Field Observation of Wave Induced Pore Water Pressured Change in Seabed

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The response of seabed to sea wave loading was observed in New Ishikari Gulf Port, Hokkaido, Japan. We developed the observation rod, which is equipped with pore water pressure cells and earth pressure cells. Two observation rods were installed vertically near a sand groin located east side of the port; one of the two observation rods was surrounded by permeable columns installed vertically into the seabed. The fluctuating pore water pressure and horizontal total earth pressure in the seabed were thus monitored at different levels of depth. The purpose of the field observation is to evaluate the response properties of the seabed to response and determine the response parameters which control the response. The effect of permeable column method for stabilizing seabed was also discussed through the comparative examination of the observed responses.

Key Words : *seabed response, sea wave loading, field observation, response parameters, permeable column method*

1. INTRODUCTION

On and off shore structures and port and harbor facilities are occasionally damaged in stormy weather condition including attacks of typhoons. This type of damage is sometimes accelerated by the failure of seabed foundation induced by sea wave loading. For example Oka et al. (1995) investigated the severe damage to a breakwater built on a sandy seabed in Pomporoto Port, Hokkaido, Japan. The break water was settled down into the sand seabed by 1.4m, where the sand layer of about 4m in thickness was underlaid with thin continuous clay layer and hard rock. Through a field geotechnical exploration and analytical examination of the damaged breakwater, it was found that the seabed was instabilized by the sea wave loading, and the load bearing capacity reduced not enough for the weight of the breakwater. Fluctuating water pressure on the seafloor induces an uneven distribution of pore water pressure in the seabed, which generates hydraulic gradient and associated upward seepage force. The seepage force would cause periodical reduction of effective stress leading to the reduction of stiffness and strength.

The response of seabed to sea wave loading must be analyzed with appropriate constitutive model and formulation of geomaterial as a multi-phase material: solid phase for soil particle structure, liquid phase for pore water, and gas phase for pore air. The interaction of seabed with sea wave must be also taken into account appropriately with the appropriate modeling of the interaction between the phases of seabed material. Madsen (1978) and Yamamoto (1978) have developed an analytical method for the harmonic changes in pore water pressures and effective stresses in sand seabed induced by sea wave loading, using Biot's equations for the poro-elastic solid as a binary-phase material; see Biot (1941). Their method is classified as a coupled analysis. Zen and Yamazaki (1991) measured the fluctuation of excess pore water pressure and effective stress in the seabed at a breaker zone in a real ocean environment. Asahara et al. (2007) and Miura and Asahara (2007) investigated intensively the appropriate modeling and formulation for the coupled analysis of seabed-structure-sea wave system; exact solutions were derived under different dimensional conditions, and numerical analysis method with the modeling was developed.

Asahara et al. (2008) proposed a rational method for stabilizing seabed against sea wave loading, where permeable columns are installed into seabed. The stabilization method was named *permeable column method*. The permeable columns are expected to introduce water pressure from the seafloor into the seabed and lessen uneven pore water pressure distribution, associated hydraulic gradient and seepage force, which make the seabed instable.

We conducted a field observation of seabed response to sea wave loading in New Ishikari Gulf Port, Hokkaido, Japan. The two rods each equipped with pore water pressure cells and earth pressure cells were installed into the seabed, and the fluctuating pore water pressure and earth pressure in the seabed were monitored at several depth levels. The details of the field observation are described in this paper, and the observed response behavior is analyzed. The applicability of the method for determining response parameters, and the reliability of the permeable column method are examined with the response behavior of seabed obtained in the field observation.

2. ANALYTICAL SOLUTION

Asahara et al. (2007) and Miura and Asahara (2007) investigated appropriate modeling and formulation of seabed geomaterials for solving the response of seabed to sea wave loading. The geomaterials were modeled as a binary-phase linear elastic material: solid phase for soil particle structure, and fluid phase for the mixture of pore water and pore air. The several types of solutions derived with various formulations under the variety of dimensional and dynamic conditions. Through the comparative examinations of the solutions, it was found that the followings were acceptable for practical analysis methods with sufficient accuracy:

1) quasi-dynamic u-p formulation for wide variety of geomaterial forming seabed, including clay, silt, sand, gravel, and soft rock.
2) one-dimension analysis, as long as the part of seabed shallower than sixteenth of wave length is considered.

(1) Derivation of exact solution

The governing equations with quasi-dynamic u-p formulation under one-dimensional condition is expressed as follows:

$$\begin{aligned} &-(\lambda+2G)\frac{\partial^2 \Delta u_z}{\partial z^2}+\frac{\partial \Delta p}{\partial z}=0 \\ &-B_f\frac{\partial \Delta u_z}{\partial t \partial z}+B_f\frac{k}{\rho_w g}\frac{\partial^2 \Delta p}{\partial z^2}-\frac{\partial \Delta p}{\partial t}=0 \end{aligned} \qquad (1)$$

where z-axis is taken as positive in vertical downward direction; Δu_z is absolute displacement increment of solid phase, Δp is pore fluid pressure increment. Parameters λ and G are Lamé's elastic moduli, k is coefficient of permeability, ρ_w is bulk density of water.

$$B_f = \frac{K_f}{n}, \quad \frac{1}{K_f} = \frac{1}{K_l} S_r + \frac{1}{K_g}(1 - S_r) \tag{2}$$

where n is porosity, K_f, K_l and K_g are the bulk moduli of fluid phase, liquid phase and gas phase, respectively. The bulk modulus of fluid phase K_f is a function of degree of saturation S_r. The boundary value problem considered in this study is as follows; the flat seabed with uniform thickness of D is underlaid by hard impermeable base, and is subjected to traveling sinusoidal water pressure change on the surface, as shown in **Fig.1**.

at the surface (z = 0);

$$\Delta p = p_0 e^{i\omega t} e^{i\kappa x}, \quad \Delta\sigma_z = 0 \tag{3a}$$

at the bottom (z = D);

$$\Delta u_z = 0, \quad \partial \Delta p / \partial z = 0 \tag{3b}$$

The analytical solution is

$$\Delta p = p_0 \left(B' + (1 - B') \frac{e^{-\zeta z} + e^{-2\zeta D} e^{\zeta z}}{1 + e^{-2\zeta D}} \right) e^{i\theta} \tag{4}$$

where

$$\begin{aligned} & e^{i\theta} = e^{i\omega t} e^{i\kappa x}, \quad \theta = \omega t + \kappa x, \\ & \zeta = \sqrt{i\omega h_v} = \sqrt{\frac{\omega h_v}{2}} + i\sqrt{\frac{\omega h_v}{2}}, \\ & h_v = \frac{\rho_w g}{k B_f (\lambda + 2G)/(\lambda + 2G + B_f)} = \frac{1}{c_v B'}, \\ & B' = \frac{B_f}{\lambda + 2G + B_f} \end{aligned} \tag{5}$$

where B' is Skempton's B-value under one-dimensional condition, and h_v is a newly introduced parameter named hydraulic consolidation factor. This is the reciprocal of coefficient of consolidation with compressibility of pore fluid taken into account. Since $e^{-2\zeta D}$ is negligibly small and can be ignored in Eq.(4), the following formula is obtained:

$$\Delta p = p_0 (B' + (1 - B') e^{-\zeta z}) e^{i\theta} \tag{6}$$

The value of h_v ranges from 1(sec/m^2) to 5(sec/m^2) for typical sand material; see Asahara et al. (2007). So as long as the thickness of sand layer D is more than 2m, the calculation error would be several percent at most. Equation (6) tells that the response of seabed to sea wave loading is fundamentally controlled by the response parameters h_v and B'; and therefore the evaluation of the response parameters is indispensable for the analysis of the behavior of seabed-structure-sea wave system and the design of the structures.

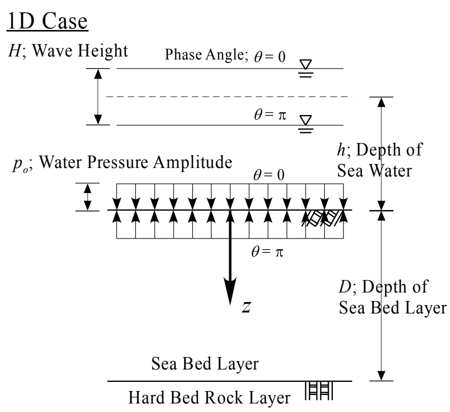

Fig.1 Boundary condition for the seabed of finite depth subjected to sea wave loading

(2) Liquefaction depth in the seabed subjected to sea wave loading

Although there are some kinds of criterions for the liquefaction of ground, the liquefaction condition of seabed subjected to sea wave loading can be defined as "vertical effective stress becomes negative periodically $(\sigma_z + \Delta\sigma_z)_{min} < 0$". The vertical effective stress change in seabed is calculated from the solution Eq.(6).

$$\Delta\sigma_z = p_0 - \Delta p = p_0 (1 - B')(1 - e^{-\zeta z}) e^{i\theta} \tag{7}$$

The amplitude of vertical effective stress change is

$$\begin{aligned} |\Delta\sigma_z| &= p_0 (1 - B') \left| (1 - e^{-\zeta z}) \right| \\ &= p_0 (1 - B') \sqrt{1 + e^{-2\sqrt{\frac{\omega h_v}{2}} z} - 2 e^{-\sqrt{\frac{\omega h_v}{2}} z} \cos\left(\sqrt{\frac{\omega h_v}{2}} z\right)} \end{aligned} \tag{8}$$

If this amplitude exceeds the vertical effective stress at hydrostatic condition $(\rho_t - \rho_f) g z$, the seabed liquefies periodically. We can calculate the maximum depth where the liquefaction condition is met;

$$|\Delta\sigma_z| = (\rho_t - \rho_f)gz \qquad (9)$$

Then liquefaction depth z_l is given by

$$z_l = H_p\sqrt{(1+e^{-2\sqrt{\frac{\omega h_v}{2}}z_l} - 2e^{-\sqrt{\frac{\omega h_v}{2}}z_l}\cos(\sqrt{\frac{\omega h_v}{2}}z_l))} \qquad (10)$$

where H_p is hydraulic potential head

$$H_p = \frac{p_0(1-B')}{(\rho_t - \rho_f)g} \qquad (11)$$

Figure 2 shows the relationship between the value of hydraulic consolidation h_v times angular frequency ω and the liquefaction depth z_l with H_p as a parameter. The stability of seabed subjected to sea wave loading can be estimated by using the figure.

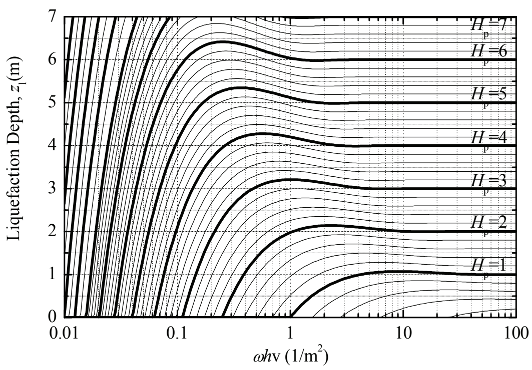

Fig.2 Chart for determining liquefaction depth with estimated response parameters.

3. FIELD OBSERVATION

(1) Observation site

The response of seabed to sea wave loading was observed in New Ishikari Gulf Port. Hokkaido, Japan, for about one and a half months in September and October, 2007. The land-side area of the east groin was selected for the measurement of pore water pressure and earth pressure in the seabed. The groin of about 500m in total length was constructed of caissons mounted on rubble mound and armored with breakwater blocks on the sea side; the head half is shown in **Fig.3**, and the typical vertical section along A-A line in **Fig.4**. According to the exploration logging which was obtained for the design of the groin, the seabed consisted of a uniform sand with

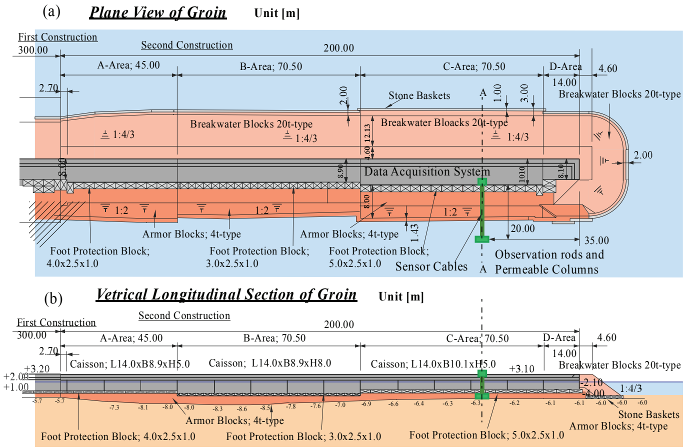

Fig.3 The east groin (New Ishikari Gulf Port): (a) plane view, (b) vertical longitudinal section view

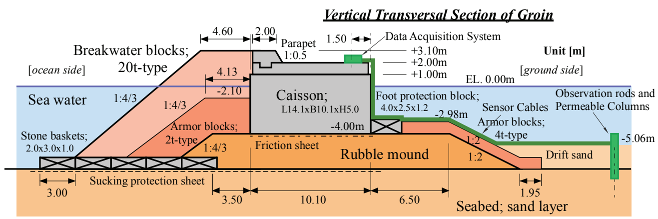

Fig.4 Typical section of the east groin (A-A section)

silt of 5% or less, and N-value measured in a series of standard penetration tests was less then 5 until the depth of 5m. The depth of seawater was about 5m, and the seabed was covered with drift sand of about 1m in thickness deposited after the construction of the groin.

(2) Instrumentation and Measurement

Two rods were developed for monitoring the response behavior of the seabed. The rod, named *observation rod*, was made of stainless steal tube as shown in **Fig.5**, so that water jet was used at the tip for smooth penetration. Each of the observation rods was equipped with five pore water pressure cells and four earth pressure cells.

The pore water pressure cells were fixed on the observation rod; the top one was for monitoring water press in seawater near the seafloor, and the others were four pore water pressure inside the seabed with an interval of 50cm. The pore water

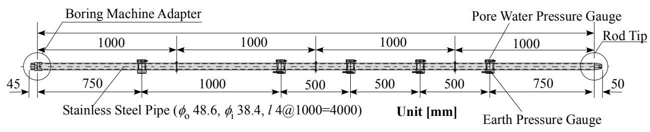

Fig.5 Observation rod equipped with pore water pressure cells and earth pressure cells.

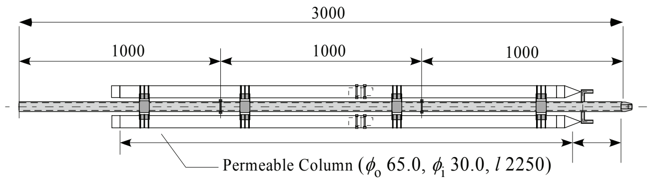

Fig.6 Permeable column rod.

pressure cell which is cylindrical in shape has a strain gauge type sensor inside, and metal filter with 10μm on the top (Capacity: 200 (kPa), Accuracy: 1% of full scale). The earth pressure cell was also fixed on the observation rod for monitoring horizontal component of total earth pressure. The earth pressure cell has a strain gauge type sensor inside, and sensitive face was 23mm in diameter (Capacity: 200 (kPa), Accuracy: 2% of full scale). The pore water pressure cell and the earth pressure cell both were contained in sensor holder and the sensor holders were fixed on the observation rod.

Two permeable columns of 2.25m in length, and 65mm and 30mm in outer and inner diameters, respectively, were fixed to a rod. The rod, named *permeable column rod*, was made of steel pipe to penetrate into the seabed by using water jet through the tip and side nozzles as shown in **Fig.6**. The permeable column was a porous filter made of polypropylene threads with a nominal opening of 150μm.

The two observation rods were installed into the seabed as shown in **Fig.4** and **7**; one of the two observation rods were surrounded with four permeable column rods. The distance between the observation rods was 5m and size of the square formed with the permeable rods was 1.5m. Settlement of the rods is shown in **Fig.8**. The

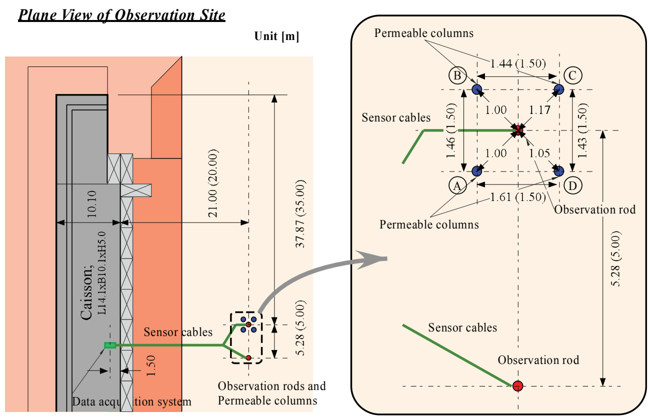

Fig. 7 Arrangement of observation rods and permeable columns

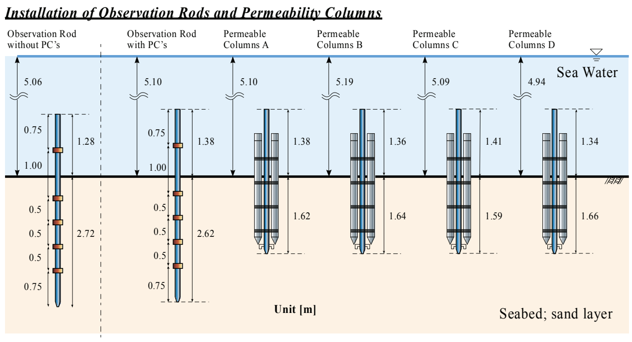

Fig. 8 Installed observation rods and permeable column rods

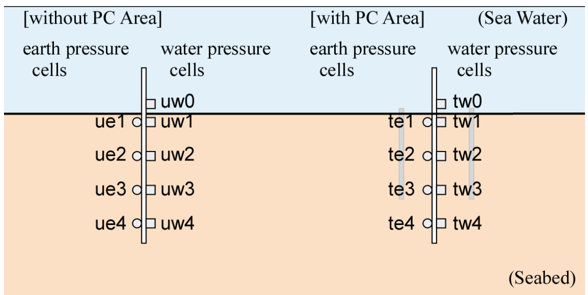

Fig. 9 Symbols allocated to the sensors

Table 1. The elevation of observation rods and sensors

Untreated Area (without PC Area)		Treated Area (with PC Area)	
Sensors	E.L (m)	Sensors	E.L (m)
Seabed	-5.06	Seabed	-5.10
uw0	-4.53	tw0	-4.47
uw1,ue1	-5.53	tw1,te1	-5.47
uw2,.ue2	-6.03	tw2,te2	-5.97
uw3,.ue3	-6.53	tw3,te3	-6.47
uw4,uw4	-7.03	tw4,te4	-6.97

comparison of the behaviors observed with the two observation rods would tell the effect of the permeable columns. **Figure 9** shows the symbols allocated to the sensors, and **table 1** lists the elevations of the observation rods and the sensors.

The data recorder was set up on the caisson, and the cables from the sensors were introduced to the data recorder as shown in **Fig.4**. The data recorder was able to collect and store data from all the 18 sensors with a sampling frequency of 100Hz for 30 hours by using four voltaic batteries. Measured data obtained with the sensors were first calibrated for the dynamic components of the measured values, and the absolute values for the pore water pressure and earth pressure was calculated from the calibrated values with the formation of the seabed, elevation of the sensors and tidal seawater level during measurement. The information of the tidal wave was officially provided by the Marine Meteorological Observatory at Otaru Port, the nearest to the observation site.

4. OBSERVED DATA AND DISCUSSION

Shown in **Fig.10** are typical time histories of the response of seabed to sea wave loading recorded at 19:00 on September 25, 2007. The top figure is for the sea wave level calculated from the pore water pressure measured at uw0 or tw0 with linear wave theory. The middle figure is for water pressure on the seafloor and pore water pressures, and the bottom figure is for earth pressure. It is clear that the amplitude of pore water pressure becomes smaller with depth due to the attenuation during propagation downward from the seafloor in the middle figure. The similar tendency can be seen also in earth pressure in the bottom pressure. As explained by the simplified solution in Eq. (6), the intensity of attenuation is dependent clearly on the response parameters such as B' and h_v.

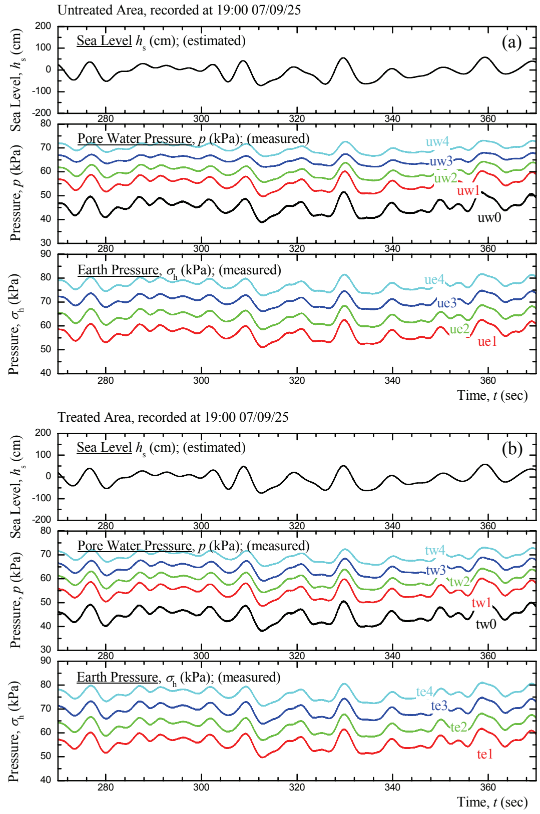

Fig. 10 Time history of seabed response to sea wave loading; (a) without permeable columns, (b) with permeable columns.

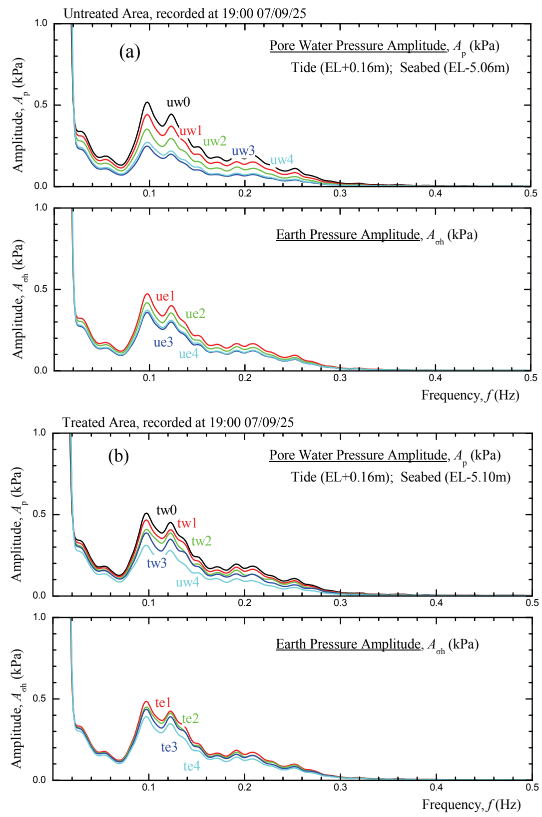

Fig. 11 Fourier spectra of pore water pressure and earth pressure; (a) area without permeable columns, (b) area with permeable columns.

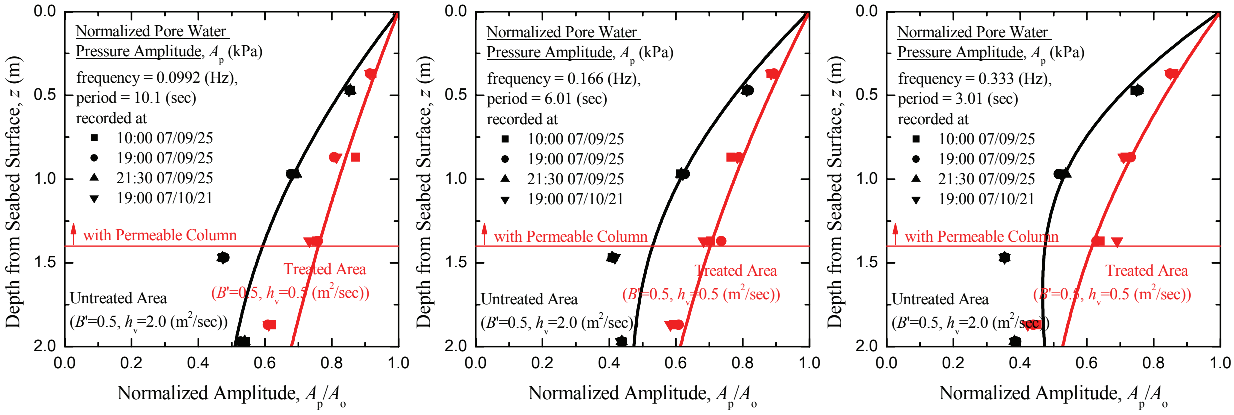

Fig. 12 Distribution of normalized pore water pressure amplitude for period of; (a) 10.1 sec, (b) 6.01 sec, (c) 3.01 sec.

Shown in **Fig.11** is Fourier spectra of the measured fluctuating pore water pressure and earth pressure for the response presented in **Fig.10**. Wave amplitude was dominant from frequency of 0.9Hz to 1.4Hz under the wave condition. The amplitude of pore water pressure is maximal at the seafloor (uw0 or tw0) and becomes smaller with an increase of depth due to the attenuation properties of pore water pressure induced by sea wave loading. This tendency can be seen over all the dominating frequencies.

Figure 12 shows the vertical distribution of the amplitudes of pore water pressure at three dominating frequencies. The amplitudes were normalized with that at seafloor evaluated from uw0 or tw0 with the linear wave theory. The curves; the observed data was fitted with the curves calculated with the simplified solution in Eq. (6) through the following steps:

-- [the area without permeable columns] the values of response parameters h_v and B' were selected so that the curve fit the data.

-- [the area with permeable columns] with the common value of B', the value of h_v only was selected to fit the data, because the permeable columns are considered to change only the permeability of the seabed.

In the abovementioned process the data uw3 were neglected as a dubious value; it was inferred that the filter in the pore water cell was not in good condition.

Table 2. Response parameters estimated by using fitting

	Untreated Area (Without PC)	Treated Area (With PC)
B'	0.50	
h_v (sec/m)	2.0	0.50

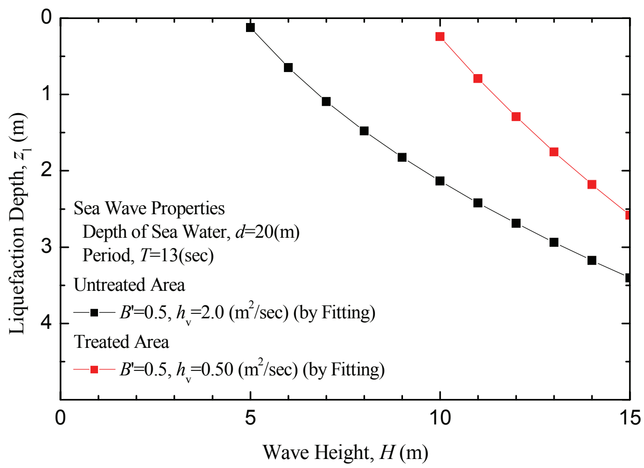

Fig. 13 Liquefaction depth as a function of wave height

And the data tw4 was disregarded, because the penetration depth of the permeability columns was about 1.4m and not enough for influencing the sensor tw4. The values determined are listed in **Table 2**. The effect of the permeability columns on the improvement of the over all permeability of the seabed can be seen clearly in **Table 2**. A decrease of h_v is related to an increase of permeability coefficient k. Shown in **Fig.13** is the liquefaction depth of the seabed as a function of sea wave height for both the areas with and without permeable columns. The response parameter values determined by the fitting (**Table 2**) were used. Although the seabed is expected to liquefy by the depth of around 2.5m without permeable columns, the liquefaction depth becomes zero with the permeable columns under the condition employed in this study. It can be said that the permeable column method will be effective on the stabilization of seabed.

5. CONCLUDING REMARKS

The response of seabed to wave loading was observed by means of the observation rods developed for this study. The behavior of pore water pressure and earth pressure was measured and analyzed, and the method for evaluating the response parameters which determining the response behavior was discussed. And the reliability of the permeable column method was investigated. The conclusions can be summarized as follows:

- The response parameters of the seabed were evaluated by fitting the observed data with the simplified analytical solution.
- In the comparison between the observed behaviors in both the areas with and without permeable columns, the effect of the permeable column method was clearly seen. The overall permeability of seabed was raised and the value of h_v decreased to one fourth.
- The liquefaction depth was predicted for both the areas with and without permeable columns, and it was found that .the permeable column method will be effective on the reduction in liquefaction depth. Under the condition of seabed and permeable columns arrangement in this study, notable reduction of the instable depth was expected.

REFERENCES

Asahara, S., Miura, K., Otsuka, N., Ueno, K., and Takahara, T. (2007): Coupled Analysis of the Behavior of Seabed Subjected to Sea Wave with Different Formulation of Geomaterials, ISOPE-2007.

Asahara, S., Miura, K., Otsuka, N., and Tanaka, J. (2008): FEM Analysis of Seabed Stabilization Method against Sea Wave Loading with Permeable Columns, ISOPE-2008.

Biot, M. A. (1941): General Theory of Three-Dimentional Consolidation, Journal of Applied Physics, Vol.12, pp.155-164.

Kokusho, T. (2000): Correlation of pore-pressure B-value with P-wave velocity and Poisson's ratio for imperfectly saturated sand or gravel, Soils and Foundations, Vol.40, No.4, pp.93-100.

Madsen, O. S. (1978): Wave Induced Pore pressures and Effective Stresses in a Porous Bed, Geotechnique, Vol.28, No.4, pp.377-393.

Miura, K. and Asahara S. (2006): Analytical Method for the Response of Seabed to Wave Loading regarding the liquefaction or instabilization of the seabed, GeoMechanics Group, Toyohashi University of Technology.

Miura, K., Asahara, S., Otsuka, N., and Tanaka, J. (2008): Field Observation of Wave induced Seabed Behavior for the estimation of geomaterial properties and the effect of permeable column method, ISOPE-2008.

Miura, K., Yoshida, N., and Kim, Y. S. (2001): Frequency Dependent Property of Waves in Saturated Soil, Soils and Foundations, Vol.41, No.2, pp.1-19.

Oka, F., Yashima, A., Miura, K., Ohmaki, S., and Kamata, A. (1995): Settlement of Breakwater on Submarine Soil due to Wave-Induced Liquefaction, 5th International Symposium on Offshore and Polar Engineering Conference, Vol.2, pp.237-242.

Yamamoto, T. (1978): Sea Bed Instability from Waves, Proceedings, 10th Annual Offshore Technology Conference, Paper No. 3262, Vol.I, pp.1819-1824.

Zen, K., and Yamazaki, H. (1991): Field Observation and Analysis of Wave-induced Liquefaction in Seabed, Soils and Foundations, Vol.31, No.4, pp.161-179.