Study of Sand Boiling Characteristics Along Tokyo Bay During The 2011 Tohoku-Pacific Ocean Earthquake

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SUMMARY
During the 2011 Tohoku-Pacific Ocean Earthquake, liquefaction damage occurred in a wide range of the reclaimed land in the Tokyo Bay area. This study examined the size of grain particles and permeability characteristics of the boiled sand samples that were obtained in the bay area. We examined the characteristics of the boiling sand using a model of the boiling phenomenon. As a result, the soil of the boiled sand was classified as fine sand containing much fine-grain soil. In the model experiment, the soil particles erupted together with water like the boiling sand sample. The case with which the soil fraction erupted in the water to spurt up is related to the square of the particle diameter. The case of underwater subsidence of a soil fraction is related to the cube of particle diameter. Thus, if fine sand containing fine-grained soil liquefies, it is possible that much sand boiling would occur.

Keywords: Liquefaction, Sand boil, Grain size distribution, Permeability

1. INTRODUCTION

The 2011 Tohoku-Pacific Ocean Earthquake occurred off in Miyagi Prefecture on March 11, 2011. Liquefaction damage caused by this earthquake was observed in a wide area from the Tohoku district to the Tokyo Bay area. Liquefaction occurred mainly in reclaimed land and Old River channels. It is damage was very serious although the Tokyo Bay area is about 380 km from the epicentre. The main damages were soil subsidence and tilting of wooden houses. Moreover, water, sewage, and gas pipes were damaged. Very much sand spurted up due to liquefaction. Samples of the boiling sand were obtained in field investigations immediately after an earthquake. We investigated the physical characteristics and water penetration characteristics of the samples. We also investigated the sedimentation rates of the boiling sand that erupted at the time of the quasi-liquefaction by a model experiment. We considered the causes sand boiling using the test results. In addition, we compared the results with those of the Christchurch Earthquake of New Zealand, which had many sand eruptions.

2. LIQUEFACTION IN TOKYO BAY AREA

Reclamation of the Tokyo Bay area started in the Edo period (1603-1868), but much reclamation has been performed since World War II. Past liquefaction damage was confirmed in the 1923 Kanto earthquake and the 1987 Chiba-ken Toho-oki earthquake. In the 1923 Kanto earthquake, liquefaction was confirmed in Tsukishima in Tokyo. In the 1987 Chiba-ken Toho-oki earthquake, liquefaction was confirmed in large areas of Chiba to Kisarazu. The places where liquefaction occurred in the Tohoku-Pacific Ocean earthquake are shown in Figure 2.1. this figure is based on field investigation results. We carried out field investigations using the same method used in the earthquake that occurred in New Zealand in February, 2011. The conditions examined are shown as follows.

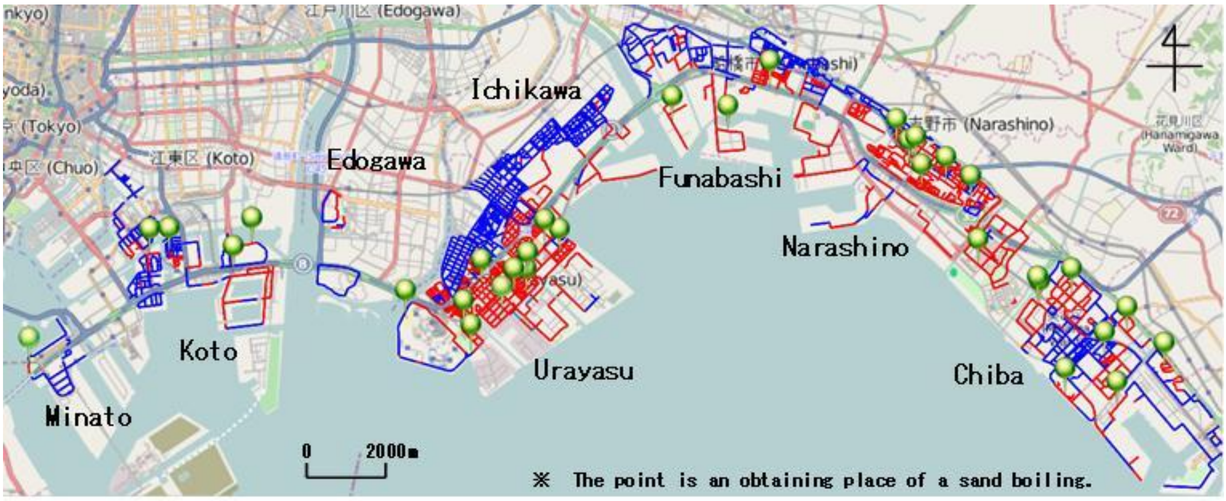


Fig.2.1. Liquefaction damage in Tokyo Bay area

Fig.2.2. Sedimentation of the sand boiling in Urayasu

Fig.2.3. Many sand boiling in a residential section in Chiba

1) Red line: Case in which sand boiling due to liquefaction can be confirmed on a road or housing site.
2) Blue line: Case in which sand boiling due to liquefaction can be confirmed on neither a road.

A green point shows the sampling point of the sand boiling. This figure shows that liquefaction occurred in the large area from Odaiba in Tokyo to near the Chiba port in Chiba. Especially seriously damaged was Urayasu. Moreover, a wide range liquefactions were observed in Ichikawa and Nrashino. Many of the damaged structures were wooden houses, which exhibited subsidence and tilting, and the Life-Line institution which carried out functional injury. On the other hand, medium-rise structures have better pile foundation structures and ground improvement, so building damage was not confirmed. As for ground damage, pressure from below sidewalks and land subsidence were confirmed. Moreover, very many sand boilings characteristically erupted. Figure 2.2 and 2.3 show the sedimentation of sand boilings confirmed by the field survey. The sedimentation thickness of the sand boiling was confirmed to be about 30 cm. As shown in Figure 2.3, the sand boiling that erupted was sometimes so massive that it covered the road. The maximum depth of land subsidence confirmed by the field survey was about 50 cm. Urayasu reported the amount of land subsidence after the earthquake. Figure 2.4 (Urayasu City, 2011) shows the difference in values before and after the earthquake measured by aviation laser metrology. The figure confirms subsidence of about 30-50 cm in the area in which much liquefaction to the settlement of the ground occurred after the earthquake. An area in which the liquefaction was not generated was a northern area of the old coastline, and settlement there was slight compared with the liquefied area. Furthermore, it seems that there is a spot where damage is intense other than these areas.

The liquefaction damage in the Tokyo Bay area resembled the damage at the time of the main shock

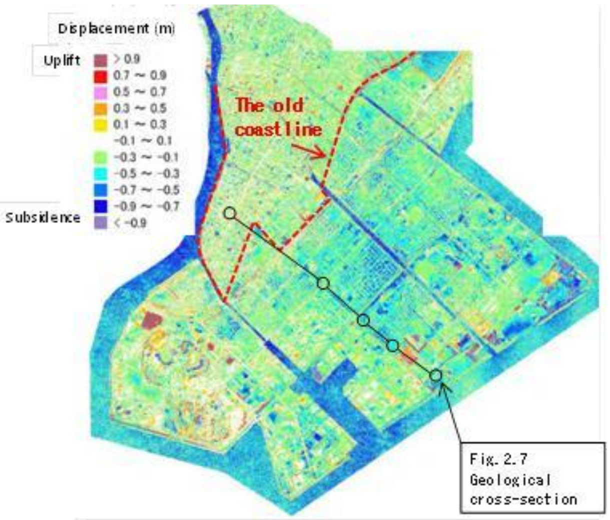


Fig.2.4. Displacement after the earthquake in Urayasu（Urayasu City, 2011）

Fig.2.5. Sedimentation of the sand boiling in Christchurch (Main shock)

Fig.2.6. Sedimentation of the sand boiling in Christchurch (After Shock)

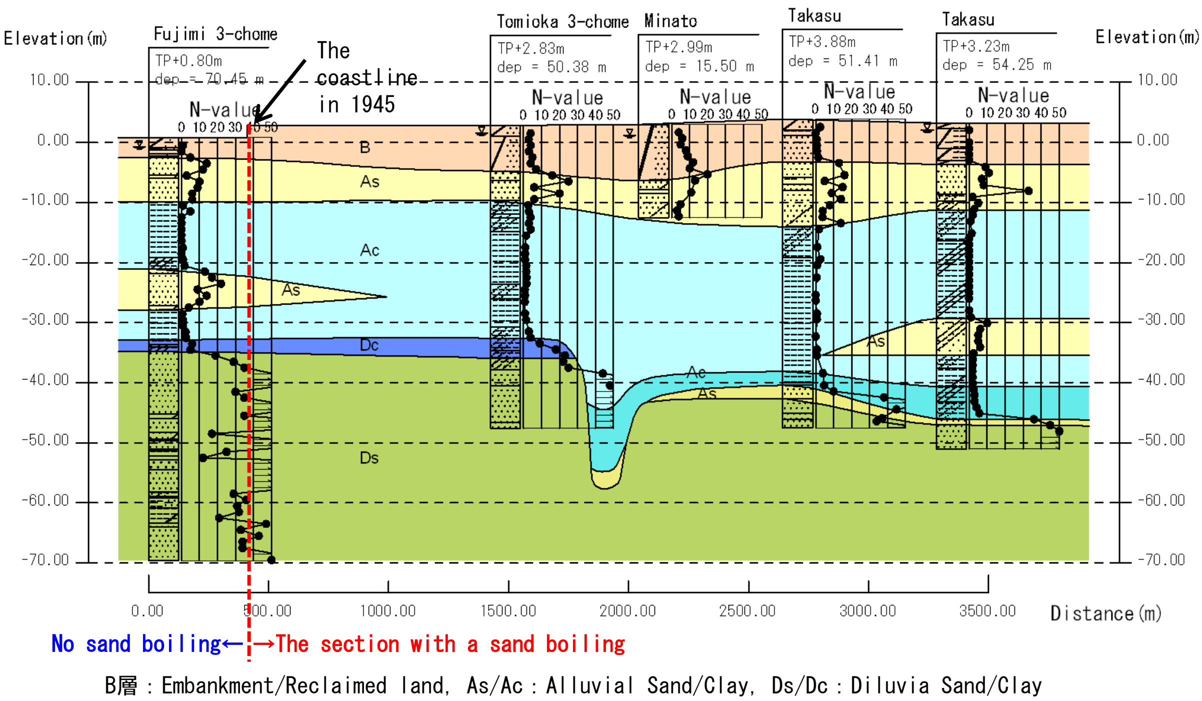


Fig.2.7. Estimated geological section of the Urayasu center section

Table 3.1 Physical characteristics Average of a sand boiling

Place	The number of samples	Gravel fraction (%)	Sand fraction (%)	Fine fraction (%)	Mean grain size (mm)	Uniformity coefficient	Plasticity index
Minato-ku	1	0.3	95.9	3.8	0.199	1.99	NP
Koto-ku	4	0	70.4	29.6	0.121	3.49	NP
Urayasu	9	1.2	83.0	15.8	0.164	3.29	NP
Ichikawa	1	0.1	82.2	17.7	0.150	－	NP
Funabashi	2	0.1	89.4	10.5	0.175	2.26	NP
Narashino	5	0.2	66.7	33.1	0.098	2.81	NP
Chiba-Mihama	10	0.1	57.4	42.5	0.106	2.61	Np～5.7
Takahama, Mihama-ku, Chiba : Fc=82.4%, W_L=73.9%, Ip=30.6							

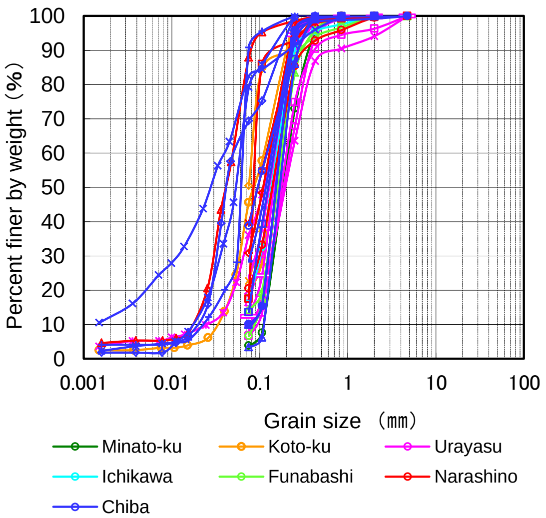


Fig.3.1. Grain size distribution curves of sand boiling in Tokyo Bay area

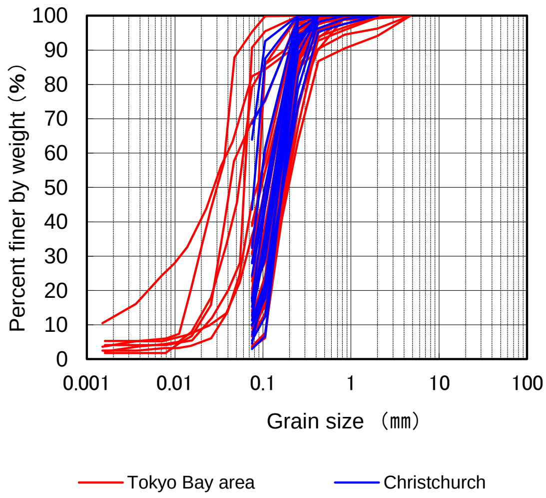


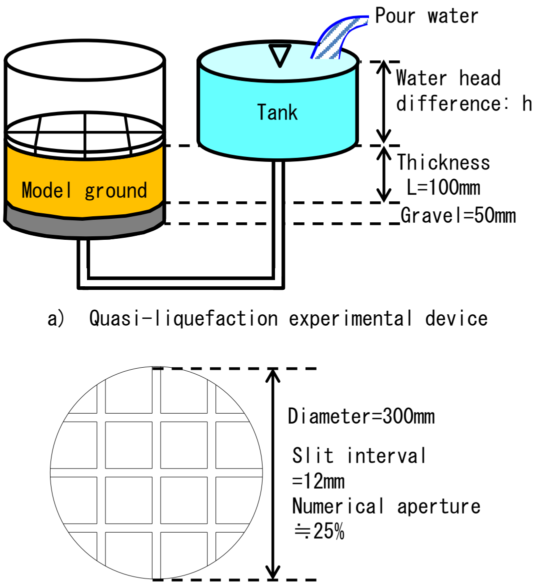
Fig.3.2. Grain size distribution curves of sand boiling in Tokyo Bay area and Christchurch

and aftershock in Christchurch. Both sites had liquefied areas that were very wide, with very much sand boiling. Figure 2.5 and 2.6 show the sedimentation of the sand boiling that the authors confirmed at the same place at the time as the field survey in Christchurch. In Christchurch, liquefaction at the time of the main shock and re-liquefaction at the time of aftershock were confirmed, and also a third liquefaction was confirmed at the time of a later aftershock.

Figure 2.7 show a geological cross-section in the northwest-southeast direction in the center of Urayasu. The area where the sand boiling occurred was confirmed to be an area of reclaimed land made from the coastline in 1945. As for the groundwater level, the water level exists about -1 to -2 m below the surface of the ground. The N value of the standard penetration test of the embankment layer in a liquefied area was in a very loose at an average of three times in a range of 0 to 9. The embankment layer was about 7-9 m thick. The N value of the alluvial sandy soil layer was an average of 10 times in a range of 2 to 33. The alluvial sandy soil layer had a medium density. A liquefied layer is below the groundwater level. The layers which liquefied are banking layer and some loose alluvium sandy soil layers.

3. GRAIN SIZE DISTRIBUTION OF BOILING SAND IN TOKYO BAY AREA

Figure 3.1 shows the grain size distribution curve of the boiling sand obtained at the time of a field survey. Table 3.1 is the mean grain size distribution of the samples obtained in each district. The mean fine fraction content (F_C) of the sand boiling in each extraction area was 3.8% to 42.5%. The



a) Quasi-liquefaction experimental device

b) Arrangement plan

Fig.4.1. Schematic diagram of an experimental device

Table 4.1 Physical properties of an experiment sample

Soil sample			Urayasu	Toyoura
Soil particle density	*ρs*	(g/cm^3)	2.643	2.650
Gravel fraction		(%)	0.0	0.0
Sand fraction		(%)	64.0	100.0
Fine fraction	*Fc*	(%)	36.0	0.0
Mean grain size	*D50*	(mm)	0.1123	0.1700
Plasticity index	*IP*		NP	NP
Maximum void ratio	*emax*		1.477	0.996
Minimum void ratio	*emin*		0.828	0.613

Table 4.2 Experimental condition

○ The experimental condition of Urayasu sand

Case	Relative density *Dr* (%)	Hydraulic gradient *h/L*	Hydraulic conductivity k_{15} (m/s)	Note
1～3	20	1.00, 1.25, 1.50	6.17E-05	Very loose
4～6	30	1.00, 1.25, 1.50	2.60E-05	loose
7～9	50	1.00, 1.25, 1.50	1.70E-05	Middle
10～12	70	1.00, 1.25, 1.50	1.00E-05	dense

○ The experimental condition of Toyoura sand

Case	Relative density *Dr* (%)	Hydraulic gradient *h/L*	Hydraulic conductivity k_{15} (m/s)	Note
1～3	20	1.00, 1.25, 1.50	3.98E-04	Very loose
4～6	30	1.00, 1.25, 1.50	3.50E-04	loose
7～9	50	1.00, 1.25, 1.50	3.07E-04	Middle
10～12	70	1.00, 1.25, 1.50	2.25E-04	dense

uniformity coefficient (*Uc*) was 1.99 to 3.49 by soil texture with uniform grain size composition. Moreover, the plasticity index (*IP*) of almost all samples was non-plastic, and the fine grained soil contained in a sand boiling had an unplastic soil texture. A sample form Takahama 7-chome, Mihama-ku, Chiba-shi, was confirmed to have F_C=82.4% and *IP*=30.6. The samples were sandy silt from silty sand, and the sand with fine particle diameter.

Figure 3.2 shows a comparison of the grain size distribution of the sand boiling of the Tokyo Bay area and Christchurch. The grain size distribution of the sand boiling generated in both was similar. Both areas had very many sand boilings. The cause is considered to be the effect of sandy soil with a fine paticle diameter containing unplastic fine grained soil.

4. EXPERIMENT TO DETERMINE EASE OF ERUPTING OF SAND THAT LIQUEFIED

This experiment reproduced the liquefaction caused by boiling using samples obtained in order to examine the numerous sand boilings at the time of liquefaction in the Tokyo Bay area and Christchurch earthquakes. The samples used were two kinds: sand that does not contain fine grained soil and a soil boilings sample. The sand that does not contain fine grained soil is Toyoura sand. The sand boiling sample (Urayasu sand) was obtained in Tekko-dori, Urayasu-shi. The result indicated the amount of fine grain sand included in a sample.

4.1 Experimental Method

Experimental recreation of the sand boiling phenomenon at the time of liquefaction used the boiling phenomenon. Figure 4.1(a) shows a schematic diagram of the testing device. An acrylic pipe 300 mm in diameter was used for the testing device. The lower layer of the model was covered with the fine gravel layer (diameter=5 mm) 50 mm deep as the filter layer. A filter layer is installed to prevent the water from a head tank from hitting the model ground directly. The thickness of the model ground was

Fig.4.2. Before and after an experiment using Urayasu sand

Fig.4.3. Before and after an experiment using Toyoura sand

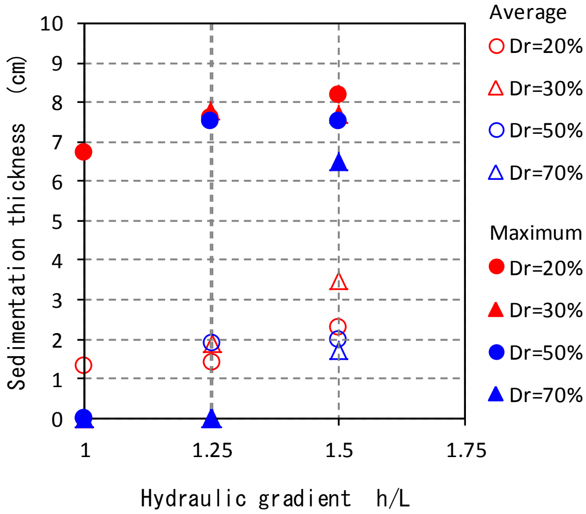


Fig.4.4. Relationship between hydraulic gradient and sedimentation thickness

100 mm at the upper layer of the filter layer. The surface part of the model ground had arranged blocks that replicated the interlocking blocks currently installed in the sidewalk. Figure 4.1(b) shows the installation to the model ground of blocks. The experiment measured the sedimentation thickness of the sample that erupted on these blocks. The eruption time of boiling sand was for 3 minutes. The sedimentation thickness was measured at the time groundwater level is returning to an early head position (h=0 mm). Table 4.1 shows the physical properties of the samples used. Table 4.2 shows test condition. The density of the model ground varied in four cases from a very loose condition to a dense condition. The coefficient of permeability of each density of the model ground is shown in Table 4.2. Moreover, three hydraulic gradients were used in each density.

4.2 Experimental Result

Figure 4.2 and 4.3 show the sedimentation after an experiment using Urayasu sand and Toyoura sand. In the test conditions of the figure, the hydraulic gradient was h/L=1.5 at a relative density Dr=30%. In the case of Urayasu sand, the sand that erupted accumulated on the whole surface of a block. On the other hand, Toyoura sand is the grade from which some sand erupted on the block. Toyoura sand did not boil like the Urayasu sand did in this experiment. Since the Urayasu sand at the time of boiling had low water permeability, water oozed out gradually. Then, the water that oozed out erupted from the weak layer portion of the model ground by piping failure. Many samples erupted together as a fountain at the time. On the other hand, the coefficient of permeability of Toyoura sand is one order larger than that of Urayasu sand. When a change was made to the water level from the ground surface, water oozed out from the whole surface of the model ground. Since Toyoura sand is not a piping sand boil like Urayasu sand, there was almost no sand boil. Figure 4.4 shows the experimental result of each case of Urayasu sand. The mean value in a figure shows the thickness of the sand deposited on each block. The maximum value shows the largest value deposited. The test result showed that the sedimentation thickness of a sand boiling increased when the hydraulic gradient was increased. Moreover, when the model ground became dense, the frequency of sand boiling decreased. At a

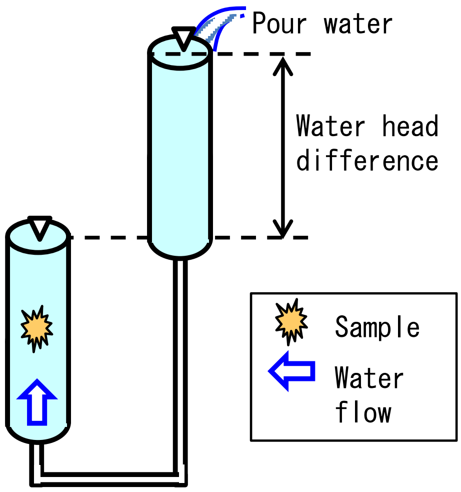


Fig.5.1. Experimental device to determine the ease of floating up of a soil particle

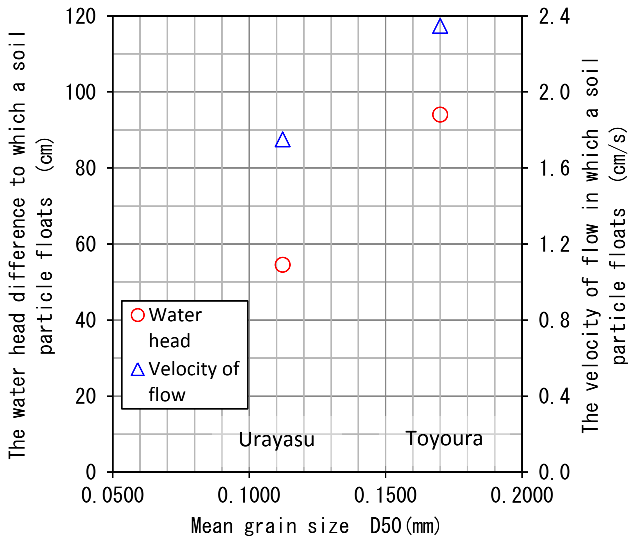


Fig.5.2. Relationship between a hydraulic gradient and sedimentation thickness

relative density of *Dr*=70 % and a hydraulic gradient of *h/L*=1.5, sand boiling occurred for the first time. However, although the same experiment was also conducted with Toyoura sand, the sample did not deposit on the block like Urayasu sand.

5. EXPERIMENT TO DETERMINE THE EASE OF FLOATING UP OF SOIL PARTICLES BY FOUNTAIN OF LIQUEFACTION

Excess pore water pressure in an earthquake works so that it may disappear after an earthquake. Sand boiling is a phenomenon that arrives at the surface of the ground at the time of dissipation of excess pore water pressure. In this case, the soil particle in a fountain can be considered to ease the change rising from differences in size. This experiment compared the difference in the ease of rising of Urayasu sand and Toyoura sand using a simple model experiment.

5.1 Experimental Method

Figure 5.1 shows the experimental device to determine the ease of rising of soil particles. Two acrylic pipes 94mm in diameter were used. The flowing water was made to erupt from a head-tank bottom face by attaching the water head difference of two head tanks. The water head difference and the velocity of flow when a sample continues floating within a head tank were measured. Moreover, the soil particle sample was directly supplied in the midrange of a flowing water head tank. The physical properties of the samples examined are shown in Table 4.1.

5.2 Experimental Result

The result is shown Figure 5.2. The water head height at which a soil particle of Urayasu sand continues floating within a head tank is 54.5 cm. On the other hand, the water head height at which Toyoura sand continues floating is 94.0 cm. Moreover, the velocity of flow at which Urayasu sand continues floating is 1.7 cm/s, and the velocity of flow at which Toyoura sand continues floating is 2.3 cm/s. The difference in the velocity of flow of each sample was about 1.4 fold. The ease of floating up of a soil particle can be examined by postulating a soil particle to be a globular. When a spherical radius is r, the surface area and volume are as follows.

$$\text{Surface area of a soil particle (cm}^2\text{)}: \; S = 4\pi r^2 \tag{5.1}$$

$$\text{Volume of a soil particle (cm}^3\text{)} \ : \ V = (4/3)\pi r^3 \tag{5.2}$$

The power in which a soil particle falls under the effect of gravity is as follows (settling force).

$$\text{Settling force :} \ \ W = V\gamma' = (4/3)\pi r^3 \times \gamma' \tag{5.3}$$

γ' : Submerged unit weight

On the other hand, the power in which a soil particle rises with the flowing water from the lower part of a head tank is as follows (force of rise).

$$\text{Rising force :} \ \ F = \alpha S = \alpha 4\pi r^2 \tag{5.4}$$

α : Constant resulting from flow velocity

It becomes F>W in order for a soil particle to ride the flattening out of the fountain from the head-tank lower part and to rise. Then, the ratio of the settling force W to the rising force F is shown below.

$$L = F/W = \alpha 4\pi r^2/\{(4/3)\pi r^3\gamma'\} \ = 3\alpha/r\gamma' \tag{5.5}$$

This means that a soil particle rises in the condition of “$3\alpha/r\gamma' > 1$”. Therefore, the ease of rising of a soil particle is affected by particle diameter. That is, a soil particle rises more easily as it is diameter becomes smaller. Combining formulas (5.3) and (5.4) yields “F=W”. It follows that the constant of the velocity of flow at the time a soil particle rises with the average particle diameter of each sample.

$$\text{Urayasu sand :} \ \ \alpha = r\gamma'/3 = 0.019\gamma' \tag{5.6}$$

$$\text{Toyoura sand :} \ \ \alpha = r\gamma'/3 = 0.028\gamma' \tag{5.7}$$

The above demonstrates that when the submerged unit weight of a soil particle is fixed, the difference in the ease of rising of each sample is about 1.5 fold. Moreover, the difference in the flow velocity at the time of rising of each particle is about 1.4 fold. This result shows that the value is comparable to the estimated value computed from average particle diameter.

6. CONCLUSION

During the 2011 Tohoku-Pacific Earthquake, liquefaction occurred across a wide range of the Tokyo Bay area. The field survey confirmed that there are very many occurrences of sand boiling due to liquefaction. The following characteristics could be considered as causes of the huge amount of sand boiling generated.

1) The particle diameter of the boiling sand was uniform, and it was fine sand containing fine-grained soil. Moreover, fine-grained soil is an unplastic soil.
2) Because boiling sand contains fine-grained soil, it is water permeability is poor. Excess pore water pressure is accumulated by many cyclic shears, and the sand that liquefied is considered to erupt from the weak part in the ground.
3) The ease of eruption of a soil particle is affected by the size of the soil particle. It is thought that the reclaimed land of the Tokyo Bay area is a material that floats up easily when it is in a fountain because the particle size is fine.

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REFERENCES

Wakamatsu, K. (2011). Maps for Historic Liquefaction Sites in Japan. University of Tokyo Press (in Japanese).

JGS disaster urgent investigating commission. (2011). The damage report by the 2011 Christchurch earthquake. The Japanese Geotechnical Society, 19-20 (in Japanese).

Urayasu City Office. (2011). Correspond to an East Japan Great Earthquake. HP: http://www.city.urayasu.chiba.jp/secure/26068/shiryo1_4taio_r.pdf. (in Japanese).

Chiba Prefecture Govemment. (2011). Chiba geological environment information bank. HP: http://wwwp.pref.chiba.lg.jp/pbgeogis/servlet/infobank.index. (in Japanese).

The Japanese Geotechnical Society. (1998). Interpretation and the example of application of a ground survey and a soil laboratory test result. Maruzen, 328 (in Japanese).