CHAPTER 101

Prediction of Properties of Marine Sand by In-Situ Measurement of Wave Induced Pore Pressure

Yoshihiko MAENO* and **Takashi HASEGAWA****

ABSTRACT

The purpose of this paper is to predict the physical and mechanical properties of deposits near the surface of the seabed by in-situ measurements of the wave-induced pore pressure.

First, the wave-induced pressure both at the surface of the seabed and inside the seabed are examined by frequency analysis, to clarify the propagation characteristics of pressure in the seabed.

Secondly, a theoretical equation which gives the relationship between pore pressure fluctuation and wave pressure fluctuation is proposed.

Thirdly, the porosity of the seabed is predicted by the propagating characteristics of the pore pressure within the seabed based on the results of both the model tests by wave tank and the field measurements of the wave-induced pore pressure.

Finally, by fitting the theoretical equation to the spectral ratio of the in-situ measured pore pressure fluctuation to wave pressure fluctuation, the bulk modulus of the seabed and the degree of saturation are predicted.

INTRODUCTION

Wave-induced instabilities near the surface of the seabed, in which the deposit is confined at low pressure, is an interesting theme in coastal engineering. These instabilities are observed in many configurations, e.g., seabed slide, liquefaction of the seabed, moving of soil mass, shore process and so on. To analyze the stability of the seabed based on the theory of effective stress, knowledge of both the properties of the deposit and the wave-induced pore pressure developed in the seabed are needed. Many authors (e.g. Madsen, 1978; Yamamoto, 1977) have investigated the theory of predicting wave-induced pore pressure in a seabed by both theoretical considerations and in-situ measurements. The authors (1985a,1985b) also proposed an empirical equation evaluated by wave steepness to predict the wave induced pore pressure in the seabed. However, it is difficult to clarify the properties of the deposit near the surface of the seabed by element tests because of its low confined condition. Investigation through the in-situ measurement, therefore, is more desirable.

In this study, the physical and mechanical properties of the deposit are investigated by in-situ measurements of the wave-induced

---

* Assistant Professor, Dept. of Civil Eng., Maizuru College of Technology, 234 Shiraya Maizuru, Kyoto, 625.

** Professor, Dept. of Agricultural Eng., Kyoto University, Oiwake-cho Sakyo-ku, Kyoto, 606.

pore pressure. The wave pressure at the seabed surface and the wave-induced pore pressure in the sand layer were measured at Nabae Beach in Wakasa Bay which is in the Sea of Japan off of Fukui Prefecture, Japan. The propagation characteristics of the wave-induced pore pressure were examined by the frequency analysis (Maeno and Hasegawa, 1985c). In particular, the spectral ratio of the measured wave-induced pore pressure fluctuation to the measured wave-induced pressure fluctuation at the seabed surface is noted as a powerful tool in examining the properties of the seabed deposit. Furthermore, the authors propose a theoretical equation which gives the relationship between the wave-induced pore pressure and the wave-induced pressure. The equation, which is a function of frequency, is compared with the spectral ratio. This equation is based on the assumptions that the seabed consists of fully saturated porous media and that the wave-induced pressure fluctuates at a frequency low enough to disregard the effects of viscous fluid.

THEORETICAL CORRELATION BETWEEN WAVE PRESSURE AND PORE PRESSURE

Correlation between Pore Pressure and Volumetric Strain

Many of the first order features in the relation between pore pressure and ground motion can be explained by the theory of elastic wave propagation (Mavko and Harp, 1984). As the saturated porous media consists of both solids and liquids, if it is assumed that the saturated sediments behave as a linear elastic solid and that the frequency of wave excitation is low enough that viscous fluid effects are negligible, the elastic wave-induced pore pressure is predicted to be proportional to the solid volumetric strain by the reciprocity theorem (Jaeger and Cook, 1969) of saturated porous media.

Therefore, the wave-induced pore pressure is related to the volumetric strain of the solid skeleton as given in Equation (1) (Jaeger and Cook, 1969).

$$P = \{ Kf(Ks-Kc)/[n(Ks-Kf)]\} \varepsilon \qquad (1)$$

where P is the pore pressure, is the volumetric strain of the solid skeleton, Ks is the bulk modulus of mineral grains costituting the solid skeleton, Kf is the bulk modulus of fluids, Kc is the bulk modulus of composites and n is the porosity.

Motion of Fluids in Porous Media

Biot(1956a,b) considered the motion of fluids in porous media and classified fluid motion into two mechanisms as follows. One is the motion induced by the relative acceleration between the solid phase and liquid phase; the other is induced by the pressure gradient caused by uneven compaction, and dissipated through the porous media according to Darcy's law. Both of them possess special individual features.

For example, the former is induced by both the compressional wave of the first kind and the shear wave and accelerates the solid skeleton. The force of inertia influences the phase lag between the fluid motion and the solid motion. The latter, called the local squirt flow, is induced by the greater pressure gradient caused by the friction force between the liquid and the pore face when elastic waves are transmitted through the porous media. This pressure gradient depends on both the shape and the sinuosity of the pores.

Effects of Pore Shape on Fluid Motion

Biot(1956a,b) also considered the effects of the pore shape on frequency, depending on the force of friction. He examined pore shapes for the slit model and the round model. These models are understood by the aspect ratio of the section of pores. This ratio is assumed to be less than unity for the slit model and unity for the round model. These two pore shapes are extreme cases in the two poles. Although the pore shape in sediments is usually in the region between round and slit, it is reasonable to assume that round and slit models can be used to characterize the fluid motion.

Therefore, his elastic wave propagation theory is taken into account as the structure factor consists of both the shape and sinuosity of pores. However, this treatment of pore shape for wave propagation theory does not take into account the local fluid motion but, rather, takes into account the effects of pore shape on the local fluid motion by varying the value of the structure factor.

Biot(1962) also considered the squirt flow in porous media and investigated the effects of the shape and sinuosity of pores on the spectral ratio of the pore pressure to the volumetric strain. For the compressional wave of the first kind, the slit pore shape induces higher pore pressure than the round pore shape. For the first fluid motion, the spectral ratio of pore pressure to the volumetric strain increases with frequency. For the second fluid motion, that is a local squirt flow, the spectral ratio of pore pressure to the volumetric strain decreases for the round shape and increases for the slit shape as the frequency increases.

Correlation between Pore Pressure and Acceleration for Earthquakes

Mavko and Harp(1984) investigated theoretically the correlation between the pore pressure and the acceleration at the surface of the ground by relating both the horizontal and vertical acceleration to the volumetric strain during an S-wave train and a P-wave train respectively. For example, the spectral ratio of the pore pressure to the vertical acceleration at the surface of the ground during a P-wave train is defined in Equation (2).

$$P = \{zKf(Ks-Kc)/[nVp^2(Ks-Kf)]\}\, Ap \qquad (2)$$

where Vp is the velocity of the compressional wave of the first kind, Ap is the vertical component of the acceleration at the surface of the ground and z is the depth under the ground surface.

They analyzed both wave-induced pore pressure and the acceleration recorded during the 1980 Mammoth Lakes, California, earthquake sequence. Also they showed the spectral ratios of the pore pressure to the vertical acceleration and the horizontal acceleration during a P-wave train and an S-wave train, respectively.
During P-wave arrivals, there is a negative linear correlation between

the spectral ratio and the frequency. During S-wave arrivals, there is no linear correlation between the spectral ratio and the frequency. The spectral ratio decreases exponentially with the frequency. Assuming that P-waves consist mainly of the compressional wave of the first kind, since the spectral ratio of pore pressure induced by the compressional wave of the first kind to the vertical acceleration is shown to decrease linearly with the frequency, the pore shape is round and the fluid motion in the pores dominates the second model of fluid motion, that is the local squirt flow.

Theoretical Equation between Pore Pressure and Wave Pressure

The authors considered the spectral ratio which is defined as the ratio of the power spectrum of the wave-induced pore pressure fluctuation within the seabed to the spectrum of the wave-induced pressure fluctuation at the surface of the seabed. The correlation between the wave-induced pore pressure fluctuation within the seabed and the wave pressure fluctuation at the surface of the seabed under the plane strain condition is derived as follows.

The displacements of the seabed under the wave action are evaluated by Biot's elastic wave propagation theory (Yamamoto, 1981). However, the wave-induced motion of the seabed is a slow phenomenon according to Zienkiewicz's(1980) classification of Biot's dynamic and quasi-static formulation, because the seabed is composed of a sand layer and the period of the gravity wave is less than 1.0 Hz. The accelerations of both the solid and liquid phases are negligible for the formulation of this phenomenon. Then this formulation corresponds to formulations by the quasi-static consolidation theory. Therefore, the displacements are derived according to Biot's(1941) consolidation theory (Yamamoto, 1977).

Equations (4) and (5) give the displacements of the seabed (Yamamoto, 1977). The harmonic load is given in Equation (3).

$$T = P_0 \exp[i(Nx+\omega t)] \tag{3}$$

$$\begin{aligned} U = {} & i\{m[i(1-2\nu)\omega''-1-2(1-\nu)N'']\exp(-Nz)/[-N''+i(1+m)\omega''] \\ & -[1-mN''/[-N''+i(1+m)\omega'']]Nz\exp(-Nz)+m\exp(-N'z)/ \\ & [-N''+i(1+m)\omega'']\}(P_0/2NG)\exp[i(Nx+\omega t)] \end{aligned} \tag{4}$$

$$\begin{aligned} W = {} & \{[1+m[1+(1-2\nu)(i\omega''-N'')]/[-N''+i(1+m)\omega'']\exp(-Nz) \\ & -[1-mN''/[-N''+i(1+m)\omega'']]Nz\exp(-Nz)-m(1+N'')\exp(-N'z)/ \\ & [-N''+i(1+m)\omega'']\}(P_0/2NG)\exp[i(Nx+\omega t)] \end{aligned} \tag{5}$$

where

$$N'^2 = N^2+i\omega' \tag{6}$$

$$\beta = (1-\nu)/(1-2\nu) \tag{7}$$

$$\omega' = \omega/c \tag{8}$$

$$\omega'' = (\omega'/N^2) \tag{9}$$

$$c = (k/\gamma)/\{n/Kf'+(1-2\nu)/[2G(1-\nu)]\} \tag{10}$$

$$m = nG/[Kf'(1-2\nu)] \tag{11}$$

$$N'' = (N'-N)/N \tag{12}$$

$$1/Kf' = 1/Kf+(1-Sr)/Pa \tag{13}$$

and Kf' is the apparatus bulk modulus of the pore fluid, G is the shear modulus, ν is Poisson's ratio, ω is the angular frequency, k is the permeability, Sr is the degree of saturation, Pa is the absolute pore pressure, and U and W are the displacements in the x- and z-directions respectively.

The dilatational strain is given in Equation (14).

$$\begin{aligned}\varepsilon &= \partial U/\partial x + \partial W/\partial z \\ &= \{-[(1-Nz)(1+m)+m(1-2\nu)](-N''+i\omega'')\exp(-Nz) \\ &\quad +mN''\exp(-N'z)\}P_0\exp[i(Nx+\omega t)]/G[-N''+i(1+m)\omega'']\end{aligned} \tag{14}$$

The term of $P_0\exp[i(Nx+\omega t)]$ in Equation (14) is the harmonic fluctuation of the wave pressure at the surface of the seabed. Thus, Equation (14) shows the relationship between the volumetric strain and the harmonic fluctuation of the wave pressure at the seabed surface. Therefore, the relationship between pore pressure and harmonic fluctuation of the wave pressure at the seabed surface is obtained from Equations (1) and (14).

$$\begin{aligned}P = {} & Kf(Ks-Kc)\{-[(1-Nz)(1+m)+m(1-2\nu)](-N''+i\omega')\exp(-Nz) \\ & +mN''\exp(-Nz)\}T/\{nG(Ks-Kf)[-N''+i(1+m)\omega'']\}\end{aligned} \tag{15}$$

METHOD OF FIELD EXPERIMENTS

In-situ measurements of wave-induced pore pressure were conducted at Nabae beach in Wakasa Bay, Fukui Prefecture, Japan, because the physical properties of the deposit and the seasonal change of the shore profile have been already measured at this site. Table 1 shows the properties of Nabae sand. Since the uniformity coefficient is 1.53, Nabae sand is fairly uniform. The grain size distribution of Nabae sand is uniform wherever samples are extracted.

Table 1. - Properties of Nabae Sand.

Specific gravity	2.70
Uniformity coefficient	1.53
Effective grain size	0.114 mm
Average grain size	0.160 mm
Permeability	0.023 cm/s

Figure 1 shows the system for measurements. In our preliminary experiments, pressure transducers were placed on the surface of the seabed and buried in the seabed on one straight line. The wave-induced pressure was measured simultaneously at both the surface of the seabed and at two different depths within the seabed. The wave pressure fluctuation was measured at the surface of the seabed, and the pore pressure fluctuation was measured in the seabed. In this study, the wave-induced pore pressure was measured with a probe as follows. A pressure transducer with porous cap is fixed inside the probe at a point 15 cm from its tip. The probe has a length and diameter of 250.0 cm and 26.0 mm, respectively, and is tipped with a cone with a 30 degree angle. To clarify the properties of the deposit near the surface of the seabed where the confining pressure is fairly low, the wave-induced pore pressure was measured at a depth of 33 cm on August 9, 1985 and at a depth of 37 cm on August 10, 1985, below the mudline.

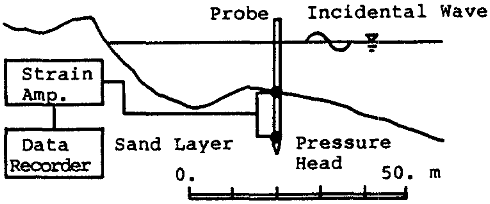


Figure 1. Experimental Set-Up of Field Measurements.

EXPERIMENTAL RESULTS AND DISCUSSIONS

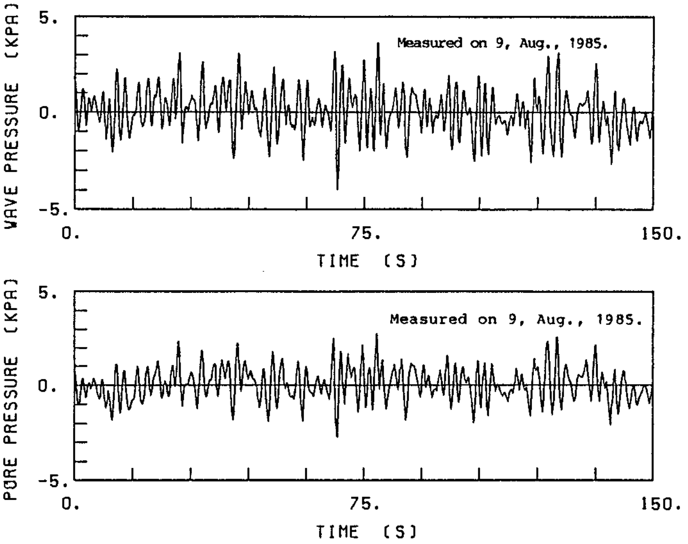
Frequency Analysis of In-Situ Measurement

Figures 2(a) and 2(b) show the fluctuations of the wave-induced pressure at the surface of the seabed and the wave-induced pore pressure within the seabed. It can be seen from these figures that both the wave pressure and the pore pressure fluctuate similarly without any great difference, and that the high frequency component is significantly damped. This fact is made clearer when compared with the power spectrum in Figures 3(a) and 3(b).

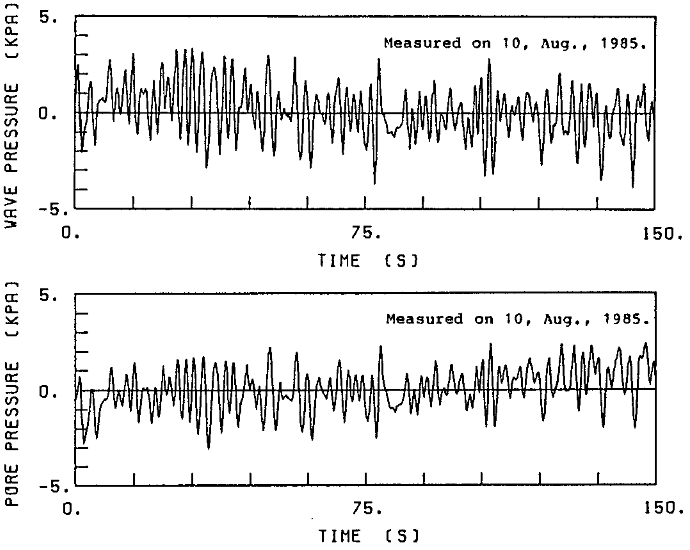
The power spectrum decreases as the frequency increases. The conditions for Fourier fast transform(FFT) analysis are as follows: the sampling interval is 0.15 s; the number of sampling points is 1024; the Nyquist number is 3.33 Hz. There are no problems in examining a frequency component below 1.0 Hz.

Figures 4 and 5 show the coherence and the phase between the wave-induced pore pressure fluctuation within the seabed and the wave pressure fluctuation at the surface of the seabed, respectively. Figures 4(a) and 4(b) show that the coherence is unity in the frequency range less than 0.6 Hz and as the frequency increases to over 0.6 Hz the fluctuation increases. This fact suggests that the propagation characteristics of wave-induced pressure vary at a frequency of 0.6 Hz.

Figure 5(a) and 5(b) show that the phase is nearly constant, that is 0.5π in the frequency range less than 0.6 Hz, and as the frequency increases to over 0.6 Hz the fluctuation also increases. Since the phase represents the lag time multiplied by the angular frequency, the lag time between the two fluctuations increases as the frequency decreases. This fact indicates that longer periodic waves propagate easily into the seabed and affect the wave-induced instabilities of the seabed as previously mentioned.

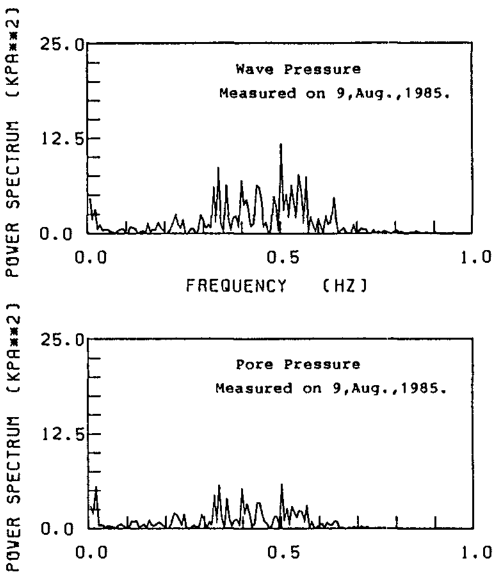


(a) Measured on August 9, 1985.

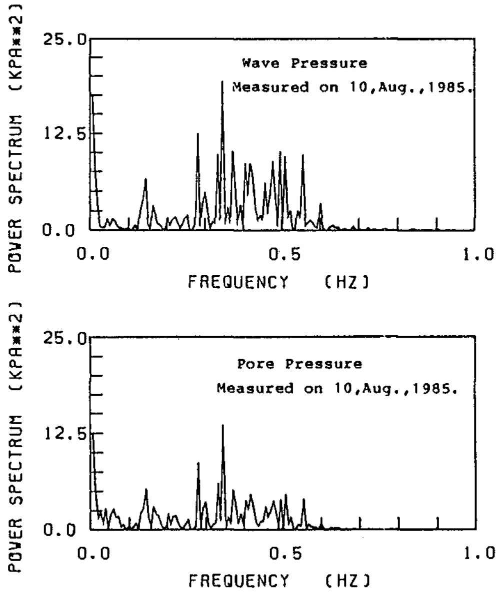


(b) Measured on August 10, 1985.

Figure 2. Comparison between Wave Pressure and Pore Pressure Fluctuations.

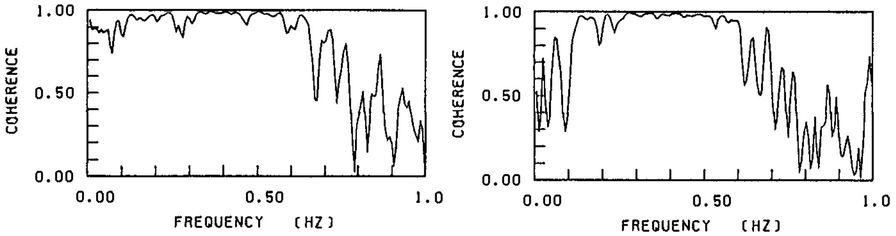


(a) Measured on August 9, 1985.



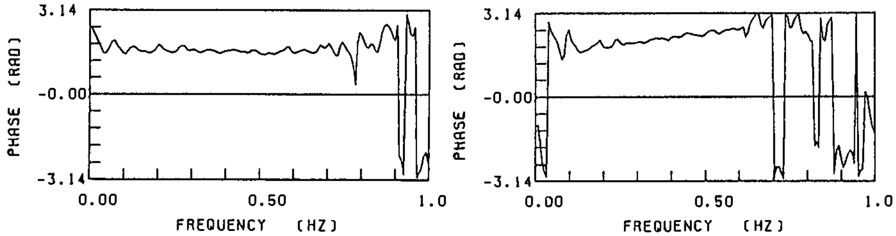
(b) Measured on August 10, 1985.

Figure 3. Power Spectra between Wave Pressure and Pore Pressure.



(a) Measured on August 9, 1985. (b) Measured on August 10, 1985.

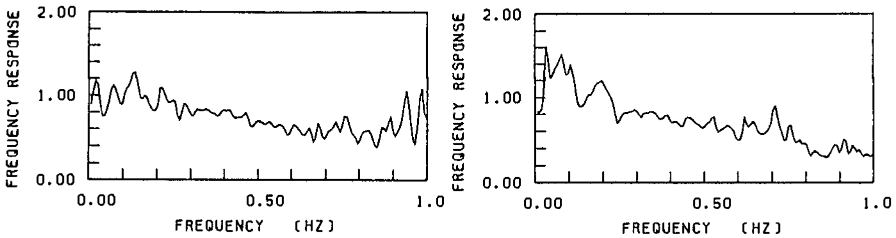
Figure 4. Coherence between Wave Pressure and Pore Pressure



(a) Measured on August 9, 1985. (b) Measured on August 10, 1985.

Figure 5. Phase between Wave Pressure and Pore Pressure.

Figure 6(a) and 6(b) show the frequency response. This figure demonstrates that the frequency response decreases linearly as the frequency increases with the greater fluctuation in the frequency range more than 0.6 Hz. This fact indicates that the low frequency component of the wave pressure fluctuation easily propagates into the seabed.



(a) Measured on August 9, 1985. (b) Measured on August 10, 1985.

Figure 6. Frequency Response between Wave Pressure and Pore Pressure.

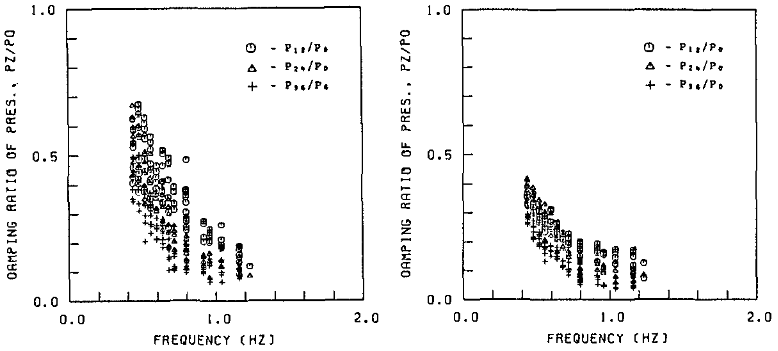
Prediction of Porosity of Sediments

Many difficulties accompany the measurement of the seabed deposits. For example, the density logs used on land have problems in performing the experiments in submarine, the method using sampling has disturbances of remolding and swelling, and the method using the radioactive log is now being developed to reduce the costs and the difficulty of operation. The simple method of the density log is proposed based on the propagating characteristics of the wave pressure into the seabed.

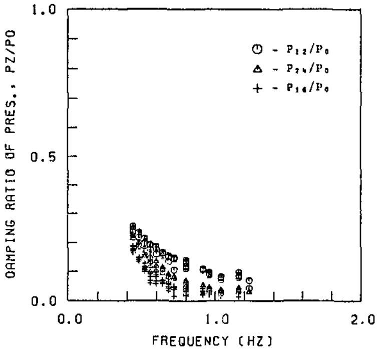
Stoll(1977) indicated that the attenuation of pressure within the seabed is understood by the mechanics both of the intergranular friction in the frame of the soil skeleton and the viscosity of the pore fluid moves in relation to the motion of the soil skeleton.

Since the frequency of the waves is less than 1.0 Hz and the seabed is composed of sand, the intergranular friction is predominant and the damping of the viscosity of pore fluid can be neglected.

The intergranular friction depends on the constitution of the soil skeleton. The density of the sand bed is chosen as the tool to decide this constitution. Therefore, the correlation between the damping and the density of the sand bed enables the prediction of the density of the sand bed.



(a) ρ_d = 1.55 tm^{-3} (b) ρ_d = 1.57 tm^{-3}



(c) ρ_d = 1.62 tm^{-3}

Figure 7. Effect of Frequency on Damping Ratio of Pore Pressure.

Figures 7(a) through 7(c) show the relationship between the frequency of the waves and the damping ratio, which is defined as the ratio of the measured pore pressure to the measured wave pressure at the surface of the bed, based on the results of our previous works (Maeno and Hasegawa, 1985b). In these figures, the subscript of P denotes the depth downward from the bed surface.

These figures show that the damping ratio decreases quadratically as the frequency increases. Since the damping ratio for the tide is infered to be unity, the damping ratio is unity at the frequency zero, and decreases with decreasing velocity as the frequency increases. This tendency is unique for a dense sand bed. However, the linear correlation between the damping ratio and the frequency can be assumed within the region of our experimental results.

Thus, Figure 8 shows the relationship between the gradient of this linear correlation and the density of the sand bed. In this figure, the gradient decreases with decreasing velocity as the density increases. This correlation can be drawn as the monotonous curve. This correlation is examined for the regular wave for various frequencies between 0.6Hz and 2.27Hz generated by the wave tank in laboratory experiments. However, the ocean waves are irregular. The damping of the non-linear waves must be defined. For the irregular waves, assuming that the damping ratio is defined as the spectral ratio of the pore pressure fluctuation within the seabed to the wave pressure fluctuation at the surface of the seabed, the correlation between the damping ratio and the density of the seabed is examined.

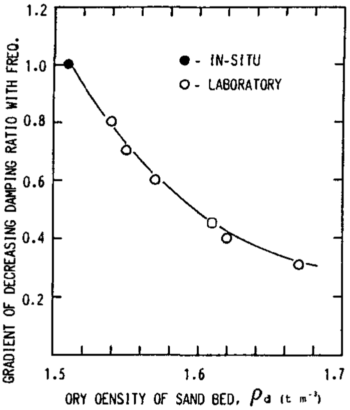
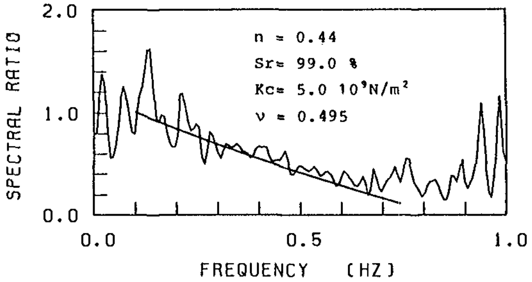
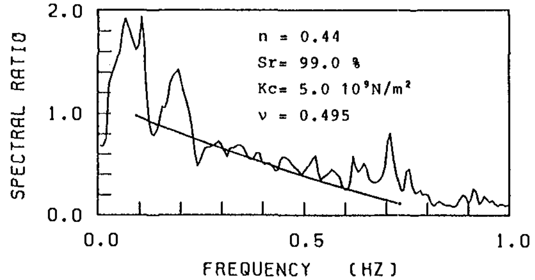


Figure 8. Relationship between Reduction Gradient of Damping Ratio and Dry Density of Sand Bed.

Figures 9(a) and 9(b) show the spectral ratio of the pore pressure to the wave pressure, which were measured at Nabae Beach in Wakasa Bay, Fukui Prefecture. In this figure, the spectral ratio decreases quadratically as the frequency increases. The linear correlation between the spectral ratio and the frequency can be assumed in the region less than 1.0 Hz. In this case, the gradient of this linear correlation is almost unity. The value of this gradient of in-situ measurements, 1.0 is plotted on the approximate curve in Figure 8. The point determined on this curve indicates the density, 1.51 tm^{-3}. This value is infered to be the density of the seabed deposits.



(a) Measured on August 9, 1985.



(b) Measured on August 10, 1985.

Figure 9. Spectral Ratio between Wave Pressure and Pore Pressure.

Since the specific gravity of this sand is 2.70 as shown in Table 1, the porosity of the seabed deposits is obtained as 0.44. Based on Komura's(1961) study on the relationship between the porosity and the average grain size, the average grain size of Nabae sand, 0.160 mm indicates that the porosity of the bed is infered to be distributed between 0.35 and 0.45. Hamilton(1972) also indicates that the deposits of the mean grain size, 0.160 mm, has a porosity of almost 0.45. The predicted porosity, 0.44 is reasonable, because the seabed near the surface is loosest.

Therefore, assuming that the spectral ratio is equivalent to the damping ratio, the density of the seabed deposits can be obtained based on the experimental correlation between the damping ratio and the density of the bed.

Further field measurements for various sites make the verification of this prediction possible.

Comparison of Theoretical Equation with Spectral Ratio

Figures 9(a) and 9(b) show the spectral ratio of the pore water pressure fluctuation within the sand layer and the wave pressure fluctuation at the surface of the sand layer. The spectral ratio decreases as the square of the frequency increases, because the frequency response between the pore pressure fluctuation and the wave pressure fluctuation decreases linearly as the frequency increases. The theoretical equation of the correlation between pore pressure and wave pressure is simulated using the parameters in Table 2.

Table 2. - Physical Parameters of Soils Used in Analysis

Bulk modulus of fluid, Kf	2.0 GPa
Bulk modulus of Mineral grains, Ks	36.0 GPa
Bulk modulus of composite, Kc	4.9-5.4 GPa
Poisson's ratio	0.495
Porosity, n	0.44

By fitting the theoretical Equation (15) to the spectral ratio, the properties of the seabed are examined, that is, the bulk modulus of composite, the porosity of the sand bed, the degree of saturation, the shear modulus and Poisson's ratio. The values of the porosity of the sand bed and Poisson's ratio can be assumed experimentally because they vary within a narrow range under the conditions in this investigation. The porosity is predicted to be 0.44 based on the considerations of the damping ratio of pore pressure as described in the previous section. Poisson's ratio of the saturated soil is in the region of 0.49 to 0.50 for the case of the shear modulus less than 1000 $kgfcm^{-2}$ (Ishihara,1970). And Poisson's ratio is predicted by Hamilton's(1979) Equation (16) consisting of the velocities of the compressional wave of the first kind and the shear wave measured in-situ in the seabed. In this case, Poisson's ratio is assumed to be 0.495.

$$\nu = \{(Vp/Vs)^2-2\}/2\{(Vp/Vs)^2-1\} \tag{16}$$

The shear modulus is derived by the bulk modulus of the composite and Poisson's ratio. The bulk modulus of the fluid and solid are assumed to have typical values as shown in Table 2.

Therefore, the values of the bulk modulus of composite and the degree of saturation can be determined by the theoretical equation which fits the spectral ratio.

In the low frequency range of less than 0.5 Hz, the theoretical value estimated by Equation (15) is in good agreement with those of the spectral ratio of in-situ measured wave-induced pore pressure fluctuation to the wave-induced pressure fluctuation at the surface of the seabed.

In this case, it is predicted that the bulk modulus of composite is between 4.9 GPa and 5.0 GPa and that the degree of saturation is between 97% and 99%. These values are compatible with Esrig and Kirby's(1977) results and those of other considerations.

Discussions

Since Nabae sand is a quite uniform marine sand, as shown in Table 1, the aspect ratio of the pore shape is predicted to be approximately unity and the round model is chosen for the pore shape of this sand. Thus, the fluid motion includes the effects of the local squirt flow with the condition of high permeability.

The propagation characteristics of the wave pressure depend on both the compressional wave and the the shear wave based on Biot's consideration of pore shape. As the spectral ratio of the wave-induced pore pressure to the wave-induced pressure is consistent with the theoretical value predicted by the proposed Equation (15), which takes into account the effects of both the dilatational wave and the shear wave, the wave-induced effects are examined not only for the compressional wave but also the shear wave.

Many authors have investigated the mechanical and physical properties of the deposits in the seabed as described above. There are many difficulties in obtaining the properties of the deposits, for example the remolding and swelling of the samples caused by extraction from the seabed. By the in-situ measuring of the pore water pressure fluctuation within the seabed, information concerning seabed mechanics was derived from this study. Examination of the spectral ratio makes it possible to predict the properties of the deposits based on the theory of wave-induced pore pressure in porous media. Moreover, spectral ratio of the wave-induced pore pressure is similar to that of the earthquake induced pore pressure and both the spectral ratios can be related to each other. It is useful, therefore, to predict the propagation characteristics of earthquake induced pore pressure by the spectral ratio of wave-induced pore pressure.

CONCLUSIONS

The following conclusions were obtained :

1. The low frequency component of wave-induced pressure fluctuation propagates into the seabed as wave-induced pore pressure more easily than does the high frequency component.
2. The phase lag between the wave-induced pressure at the seabed surface and the wave-induced pore pressure within the seabed increases as the frequency decreases.
3. The theoretical equation which gives the relationship between pore pressure and wave pressure fluctuations is proposed.
4. The porosity of the seabed deposit is predicted by the damping ratio of pressure inside the seabed.
5. By fitting the theoretical equation to the spectral ratio between the wave-induced pore pressure and the wave-induced pressure at the seabed surface, the bulk modulus of composite and the degree of saturation can be determined. These values are compatible with those of theoretical and empirical considerations.

APPENDIX I.- REFERENCES

Biot,M.A., "General theory of three-dimensional consolidation," J. of Applied Physics, Vol.26, 1941, pp.182-185.

Biot,M.A., "Theory of elastic waves in a fluid saturated porous solid," I-low frequency range, J. of the Acoust. Soc. of Am., Vol.28, 1956a, pp.168-178.

Biot,M.A., "Theory of elastic waves in a fluid saturated porous solid," II-higher frequency range, J. of the Acoust. Soc. of Am., Vol.28, 1956b, pp.179-191.

Biot,M.A., "Generalized theory of acoustic propagation in porous dissipative media," J. of Acoust. Soc. of Am., Vol.34, 1962, pp.1254-1264.

Esrig,M.I., and Kirby,R.C., "Implications of gas content for predicting the stability of submarine slopes," Marine Geotechnology, Vol.2, 1977, pp.81-100.

Hamilton,E.L., "Compressional-Wave Attenuation in Marine Sediments," Geophysics, Vol.37, 1972, pp.620-646.

Hamilton,E.L., "Vp/Vs and Poisson's ratio in marine sediments and rock," J. of Acoust. Soc. of Am., Vol.66, 1979, pp.1093-1101.

Ishihara,K., "Approximate forms of wave equations for water saturated porous materials and related dynamic modulus," Soils and Foundations, Vol.10, No.4, 1970, pp.10-38.

Jaeger,J.C. and Cook,N.G.W., "Fundamentals of Rock Mechanics," Methuen, London, England, 1969.

Komura,S., "Bulk properties of river bed sediments and its applications to sediment hydraulics," Proc. of Jap. Nat. Cong. for Appl. Mech., 1961.

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

Maeno,Y. and Hasegawa,T., "Characteristics of wave-induced pore water pressure in sand layer," Proc. of Int. Symposium on Ocean Space Utilization, Ocean Space'85, 1985a, pp.475-484, Springer-Verlag.

Maeno,Y. and Hasegawa,T., "Evaluation of wave-induced pore pressure in sand layer by wave steepness," Coastal Engineering in Japan, Vol.28, Japanese Soc. of Civil Eng., 1985b, pp.123-136.

Maeno,Y. and Hasegawa,T., "Propagation characteristics of pore water pressure in seabed under wave loading," Proc. of 32th Conference on Coastal Eng., JSCE, 1985c, pp.75-79,(in Japanese).

Mavko,G.M., and Harp,E., "Analysis of wave-induced pore pressure change recorded during the Mammoth Lakes, Calif. earthquake sequence," Bull. of the Seismological Soc. of Am., Vol.74, No.4, 1984, pp.1395-1407 .

Stoll,D.R., "Acoustic Waves in Ocean Sediments," Geophysics, Vol.42, 1977, pp.715-725.

Yamamoto,T., "Wave induced instability in seabeds," Proc. of ASCE Special Conf. Coastal Sediments'77, 1977, pp.898-913.

Yamamoto,T., "Wave-induced pore pressures and effective stresses in inhomogeneous seabed foundations," Ocean Engng., Vol.8, 1981, pp.1-16.

Zienkiewicz,O.C., Chang,C.T. and Bettess,P., "Drained, undrained consolidating and dynamic behavior assumptions in soils," Geotechnique, Vol.30, No.4, 1980, pp.385-395.