A MODEL EXPERIMENT ON THE WAVE-INDUCED LIQUEFACTION AND SETTLEMENT IN THE LOOSELY DEPOSITED SAND BED

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台風・高波時の海洋構造物の安定問題は、波浪、海底地盤および海洋構造物の力学的相互作用を含む複雑な問題であり、水理学、地盤工学ならびに海岸工学における重要な研究領域である。波浪により海底地盤内に生じる間隙水圧に関する既往の研究では、数値解析を利用するものもしくは室内実験によるものが多く、特に既存の造波水路を用いて模型実験を行う時、設置される地盤の深度は深くても水深とほとんど同程度であり、それほど地盤深度に重点を置いていないのが現状である。しかしながら、地盤工学的にみれば、作成する透水層の厚さが模型実験の結果に影響を及ぼすのは明らかであり、影響範囲を十分にとった実験装置の開発が必要である。そこで、本研究では、地盤深さの影響を考慮するため、地盤深さが水深の約3倍程度である新たな造波水路を開発し、防波堤周辺に生じる透水層の厚さによる間隙水圧と沈下量に着目して一連の模型実験を行った。その結果、透水層の厚さにより過剰間隙水圧及び沈下の発生に違いが見られた。このような実験を行う場合、透水層の深さを考慮して行うべきである。

Key Words: *Wave-induced liquefaction, Model experiment, Settlement*

1. INTRODUCTION

The interaction among wave, seabed and marine structure is an important issue in geotechnical engineering, as well as coastal engineering.

The wave-induced pore water pressure has been considered to cause the liquefaction in seabed. During a severe wave condition, wave pressures due to propagating wave generate a wave-induced pore water pressure and cyclic shear stress in the seabed. If cohesionless soils are saturated, excess pore water pressure may accumulate and lead to liquefaction. The wave-induced liquefaction may result in the serious problems such as the failure of seabed, floating of pipelines, and settlement of rubble mound, because once the liquefaction occurs, the liquefied seabed loses its shear strength.

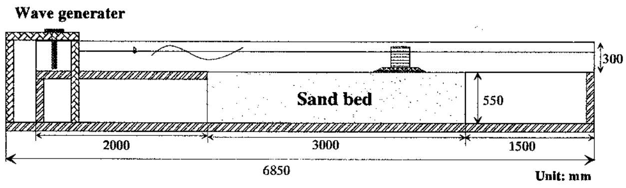
There have been some studies on the wave-induced liquefaction through model experiments using the existing wave flume. In the case to use the existing wave flume, however, the depth of sand bed is almost the same as that of water; therefore the depth of sand bed may have an effect on the results of model experiment.

In this study, a wave flume was newly developed, in which the depth of sand bed is about three times deeper than that of water. For the purpose of considering the effect of thickness of sand bed, a series of model experiment was conducted. The wave-induced pore pressure and the tendency of settlement of sand bed were investigated under various conditions.

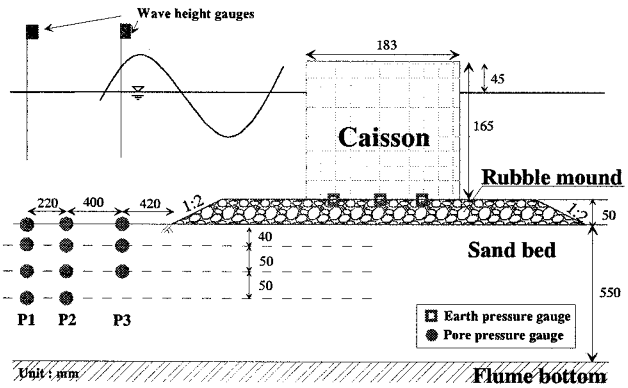
2. MODEL EXPERIMENT SET UP

The overall length of a wave flume is $685cm$, and sediments such as sand can be filled in the center part of the wave flume which is $300cm$ long, $40cm$ wide and $55cm$ deep. Model experiments on a reduced scale of 1:100 were conducted under various conditions; the depth of water, $17cm$, the wave period, $T(s)$, $0.6 \sim 1.2$, the incident wave height, $H_i(cm)$, $3.0 \sim 7.0$ and the thickness of permeable layer, $10 \sim 35cm$.

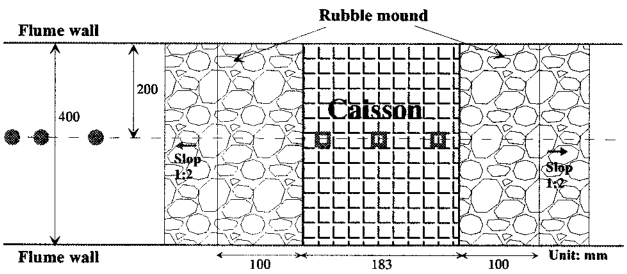
The wave flume, the cross section and the plan view of caisson type breakwater are respectively shown in **Fig. 1 (a), (b) and (c)**. In the sand bed, pore water pressure transducers ($\phi 10mm$, the length: $43mm$) and markers for measuring the displacement of sand bed were installed **(Fig.1 (b))**. Earth pressure gauges ($\phi 16mm$, the length: $6mm$) were set on the bottom of caisson as well. To measure the wave profile, wave recorders were installed on the offshore side of rubble mound.



(a) Wave flume



(b) Cross section around the caisson



(c) Plan view around the caisson

Fig. 1 Model setup with the location of the measuring devices in the wave flume.

A polymer solution instead of water was used in experiments to control the permeability of the pore water in sand bed in order to satisfy the law of similarity in terms of time dimension.

The sand used in this experiment is Toyoura sand ($D_{50} = 0.18mm$, $\rho_s = 2.644g/cm^3$, $e_{max} = 0.977$, $e_{min} = 0.606$). To reduce the air content in the pore spaces, the sand was flushed in a polymer solution. **Fig. 2** indicates the coefficients of permeability to the temperature $15^{\circ}C$ of Toyoura sand in water and in a polymer solution against the relative density, respectively. The coefficient of permeability k in water and in the polymer solution decreases linearly in accordance with the increase of the relative density D_r , respectively. The k in the polymer solution is $1/100$ times smaller than that in water due to viscosity. The sand bed was deposited using the water-pluviation method. Gravel $(D_{50} = 16mm)$ was used as the material for the rubble mound. The outer wall of caisson was made by an acrylic plastic plate, and the inside was filled with sand in order to satisfy the law of similarity on the contact pressure at the bottom of caisson. Then the weight of caisson was $26.2kg$.

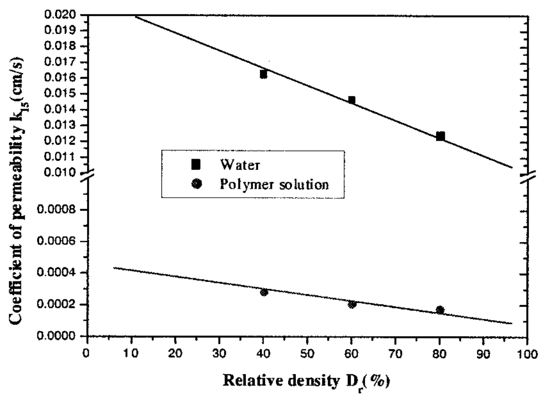


Fig. 2 Coefficient of permeability (k_{15}) of Toyoura sand in water and in a polymer solution.

3. LIQUEFACTION AND SETTLEMENT OF SAND BED

(1) Model experiment

The wave elevation and wave-induced excess pore water pressures observed at the points P1, P2 and P3 and the effective overburden pressures to the depth were shown in **Fig. 3** and **Fig. 4**. The effective overburden pressure was indirectly calculated through the relative density D_r , which was estimated from the amount of sand in the wave flume. The relative density of sand bed was about 25% from the surface of sand bed to the depth of $35cm$ and was about 80% from the depth of $35cm$ to the bottom of the wave flume. **Fig. 5** indicates the assessment of the liquefaction through the excess pore water pressure $u(= p - p_b)$

introduced by Zen (1993).

After the occurrence of standing wave, the residual excess pore water pressure began to increase rapidly, and the wave-induced liquefaction occurred from the surface of sand bed. Assuming that the liquefaction occurs when the excess pore water pressure is more than 80% of the effective overburden pressure, it can be found that the wave-induced liquefaction happen to the depth of $-14cm$ under the node of standing wave (P1) and happen to the depth of $-9cm$ under the anti-node of standing wave (P2) in **Fig. 5**. Simultaneously with the liquefaction of sand bed, behaviors of liquefied sand bed have moved following the fluctuation of water surface like a fluid. In addition, the wave height has become smaller than the original wave height by the fluctuation of the liquefied sand bed **(Fig. 3)**. **Fig. 6** indicates variation of the oscillatory pore water pressure excepting the residual excess pore water pressure component from the observed wave-induced excess pore water pressure during and after the liquefaction, respectively. During the liquefaction, the amplitude of the oscillatory pore water pressures observed from the sand bed surface to the depth of $-9cm$ is about the same. While the liquefaction was proceeding, the piping of sand was observed around the anti-node of standing wave. As the dissipation of the excess pore water pressure almost drew to an end, the oscillatory pore water pressure attenuated rapidly due to the densification of sand bed, the behaviors of the liquefied sand bed have moved inversely to the phase of the wave surface and decreased by degrees, and the wave height became gradually large and uniform after all.

Fig. 7 depicts the settlement of sand bed after the liquefaction. The detailed contents would be explained in the following subchapter.

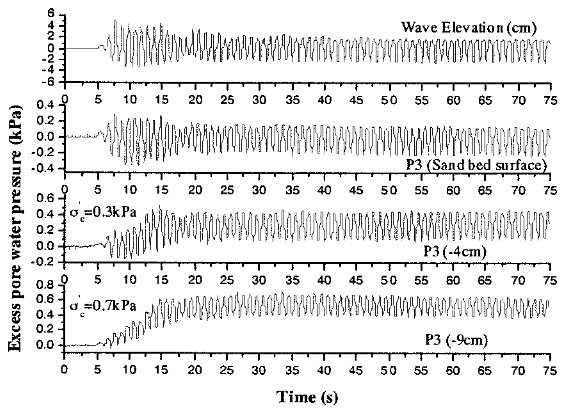
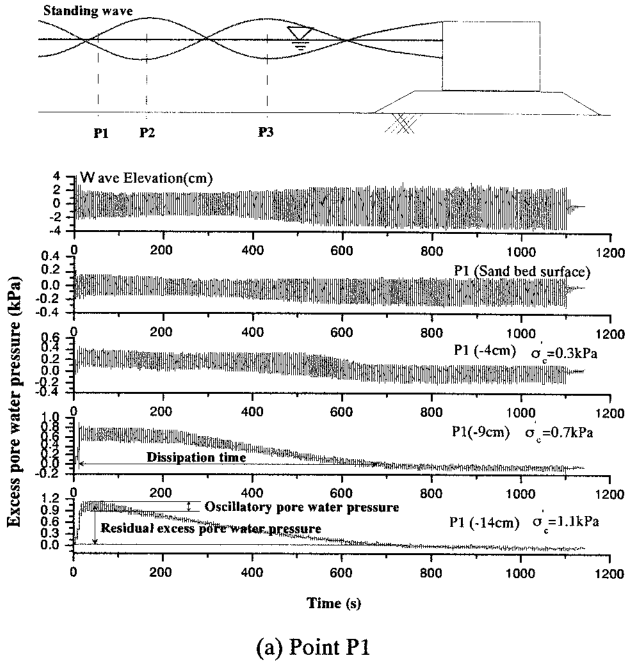
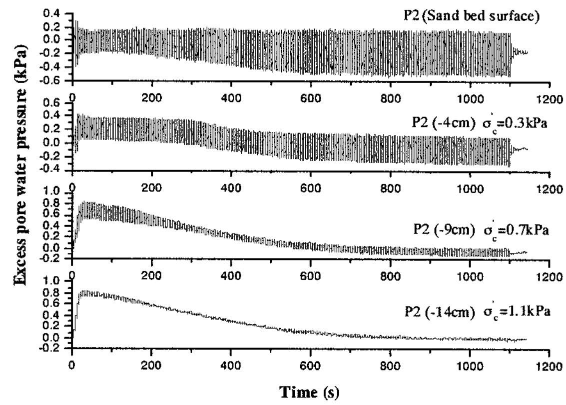


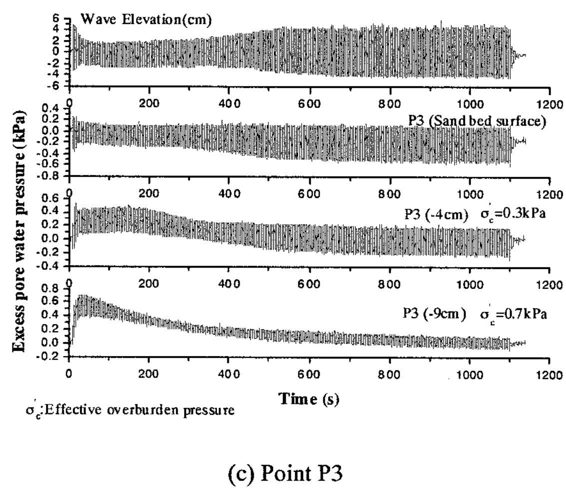
Fig. 3 Wave elevation and excess pore water pressures observed at the point P3 ($T=1.0s$, $H_i=5.5cm$).



(a) Point P1



(b) Point P2



(c) Point P3

Fig. 4 Wave elevation and excess pore water pressures observed at the points P1, P2 and P3 ($T=1.0s$, $H_i=5.5cm$).

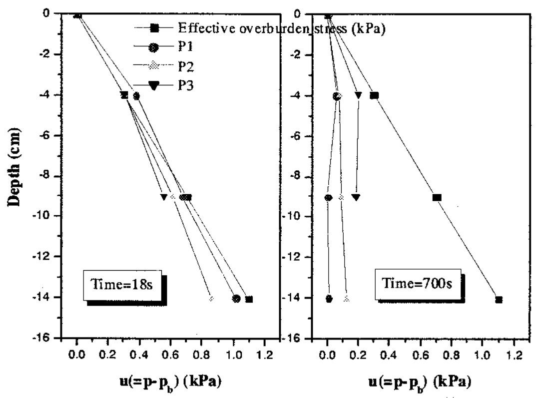


Fig. 5 Assessment of wave-induced liquefaction (p_b: Wave pressure on the sand bed surface).

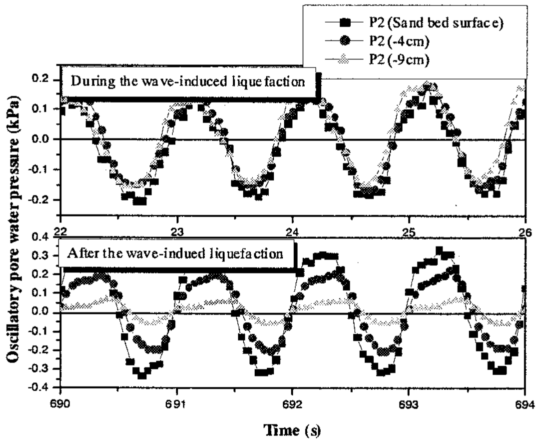


Fig. 6 Variation of the oscillatory pore water pressure at the point P2 ($T = 1.0s,\ H_i = 5.5cm$).

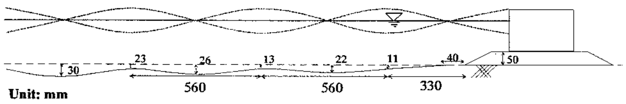


Fig. 7 Settlement of sand bed observed after the liquefaction ($T = 1.0s,\ H_i = 5.5cm$).

Fig. 8 indicates the time required for dissipation of the developed residual excess pore water pressure defined in **Fig. 4 (a)** against the wave period and the thickness of permeable layer. The longer wave period becomes, the higher the development of residual excess pore water pressure becomes. Therefore, the required dissipation time also is proportional to the wave period. In the case of wave period $T = 1.2s$, however, the dissipation time of the accumulated excess pore water pressure became small. The similar result is reported in the study of Suzuki et al. (2003), though the reason is not clearly mentioned.

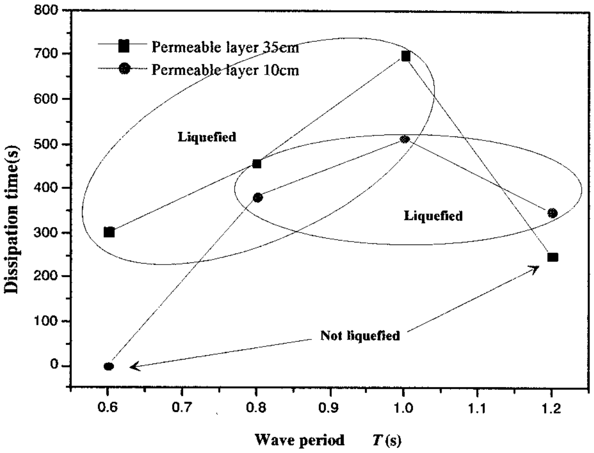


Fig. 8 Time required for dissipation of residual pore water pressure against the wave period $(H_i = 5.5cm)$.

As the thickness of permeable layer becomes shallower, the dissipation time becomes shorter. Zen (1993) mentioned the reason through the dimensionless coefficient of drainage, C .

$$C = c_v \frac{T}{l^2} \tag{1}$$

where, c_v is the coefficient of consolidation, T is the wave period and l is the thickness of permeable layer. Coef. (1) shows that the dissipation time of pore water pressure becomes faster as c_v becomes larger and T becomes longer. On the contrary, as the thickness of permeable layer l is thinner, the drainage coefficient C , that is, the capability of drainage becomes higher. The time required for the increase in pore water pressure becomes longer and the dissipation time becomes faster. Hence, it can be said that the liquefaction is considerably difficult to occur. To help understanding, the increase of the residual excess pore water pressure depending on the thickness of permeable layer was shown in **Fig. 9**. The residual excess pore water pressure was calculated from the mean value of the observed wave-induced excess pore water pressure. It can be confirmed that the differences of the increase in the residual excess pore water pressure can not be observed at the depth of $-4cm$, but in the cases of the depth of $-9cm$ and $-14cm$, the differences can be observed clearly.

As the thickness of permeable layer becomes thicker, the increase in the residual excess pore water pressure becomes more rapidly and larger. In addition, it can be thought from **Fig. 8** that the capability of drainage becomes higher and the dissipation time becomes faster for the wave with the incident wave height H_i of $5.5cm$ and the wave period T of more than $1.2s$ through Coef. (1). Hence, it is also difficult to find the liquefaction to occur.

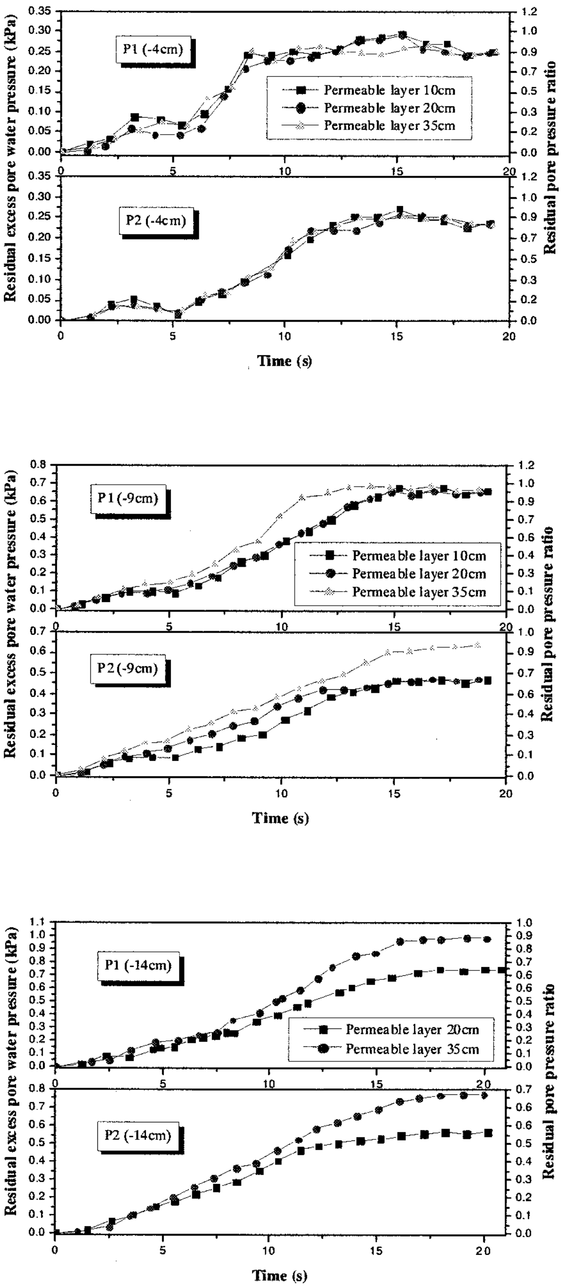


Fig. 9 Increase of the residual excess pore water pressure against the thickness of permeable layer at the points P1 and P2 ($T = 1.0s$, $H_i = 5.5cm$).

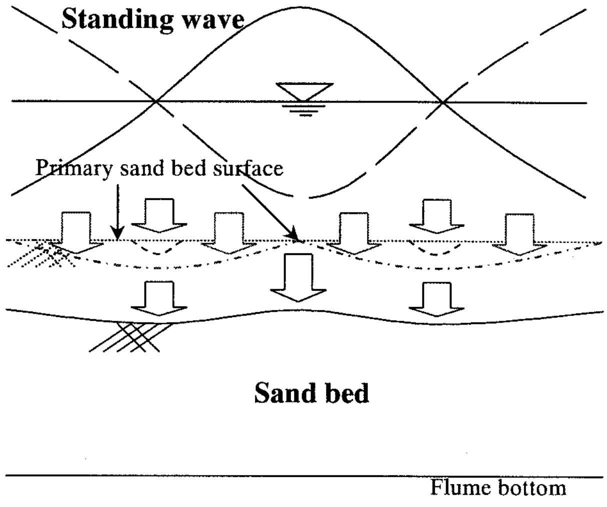


Fig. 10 The sequence of settlement.

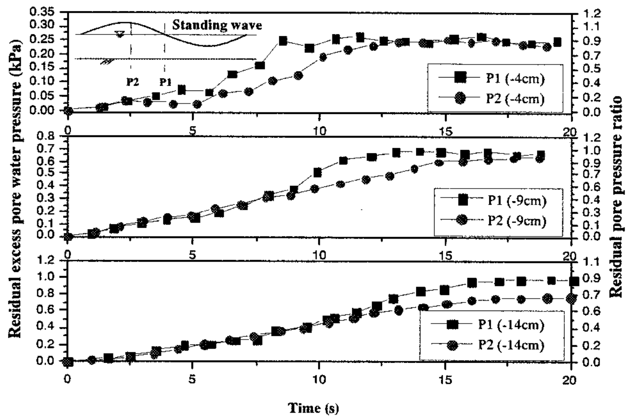


Fig. 11 Variation of the residual excess pore water pressure at the points P1 and P2 ($T = 1.0s$, $H_i = 5.5cm$).

(2) Settlement of sand bed

Fig. 10 depicts the sequence of settlement of sand bed. It is considered that, the settlement firstly begins to occur around the node of standing wave due to the liquefaction caused by the residual excess pore water pressure, then spread over the whole surface of sand bed. This can be confirmed from **Fig. 11. Fig. 11** indicates the residual excess pore water pressure, that is, the mean value of the observed wave-induced excess pore water pressure and the residual pore pressure ratio against the time. The residual excess pore pressure ratio around the node of standing wave reaches firstly to the peak value of 1.0, which means that effective stress is zero and therefore the soil has no strength and liquefies. At the sand bed under the node of standing wave, the residual excess pore pressure ratio reaches to the peak at the deeper sand bed than that at the anti-node of standing wave. Hence, it is easy to liquefy and to settle to the deeper sand bed around the node of standing wave than at the anti-node of standing wave. Hence, in the case of standing wave, as depicted in **Fig. 7,** the settlement occurs.

Vertical strain and settlement depending on the thickness of permeable layer are indicated in **Fig. 12**. It can be thought from **Fig. 12** that the larger settlement is caused, as the thickness of permeable layer becomes thicker. It can be found that there are differences of the range of liquefaction and the settlement due to the thickness of permeable layer. Hence, it is necessary to carry out an experiment considering the thickness of permeable layer.

Settlements depending on the wave period were indicated in **Fig. 13**. The longer the wave period grows, the larger the range of the wave-induced liquefaction becomes and the settlement becomes larger. As mentioned in the preceding subchapter, in the case of the wave with the wave period of more than$1.2s$, it is considered that the liquefaction is difficult to occur. Even if the liquefaction occurs, it does not propagate to the deep area of sand bed, therefore the settlement becomes smaller. In the case of the wave period, $T = 1.2s$ for the thickness of permeable layer of $35cm$, the wave-induced liquefaction did not occur, but the settlement can be caused by the dissipation of the accumulated residual excess pore water pressure. Even if liquefaction doesn't occur, there may be a possibility that the settlement occurs due to the dissipation of excess pore water pressure in the actual seabed. In the case of the wave period, $T = 0.6s$ for the thickness of permeable layer of$10cm$, the residual excess pore water pressure did not accumulated; so that it is considered that the settlement did not occur.

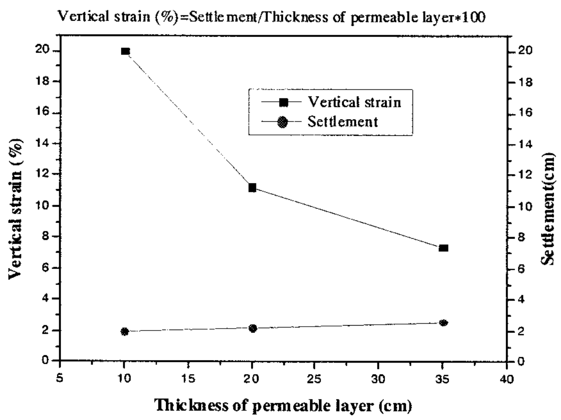


Fig. 12 Vertical strains and settlement depending on the thickness of permeable layer $(T = 1.0s, H_i = 5.5cm)$.

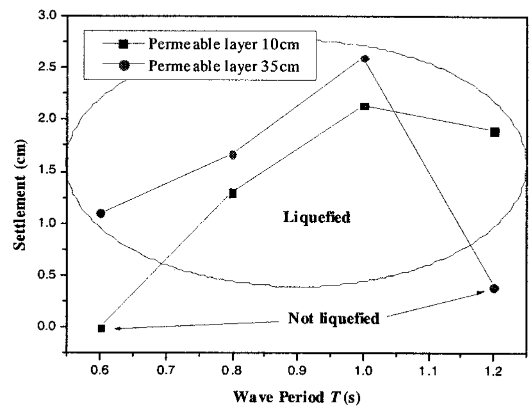


Fig. 13 Settlement depending on the wave period $(H_i = 5.5cm)$.

4. CONCLUSIONS

Based on the results presented in this study, the following conclusions can be drawn;

1) The validity of the dimensionless coefficient of drainage introduced by Zen (1993) was verified through a series of two dimensional model experiments.
2) As the thickness of permeable layer becomes thicker, the increase of the residual excess pore water pressure becomes faster and larger.
3) The settlement of sandy bed began to occur around the node of standing wave, and then spread over the whole surface of sand bed due to the liquefaction caused by the residual excess pore water pressure.
4) At the sand bed under the node of standing wave, the residual excess pore water pressure reaches to the peak value faster than that at the sand bed under the anti-node of standing wave.
5) There are the differences of the area of liquefaction and the settlement depending on the thickness of permeable layer. Hence, it is necessary to carry out experiments considering the thickness of permeable layer.
6) Even if liquefaction doesn't occur, there is a possibility that settlement occurs due to the dissipation of the accumulated excess pore water pressure in the actual seabed.

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