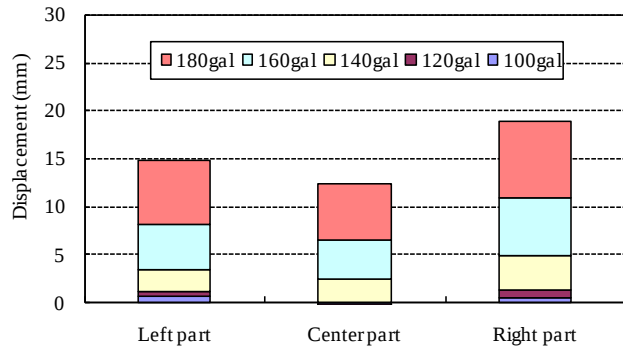


Fig. 8 Vertical displacement of logs

5. Shaking table test to clarify effectiveness as bearing pile of structure

Fig. 9 illustrates cross sections of top and side view of a model ground with locations of transducers (Yoshida et al., 2009). The container and sand were same as Fig. 4. The tests were conducted by using a composite ground which consists of three parts. The left part was improved area installed by column type logs, the right part was also improved area installed by cone type logs and the center part was unimproved ground. The shape of cone type log was copied from real wood pile. The model of log in case of the column type measured 12mm diameter and 200 mm length. The diameter of top was 14mm and that of bottom was 10mm in case of the cone type. The volume of both models was same. The underside of structure model was 150mm square and the weight was 6000g.

The shaking table tests were conducted as follows: 1) Pore water pressure transducers were installed at the

locations as shown in Fig. 9. 2) The container was first filled with water to 300 mm high from the bottom. Then a sieve with a 2 mm mesh was moved back and forth below water surface, pouring wet sand through water to form a uniform sand layer with thickness 300 mm. 3) Excess water above the sand layer was soaked up so that the water surface was level with the surface of the sand layer. 4) Thirty six logs were gradually installed into the loose sand layer with an interval 30mm. 5) The models of structure were placed over the each area. 6) Accelerometers and displacement meters were installed at the locations as shown in Fig. 9. 7) The model ground was shaken in the horizontal direction with the sinusoidal wave of 80 gal in peak amplitude, 5 Hz in frequency and 5 seconds in duration time as shown in Fig. 10. The pore water pressures and the response accelerations were recorded simultaneously on the data recorder. A vertical displacement of structures was also measured by a laser displacement meter. 8) After the excess pore water pressure had completely dissipated, the vertical displacements of logs and ground surface were measured by a point gauge. 9) The processes of 7) to 8) repeated three times with different amplitude which was from 60 gal to 100 gal at intervals of 20 gal.

Fig. 11 shows the time history of excess pore water pressure located at 100mm in depth from ground surface after undergoing shaking of 80gal, and the result of comparing the column type log, unimproved ground and the cone type log. Fig. 12 also shows the time history of settlement of model structures in the same case. The excess pore water pressure reached the maximum value after two seconds when the shaking began. It seems that the ground did not liquefied because the pressure did not reach the effective overburden pressure of 3.4kPa. However, the pressures decreased rapidly after indicating the maximum value and increased again. The time of beginning of this phenomenon correspond to the settlement of structure model as mentioned below. The settlement of structure model started when the excess pore water pressure reached maximum value and it stopped with the end of shaking in the case of improved ground. However, the settlement of the unimproved ground increased continuously until the pressure completely dissipated. It is confirmed that the settlement of structure was mitigated due to the friction of logs eve if the ground softened by generating the excess pore water pressure. Moreover, it seems that the effect of cone type log was relatively low as compared with the column type log. It is considered that the cone type log has the advantage of the area of facing the ground. However, because the excess pore water pressure generated in the ground dissipated from the lower layer of the ground toward the upper layer, the dissipation time of column type log which had small drainage area became longer than the column type.

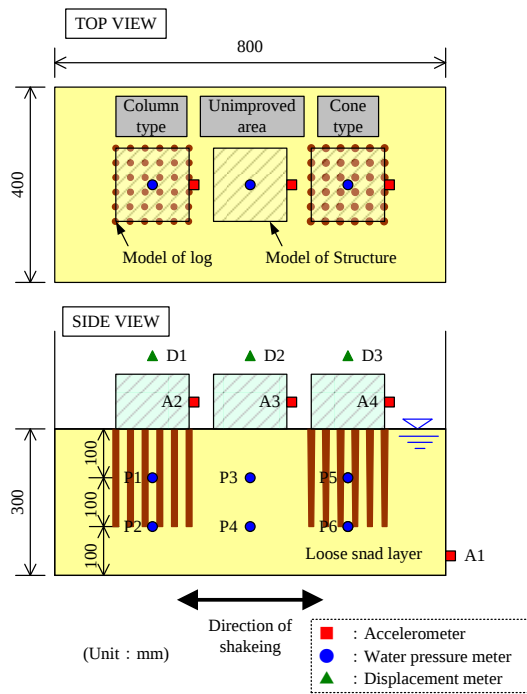


Fig. 9 General view of model ground and transducers

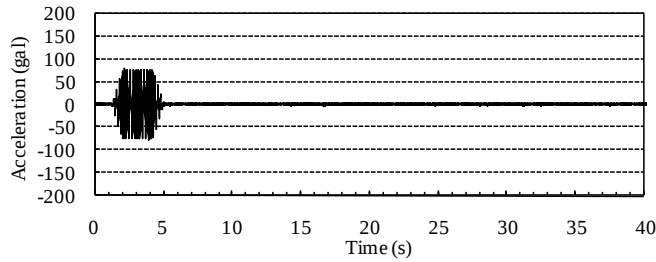


Fig. 10 Time history of input acceleration

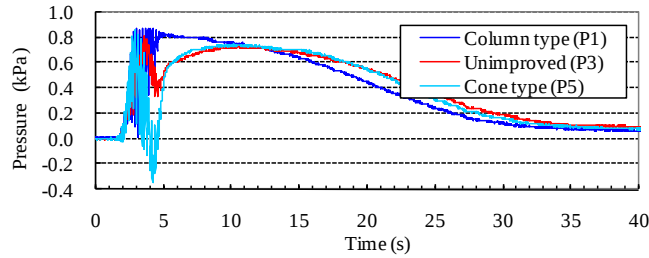


Fig. 11 Time history of excess pore water pressure

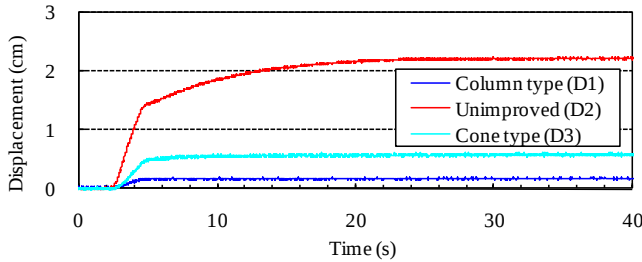


Fig. 12 Time history of settlement of structure model

6. Shaking table test to clarify effectiveness against long duration of shaking

To investigate relation between duration time of shaking and settlement of house, shaking table tests were conducted using the model ground. Fig. 13 illustrates cross sections of top and side view of a model ground with locations of transducers. The container, materials and way to make model ground were similar as shown in above chapter. The tests were conducted by using a composite ground which consists of two parts. One was improved ground where thirty six logs were installed which was shown in left side of Fig. 13, the other was unimproved ground. The density of loose liquefiable sand layer was controlled from 40 % to 60% by preliminary shaking using 300 sinusoidal waves with a frequency of 5 Hz, whose amplitude was 100gal. A model of log measured 12 mm diameter and 200 mm long. A model of house was made by water-resistant wood that measured 150 mm square and 112 mm high. The ground contact pressure of house was 1.5kN/m^2 which was scaled down one tenth of two-story wooden house with a mat foundation. Input wave used in the tests was sinusoidal wave with a frequency of 5 Hz and a peak magnitude of 120 gal. The duration time of shaking was 10, 30 and 60 second.

Fig. 14 shows residual settlement of house in relation to the duration time of shaking. It is obvious that the settlement of house increased with increase of shaking time in case of unimproved ground, but the settlement was reduced about one twentieth in case of the improved ground though the duration time was 60 second. In the previous study (Yoshida et al., 2010), it is clear that bearing capacity of ground where logs were installed could be improved due to densifying the loose sand around logs, dissipating the water pressure along the periphery of logs and restraining the shear deformation by composite ground with soil and wood in addition to

skin friction of log. According to the results as mentioned above, it is considered that these effects would be expected even if the duration time of shaking might increase.

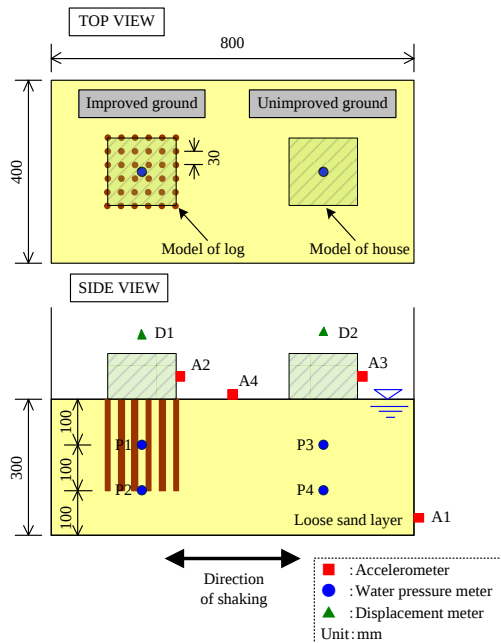


Fig. 13 General view of model ground and transducers

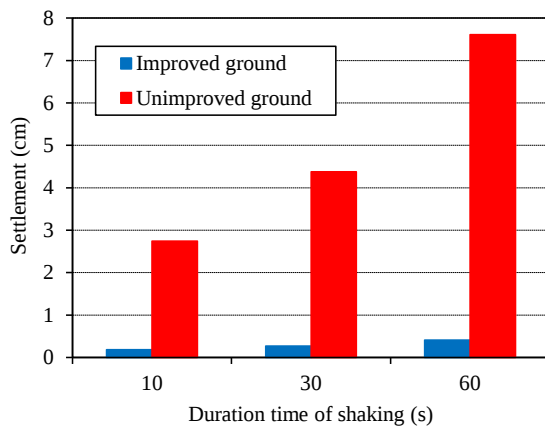


Fig. 14 Relationship between duration time of shaking and settlement of house

7. Shaking table test to investigate how to apply log pilling for existing house

To propose how to apply the technique of log pilling for existing house, shaking table tests were conducted using the model ground. Fig. 15 illustrates cross sections of top and side view of a model ground with locations of transducers. The container, materials, model of house and way to make model ground were similar as shown in above chapter. A model of log measured 12 mm diameter and 300 mm long. Four types of way to install logs were adopted in this study. Case 1 was the ground without installing logs. In Case 2, the logs were installed around foundation of house. The top and bottom of log did not be fixed. In Case 3, the top of logs were fixed. In Case 4, the logs were installed into the ground with an inclination of 15 degree. The relative density of loose sand layer was about 40%. Input wave used in the tests was sinusoidal wave with a frequency of 5 Hz and a peak magnitude of 120 gal. The duration time of shaking was 20 second.

Fig. 16 shows the time histories of settlement of house. It is clear that the log pilling around the foundation of

house (Case 2, 3, 4) was effective to reduce the settlement of house as compared with unimproved ground (Case 1). Though most settlement in all cases occurred during shaking, the settlement stopped with the end of shaking in case of improved ground. The most effective way was Case 4 and the settlement was reduced about one third of unimproved ground. If the ground liquefies below the base of house, the house settles and the liquefied soil moves laterally. Therefore the logs around the foundation of house can prevent the lateral movement of soil. This function was more effective by fixing the top of logs in Case 3. Furthermore it is confirmed that the most effective way to install logs was Case 4 because the deformed area could be smaller by installing logs with the inclination.

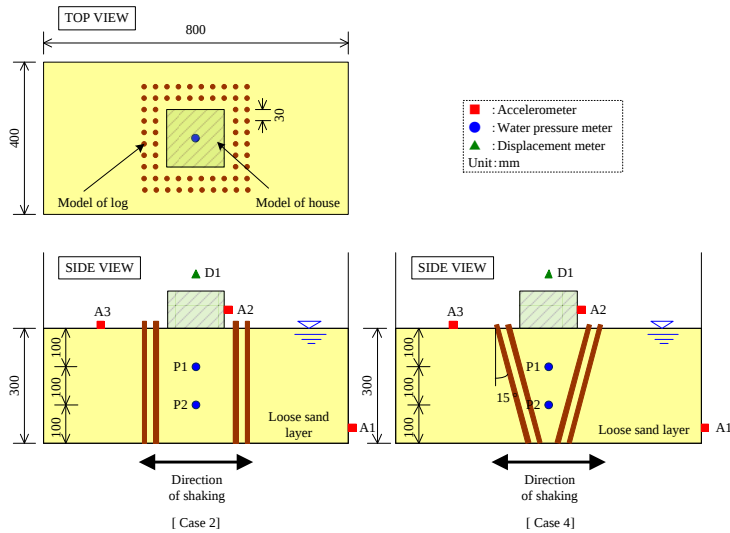


Fig. 15 General view of model ground and transducers

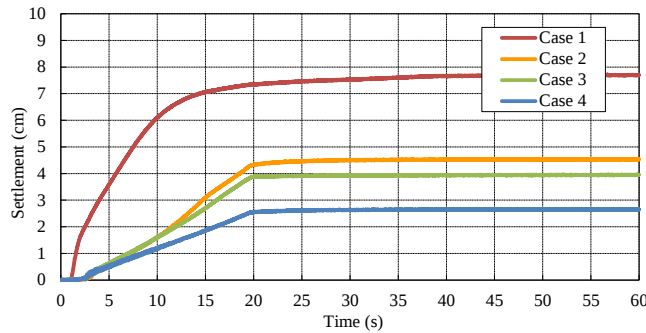


Fig. 16 Time histories of settlement of house

8. Conclusions

The three kinds of test were conducted in order to evaluate the soundness of former wood used as the pile of bridge in the soil under the water level. Furthermore, a series of shaking table tests was conducted in a 1-g gravity field in order to evaluate the performance of the logs installed in liquefiable sand layers during earthquakes and to propose the liquefaction countermeasure technique by log piling for residential houses. The following conclusions may be made on the basis of the experimental study:

- (1) The level of decay of the wood pile made of the Japanese cedar which was retrieved from the riverbed was extremely low and they have kept the soundness as the wood pile even though they were buried in the soil under the water level for 59 years.
- (2) The logs installed in the liquefiable soil layer could increase the resistance of ground against liquefaction. This effect was caused by the following four effects; 1) replacing the loose sand with logs, 2) densifying the loose sand by installing the log, 3) restraining the shear deformation by fixing the top of logs into gravel layer

- 4) dissipating the water pressure along the periphery of logs.
- (3) The bearing capacity of ground where logs were installed would be expected due to the skin friction of logs and above effects even if the duration time of shaking might increase.
- (4) The log pilling around the foundation of house was effective to reduce the settlement of house. The most effective way was to install logs with the inclination because the deformed area below the house could be smaller.

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