The Settlement, Hardness and Liquefaction of Sand Beds due to Fluctuating Water Pressure

Takaaki Minamimura¹⁾, Masaki Niiyama²⁾, Takao Akutu³⁾, Kenji Yano⁴⁾, Toshihiko Yamashita²⁾

1. Abstract

The degree of sand beds compaction affects the accumulation and erosion of shorelines, and the popuration of creatures which live in sandy beach. The properties of the settlement, hardness and liquefaction of sand beds due to fluctuating water pressure were experimentally studied. The settlement of a sand bed was accelerated by liquefaction. The thickness of liquefaction layer which is estimated from the measured values of excess pore water pressure agreed well with one from the measured values of the rate of settlement. The hardness of sand bed was determined only by void ratio independent of liquefaction or non-liquefaction beds.

2. Introduction

Sand beds are repeatedly densified and sparsified due to wave action, and loose sand beds gradually settle and become compacted. Kraus et al.(1994) experimentally showed that the erosion of compacted sand on shorelines due to waves is less than that of loose sand, and Nishi et al. reported from the results of their field study that the degree of sand compaction affects the accumulation and erosion of sandhills and shorelines. Field studies have also been conducted on the effects of the degree of sand compaction on aquatic animals; Hodgin et al.(1992) showed that the degree of sand compaction affects the life of turtles, and Akutu et al.(1996) showed that, as it is difficult for bivalves to burrow into hard sand, the population of burrowing bivalves in compacted sand beds is less than that in loose sand beds. Although clarification of wave-induced settlement and compaction of sand beds is important from both engineering and biological points of view, there have been very few systematic studies of these

 ¹⁾ Obayashi Corporation, 3, 2-chome, Kanda Tsukasa-cho Chiyoda-ku, Tokyo 101-8533, Japan.
²⁾ Laboratory of Coastal and Offshore Engineering, Division of Environment and Resources Engineering, Hokkaido University, N-13 W-8, Kita-ku, Sapporo 060-8625, JAPAN

⁽Fax:+81-11-726-2296, E-mail: y-toshi@eng.hokudai.ac.jp)

³⁾ Hokkaido Development Bureau, N-8 W2, Kita-ku, Sapporo 060-8511, JAPAN

⁴⁾ Depertment of Marine science and Technology, Hokkaido Tokai University,

^{5-1,} Minaminosawa, Mimami-ku, Sapporo 005, JAPAN

phenomena. On the other hand, it is known that the amount of settlement is greater if liquefaction of the sand bed occurs due to wave action (Zen et al, 1987).

In this study, the characteristics of settlement, hardness and liquefaction of a sand bed due to fluctuating water pressure were experimentally investigated, and the interrelationships between settlement, hardness and liquefaction were quantitatively determined.

3. Experiments

Experiments were carried out using a fluctuating pressure-type liquefaction test apparatus (Fig. 1). A two-meter-high acrylic cylinder was made by joining together cylindrical rings of 40cm in diameter and 10, 20 and 40cm in height. The sand bed was a loose sand layer with a

void ratio of 0.85 and a sand particle diameter of 0.15mm. Sand beds of four thicknesses were used in the experiments: L=0.7m, L=1.2m, L=1.5m, and L=1.8m. A sand container filled with water was set at a higher location than that of the experimental cylinder, and, using a hose, the cylinder was filled with water and sand by suction force generated due to the head gap between the container and the cylinder. The amount of air in a sand bed affects the properties of the sand bed, however, sand beds with same property containing very little air can be made by using this method. Table1 shows experimental conditions. In all cases, the period and average pressure of fluctuating water pressure were 5 sec and 10m, respectively. All experiments were first conducted at total head H=1.2m under conditions in which liquefaction does not occur, in order to determine the properties of a sand bed. For the theoretical analysis of pore water pressure, we used the theory of Zen et al. (1987). Underwater pressure and pore water pressure in the sand bed were measured at 11 points (see Fig. 1) and at sampling intervals of 0.01 sec, and the amount of settlement was determined by measuring the position of colored sand



Fig 1. Experimental Device

Table 1.	Experimental Conditions

	Sand bed	Total	Coefficient of	Coefficient of
	thickness	head	transmission	consolidation
Case	L(m)	H(m)	α	C(cm ³ /s)
1	0.7	1.2	1.15	0.35
2	0.7	6	1.15	0.35
3	1.2	1.2	1,15	0.35
4	1.2	6	1.15	0.35
5	1.2	1.2	1.2	0,35
6	1.2	6	1.2	0.35
7	1.5	1.2	1, 15	0.35
8	1.5	4	1.15	0.35
9	1.5	6	1.15	0.35
10	1.5	1.2	1.25	0.35
11	1.5	6	1.25	0.35
12	1.8	1.2	1.3	0.35
13	1.8	6	1.3	0.35

(maker) at depth intervals of 10cm or 20cm. The surface hardness of the sand bed was determined by measurement of the depth penetration of a cone penetrometer (weighing 800g) that was dropped from the surface of the sand bed. The above three measurements were repeated 6 times under conditions of fluctuating water pressure of 3,000 waves.

4. Experimental Results and Discussion

4.1 Fluctuating pore water pressure

Fig.2(a) and (b) show the distributions of depth direction of phase delay $\Delta T/T$ (= time difference between surface water pressure peak and pore water pressure peak / period) and the ratio of amplitude of pore water pressure to surface water pressure Pm/Po. Z is positive in a downward direction with the sand-bed surface as the origin. The theoretical values calculated according to the method of Zen et al. (1987) are shown in figures. In the case of the same period, the theoretical values are not affected by the amplitude of fluctuating pore water pressure. The parameters used for the theoretical calculation are the coefficient of transmission (α) and the coefficient of consolidation (C). The values of $\alpha = 1.25$ and C=0.35 were used for the theoretical calculation to coincide with the experimental results of pore water pressure under conditions in which liquefaction does not occur. The figure shows that the deeper the location of the pore water pressure gauge is, the smaller is the ratio of amplitude of pore water pressure to surface water pressure and the larger is the phase delay. Thus, the surface water pressure is transmitted throughout the sand bed accompanying attenuation and phase delay. Under conditions in which liquefaction of the sand bed does not occur (H=1.2m), the tendencies of the experimental values (i.e., decrease in Pm/Po and increase in Δ T/T with increases in Z) agreed well with the theory of Zen et al. On the other hand, under conditions in which liquefaction of the sand bed occur (H=6.0m), the decrease in Pm/Po and increase in Δ T/T with increases in Z were smaller than those of the theoretical values of Zen et al. This is thought to be due to the improvement in transmission properties of pore water pressure caused



Fig 2. The ratio of ampulitude of pore water pressure to surface water pressure and the phase delay

byliquefaction.

In order to see the effect of thickness of the sand bed on transmission properties of pore water pressure, Fig. 3(a) and (b) show the distributions of depth direction of the ratio of amplitude of pore water pressure to surface water pressure and phase delay for each thickness of the sand bed under conditions in which liquefaction does not occur. The depth distribution of Pm/Po in Fig. 3(a) shows that the ratio of amplitude of pore water pressure to surface water pressure decreases with increases in the sand bed depth and sand bed thickness, which agrees with the properties of the theoretical values of Zen et al. In Fig. 3(b), the phase delay Δ T/T increases with increases in the sand bed depth and sand bed thickness, which also agrees with the properties of the theoretical values of Zen et al. In other words, the larger the sand bed thickness is, the greater is the effect on the transmission properties of pore water pressure.



Fig 3. The ratio of ampulitude of pore water pressure to surface water pressure and the phase delay

4.2 Distribution of excess pore water pressure

Fig. 4(a) and (b) show examples of the distribution of excess pore water pressure Pe obtained by measurement and by the theoretical calculation of Zen et al. (solid line) in the case of a total head of 6.0 m. The phase where the fluctuating water pressure changes from negative to positive was made zero. The distributions of earth pressure (σ) are also shown in the figures. L=1.5m in both figures. In Fig.4(a), $\alpha = 1.15$ and the excess pore water pressure is smaller than the earth pressure, which are conditions under which liquefaction of the sand bed does not occur. Under these conditions, the measured values and theoretical values are very similar in all phases. It was found that in the phases $180^{\circ} \sim 270^{\circ}$, in which surface water pressure decreases from zero, positive excess pore water pressure increases, while in the phases $0^{\circ} \sim 90^{\circ}$, in which surface water pressure increases. Maximum excess pore water pressure occurs at phase 225° . Also, excess pore water pressure increases with depth.

A comparison of the earth pressure and excess pore water pressure in Fig. 4(b) shows that the excess pore water pressure is greater than the earth pressure in the phases 180° \sim 270°, which is the condition under which liquefaction of the sand bed occurs. In phases 0° \sim

 90° , in which the measured values are very similar to the theoretical values, the density of the sand bed is higher due to the large negative excess pore water pressure. However, in the phases in which liquefaction occurs (225° and 270°), the measured values are smaller than the theoretical values. This is thought to be due to the improvement in transmission properties of pore water pressure caused by liquefaction. As can be seen in the figure, under this condition, liquefaction occurs down to a depth of 40cm at phases 225° and 270° .



Fig 4. The distribution of depth direction of excess pore water pressure

4.3 Settlement properties

Fig.5 show the experimental results of amount of settlement ΔL at each depth of the sand bed in the case of fluctuating water pressure of 3,000 waves. Arrows in the figure show the depth of liquefaction obtained from experimental values of excess pore water pressure.

Under conditions in which liquefaction of the sand bed does not occur (unshaded portion), the amount of settlement on the surface layer of the sand bed increases with increases in thickness of the sand bed, but the average rate of settlement $\Delta L/L$ (amount of settlement / thickness of sand bed) does not change regardless of the thickness of the sand bed. The similar degrees of settlement in every layer were thought to be due the good transmission of pressure throughout the sand bed because of the small value of α (1.15) and the fact that the ratio of amplitude of pore water pressure to surface water pressure was over 0.9 in every layer, as can be seen in Fig. 3. More detailed examination of the distribution of depth direction of the ratio of settlement $\Delta 1/1$ (amount of settlement



of each layer / thickness of each layer) shows that $Z \ge 40$ cm in the case of L=1.2m and $Z \ge 70$ cm in the case of L=1.5m, the ratio of settlement decreases slightly. These regions agree with the regions in which phase delay (Fig. 3) and an increase in excess pore pressure (for example, $\theta = 225^{\circ}$) to depth direction (Fig. 4) become smaller. Next, a comparison of a liquefying sand bed (black-colored symbols) with a non-liquefying sand bed shows that the rate of settlement in the liquefying region of the sand bed (above the arrows) is about two-times greater than that in the non-liquefying region of the sand bed. This result suggests that the settlement of a sand bed is accelerated by liquefaction. The region with a higher rate of settlement coincides well with the the liquefying region calculated from excess pore pressure, indicating that the liquefying region can also be estimated from the distribution of depth direction of the rate of settlement. Moreover, in the non-liquefying region (under the arrows), the rates of settlement are very similar in both sand beds. This is thought to be because liquefaction of the surface of the sand bed at a thickness such as that in Fig. 2 or Fig. 4 has little effect on the transmission of pore water pressure to deeper layers.

Fig. 6 shows changes in the wave number N of the average rate of settlement in each thickness of sand bed in the case of a liquefying sand bed and non-liquefying sand bed. In the case of a liquefying sand bed, the average rate of settlement is that only in the liquefying region. As can be seen in the figure, in our experimental range of up to 1.8m in sand bed thickness, the average rate of settlement is not affected by the thickness of the sand bed in either the liquefying or nonliquefying sand bed, but the average rate of settlement in the liquefying sand bed is two-times greater than that in the non-liquefying sand bed. Also, the increase in the average rate of settlement in the liquefying sand bed is greater than that in the non-liquefying sand bed until about 100 waves; thus, settlement is accelerated by liquefaction of the sand bed, and the increase in the settlement rate later becomes smaller.

Fig. 7 shows the relationship between the average rate of settlement and the total head of fluctuating pressure of 1,000 waves for each sand bed thickness. As can be seen in this figure, in our experimental range of up to 1.8m in sand bed thickness, the average rate of settlement is almost the



Fig 6. Changes in the wave number of the average rate of settlement



Fig 7. Relationship between the average rate of settlement and the total head

same in every thickness of sand bed that has the same total head regardless of whether the sand bed is liquefying or non-liquefying, indicating that the average rate of settlement is not affected by the thickness of the sand bed. In the non-liquefying sand bed, the average rate of settlement is almost proportional to H. Also, as stated before, the average rate of settlement in the liquefying region is two-times greater than that in the non-liquefying sand bed.

4.4 Effect of settlement on transmission properties of pore water pressure

In order to see the effect of settlement on the transmission properties of pore water pressure, examples of change in the wave number of the ratio of amplitude of pore water pressure to surface water pressure and phase delay are shown in Fig. 8(a) and (b). These examples are for the case in which liquefaction occurs in the sand bed and the surface layer of the sand bed has sunk by 4.5cm. The ratio of amplitude of pore water pressure to surface water pressure and the phase delay remain almost constant regardless of the wave number, indicating that settlement has very little effect on the transmission properties of pore water pressure. This agrees with the results reported by Zen et al. (1987) and Yamashita et al. (1996).



Fig 8. The change in the wave number of ratio of amplitude of pore water pressure tourface water pressure and phase delay

4.5 Liquefaction region

Fig. 9 shows the liquefaction depth obtained from measured values and theoretical values of excess pore pressure (see Fig. 4) and the depth of liquefaction obtained from the amount of settlement of the sand bed (see Fig. 5). In the case of $\alpha = 1.15$, liquefaction of a sand bed theoretically does not occur if the thickness of the sand bed is less than 1.8m. In this figure, it is quantitatively shown that the larger the thickness of the sand bed and the value of α are, the larger is the liquefaction depth obtained by theoretical values of excess pore water pressure. The liquefaction depths obtained by measured values of excess pore pressure and by the

amount of settlement are almost the same. The measured values and theoretical values of excess pore water pressure and the amount of settlement are very similar when the liquefaction depth is small, but when the liquefaction depth is large, (for example, the line and ∇ of L=1.8 in the figure), the measured values become smaller than theoretical values. This tendency for the measured values becomes larger as the liquefaction depth increases. This is thought to due to the improvement in transmission properties of pore water pressure as the liquefaction depth increases (and the phase

4.6 Hardness of the sand bed

of liquefaction becomes longer).

Fig. 10 shows the relationship between void ratio e of the surface laver of the sand bed and the penetration depth Dp measured by a cone penetrometer in the case of a liquefying sand bed and non-liquefying sand bed. The void ratio e is obtained from the rate of settlement of the surface layer. As can be seen in the figure, the penetration depth is determined only by the void ratio e, and there is almost no difference in penetration depth of the liquefying and nonliquefying sand bed. In other words, it has been quantitatively shown that the penetration depth becomes smaller and the sand bed becomes harder with settlement of the sand bed.



Fig 9. The liquefaction region



Fig 10. The hardness of sand bed

5. Conclusions

The following is a summary of the results obtained in this study:

① The values of pore water pressure in the sand bed subjected to fluctuating water pressure under conditions in which liquefaction does not occur agreed well with the theoretical values of Zen et al.(1987).

 $^{(2)}$ Under conditions in which liquefaction occurs, in the phases in which the density of the sand bed is high (0° ~90°), the negative values of excess pore water pressure were similar to the

theoretical values of Zen et al. (1987), but in the phases in which liquefaction occurs (225° and 270°), the measured values of excess pore water pressure were smaller than the estimated values.

③ The rate of settlement in the liquefying region was about two-times greater than that in the non-liquefying region, indicating that settlement of a sand bed is accelerated by liquefaction.

1 In our experimental range of up to 1.8m in total thickness of the sand bed, the average rate of settlement was almost proportional to the total head of fluctuating water pressure in all thicknesses of the sand bed.

(5) Settlement had very little effect on the transmission properties of pore water pressure.

(6) It was quantitatively shown that the larger the thickness of sand bed and the value of α are, the larger is the liquefaction depth obtained by theoretical values of excess pore water pressure. (7) Liquefaction depths obtained from measured values of excess pore water pressure and from the amount of settlement were very similar.

(8) In the case where the liquefaction region is small, the measured values of excess pore water pressure and amount of settlement agreed well with the theoretical values. However, the measured values became smaller than the theoretical values as the liquefaction region became larger.

(1) The penetration depth measured by a cone penetrometer is determined only by the void ratio e regardless of whether the sand bed is liquefying or non-liquefying, and it was quantitaively clarified that the sand bed becomes harder with settlement of the sand bed.

6. References

Akutu T., K. Yano and S. Akeda, (1996): Ground Environment of Short-necked Clam Fishing Grounds in Cold Regions, Proceedings of Civil Engineering in the Ocean, Vol.12, pp.473-478 (in Japanese).

Derek A. Hodgin, Clifford Truitt and Jerris Foote,(1992): Beach compactness regulatory criteria for nesting sea turtles on the Southwest Florida Shoreline, Proc. of 5th Annual National Conference On Beach Preservation Association Technology, pp.325-339.

Kraus, N. C. and J. BM. Smith, (1994): SUPERTANK laboratory data collection project, Technical Report CERC-94-3, US Army Corps of Engineers.

Nishi.R, S.Ohmi, M.Sato, T.Uda, N.C.Kraus (1996): Hardness of seashores and sand dunes, Proceedings of Coastal Engineering, JSCE, Vol.43, pp.681-685 (in Japanese).

Yamashita. T, M.Minamimura, S.Ito, K.Tno, S.Akeda (1996): Mechanism by which bivalves come up to the surface under fluctuating water pressure, Proceedings of Coastal Engineering, JSCE, Vol.43, pp.1076-1080 (in Japanese).

Zen K., H. Yamazaki and A. Watanabe, (1987): Wave-induced Liquefaction and Densification in Seabeds, Report of P.H.R.I., Vol.26, pp.125-180 (in Japanese).