

CHAPTER 136

Effects of Energy Loss near Bed Surface on Wave-Induced Pore Pressure in Sand Layer

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ABSTRACT

The effects of energy loss near the interface between the water and the sand bed on the wave-induced pore pressure are investigated by laboratory experiments. The interface between them includes the complicated factors: (1) roughness of seabed surface such as ripples; (2) boundary layer thickness in the sediment; (3) concentration of suspended sediments. These factors have been studied with respect to dimensionless parameters (e.g. Reynolds number, sediment Reynolds number, the ratio of orbital diameter to sand grain diameter, and Shields number), since many experimental formulas including these parameters have been proposed for predicting the geometry of roughness and the concentration of suspended sediments. The parameters described above are examined in relation to the damping characteristics of the wave-induced pore pressures. The transmissivity of pressure is constant until a critical value of the dimensionless parameters, and then decreases with increasing parameters. The critical values indicate the bed regime boundary of flat bed to ripple bed. Examinations of wave-induced pore pressure make it possible to predict the bed regime boundary.

INTRODUCTION

The energy losses near the interface between the water and the surface layer of the sand bed are investigated in the relation to the transmission of the wave pressures to the wave-induced pore pressures. The energy losses affect the wave-induced instability of the surface layer of the bed. Recently the wave-induced liquefaction has been studied and considered as the transient phenomena near the surface layer of the bed. On the other hand, Maeno & Hasegawa(1987c) indicated that the rapid attenuation of wave-induced pore pressures is observed in the surface layer of the bed, and that the attenuation of pore pressures in the surface layer differs from that in the sublayer. The attenuation characteristics depend on the energy losses. Since the wave-induced pore pressure relates the instability of the seabed, examinations of the energy losses are required for making clear the mechanism of wave-induced instabilities of the bed.

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The interface between the water and the bed includes the many complicated factors: e.g., (1) the roughness of seabed surface such as dunes and ripples; (2) the concentration of suspended sediments; (3) the boundary layer thickness in the sediments. Although the factors are related to each other and the other factors may exist, the selection of these factors is reasonable on the basis of the observation in laboratory experiments. The surface geometry of sand bed is not idealized flat but rippled under wave action. The roughness of bed surface causes the complicated stream regimen such as vortex. The sediments are suspended by the interaction between the severe oscillatory flow and the bed roughness.

Maeno & Hasegawa(1985a,b) had investigated the characteristics of wave-induced pore pressure in sand layer by wave tank experiments. They measured the wave-induced pore pressures, observing the bed forms of flat bed to ripple bed. The difference between the measured pore pressure and the predicted one can be explained by these factors of energy losses.

The geometry of the bed roughness and the concentration of suspended sediments have been investigated by many authors and the many empirical formulas have been proposed for the prediction of them. The intrinsic parameters also have been indicated. The empirical formulas for ripple geometry such as the wave length and the wave steepness have been proposed with reference to the Reynolds number, the Shields number and the orbital diameter. The empirical formulas for the concentration of suspended sediments also have been proposed with reference to the Shields number. This study examines the relationship between these parameters and the transmissivity of pore pressures.

INTRINSIC PARAMETERS OF ENERGY LOSSES

Tsuchiya & Banno(1987) indicated the three dimensionless parameters as the index of classification for criteria of ripple formation. Those are the Shields number, the sediment Reynolds number (or the sediment fluid number) and the ratio of the orbital diameter of water particle in the wave motion to the diameter of the sediment grain. The many formulas for the concentration of suspended sediments are related to the Shields number, and those for the geometry of bed roughness also are related to the Reynolds number, the Shields number and the ratio of orbital diameter to sediment grain diameter. Since no studies examine the bed roughness and the concentration of suspended sediments in relation to the transmissivity of the wave pressures to the wave-induced pore pressures, this study examined the relationship between the damping characteristics of wave-induced pore pressure and the following four parameters: (1) the ratio of orbital diameter of water particle; (2) the Shields number; (3) the Reynolds number; (4) the sediment Reynolds number.

First, the ratio of orbital diameter of water particle to the grain diameter of sediments is defined as follows:

$$d_0/D = H/\sinh(kh)D \quad (1)$$

where d_0 = the orbital diameter of the water particle in the wave motion; H = the wave height; k = the wave number($=2\pi/L$); h = the water depth and D = the grain diameter of sediments and regarded as the median diameter of sediment grain, d_{50} .

Secondly, the Shields number is defined as follows:

$$\psi = \frac{u^{*2}}{(\rho_s / \rho_w - 1)gd_{50}} \tag{2}$$

$$u^* = \sqrt{(fw/2)u_m} \tag{3}$$

$$u_m = \pi d_0 / T \tag{4}$$

where u^* = the shear velocity; u_m = the maximum value of the horizontal velocity just outside the boundary layer; ρ_s and ρ_w are the densities of sand and water, respectively; g = the gravity acceleration; T = the period of the oscillatory flow; fw = the wave-current friction coefficient and Swart(1976) defined it as following form:

$$fw = 0.0025\exp[5.21(a/ks)-0.19] \quad \text{for } a/ks > 1.57 \tag{5}$$

$$fw = 0.3 \quad \text{for } a/ks < 1.57 \tag{6}$$

where a = the orbital amplitude of fluid just outside the boundary layer, $d_0/2$, and ks = the roughness length of the bed. Sleath(1984) suggested that the Engelund & Hansen(1967)'s formula of the roughness length of the bed is reasonable for many cases. Since Nabae sand is considerably uniform, the median grain diameter, d_{50} , substitutes for the grain size at the accumulation rate of 65 percents, d_{65} .

$$ks = 2d_{65} \tag{7}$$

Thirdly, the Reynolds number is defined as follows:

$$Re = u_m d_0 / \nu = \pi d_0^2 / (\nu T) \tag{8}$$

where ν = the kinematic viscosity of the fluid.

Finally, the sediment Reynolds number is defined as follows:

$$Re_D = u^* D / \nu \tag{9}$$

where D = the median grain size of sediment, d_{50} .

EXPERIMENTAL METHOD

Experiments were conducted on Nabae beach sand using the wave tank as shown in Figure 1, as well as our previous experiments (Maeno & Hasegawa; 1985a,b).

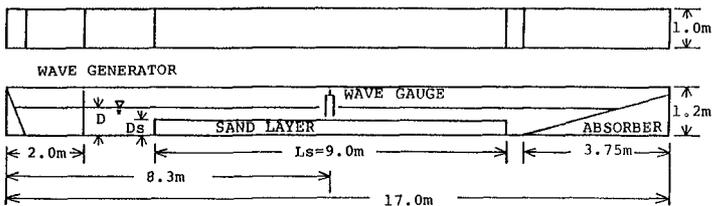


Figure 1. Experimental setup of the wave tank.

The wave tank generates the waves between the wave periods of 0.6s and 2.27s. The water depth is 0.41m over the sand bed. The length, the

width and the thickness of sand bed are 9.0m, 1.0m and 0.36m, respectively. The influences of bed size effects can be disregarded in the experiments. The physical properties of Nabae sand are given in Table 1. Table 2 tabulates the experimental conditions in addition to the published cases.

Table 1. - Properties of Nabae sand.

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

Table 2. - Experimental conditions.

Case	Length of bed (cm)	Dry density (t/m^3)	Water depth (cm)
(I)	250.0	1.61	41.0
(II)	166.0	1.54	41.0
(III)	99.5	1.67	41.0
(IV)	900.0	1.55	41.0
(V)	900.0	1.57	41.0
(VI)	900.0	1.62	41.0

The wave gauge is fixed just over the center of the bed. The pore pressures were measured at various vertical positions under the mud-line by four pressure transducers as shown in Figure 2, where the subscript z of P denotes the depth downward from the bed surface, and the x -axis is taken along the mud line of the sand bed.

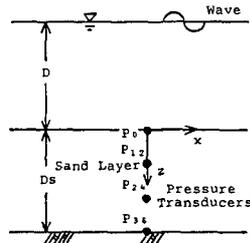


Figure 2. Definition of terms and set-up of pressure transducers.

The transmissivity of wave pressure is defined as the ratio of the measured pore pressure to the wave pressure predicted by Stokes' second order wave theory.

$$P_z = \frac{\rho g H}{2 \cosh(ND)} + \frac{3 \rho g N H^2 \tanh(ND)}{16 \sinh^2(ND)} \left[\frac{1}{\sinh^2(ND)} - \frac{1}{3} \right] - \frac{\rho g N H^2 \tanh(ND)}{16 \sinh^2(ND)} \quad (10)$$

EXPERIMENTAL RESULTS AND DISCUSSION

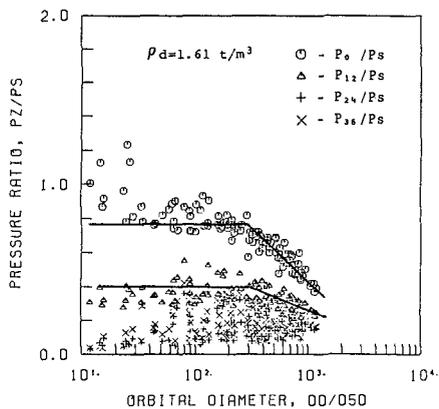
The relationships between the four dimensionless parameters pre-

viously described and the transmissivity of pressure in sand bed are investigated in order to study the effects of energy losses near the interface between the water and the sand bed on the damping characteristics of wave-induced pore pressures.

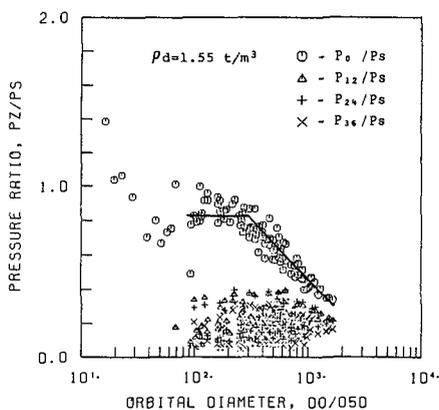
Relationship between Orbital Diameter and Transmissivity

Figures 3(a) and 3(b) show the relationship between the transmissivity of pressures and the ratio of the orbital diameter of water particle in the wave motion to the median grain size of sediment. The transmissivity of pressure keeps constant until a critical value, i.e., an orbital diameter of 300.0, and then decreases as the orbital diameter increases. This tendency is more clear in the wave pressure fluctuations at the bed surface and negligible in the deeper depth below mudline.

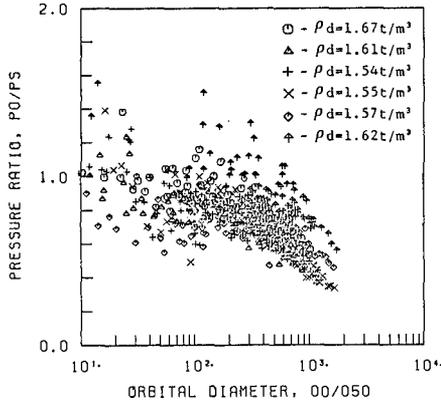
Figures 3(c) and 3(d) also show the relationship between the dimensionless orbital diameter and the transmissivities of pressure, P_0/P_s and P_{12}/P_s , for various sand bed conditions. The decreasing



(a) $\rho_d=161 \text{ t/m}^3$



(b) $\rho_d=155 \text{ t/m}^3$



(c) wave pressure for various bed conditions

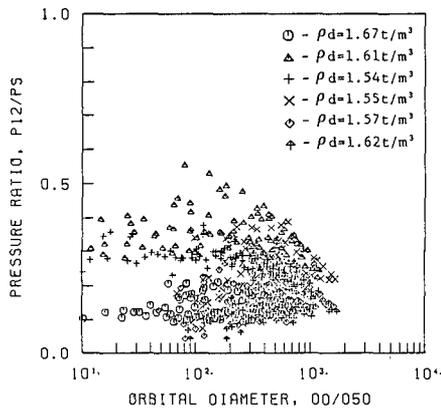
(d) pore pressure at $z=12\text{cm}$ for various bed conditions

Figure 3. Relationship between the orbital diameter of water particle and transmissivity

tendency of the dimensionless orbital diameter is more significant in the dense sand bed than in the loose sand bed. The critical value of the dimensionless orbital diameter is constant of 300, for various bed conditions.

Tsuchiya, Ueda and Oshimo(1984) showed that the dimensionless orbital diameter should be used for the index of the ripple formation for less than 1000. The experimental results are within this range of orbital diameter. The transmissivity of pressure shows rapid reduction near $d_0/D=1000$. Using the dimensionless orbital diameter many empirical formulas have been proposed for the ripple wave length (e.g., Kaneko & Honji,1979; Kaneko,1980). Sakakiyama et al.(1986) show that the ripple wave length increases with the orbital diameter until the ratio of ripple wave length to the orbital diameter reaches a limiting value of 2/3. Based on these backgrounds it is significant to examine

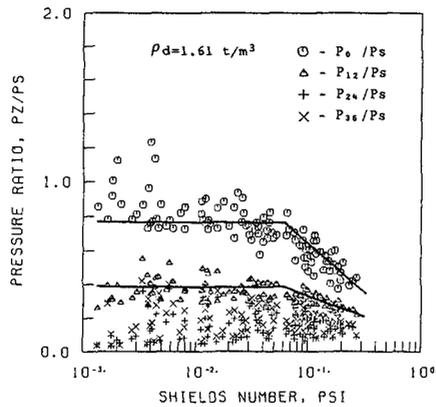
the transmissivity of pressure with reference to the orbital diameter.

Relationship between Shields Number and Transmissivity

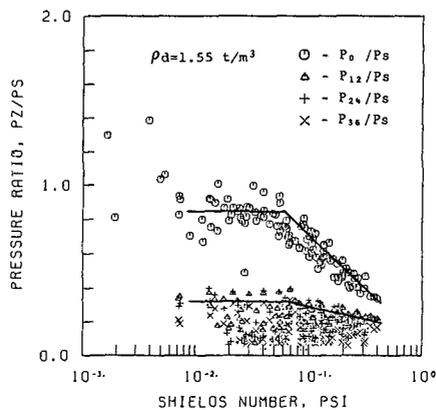
Figures 4(a) and 4(b) show the relationship between the transmissivity of pressures and the Shields number. The transmissivity also keeps constant until a critical Shields number of 0.06, and then decreases as the Shields number increases. This tendency is most predominant in the wave pressure fluctuation. The reduction of transmissivity with the Shields number becomes slower as the depth below the mudline increases. The transmissivity is constant with the Shields number for the deep depth below the mudline.

Figures 4(c) and 4(d) show the relationships between the transmissivities of pressures, P_0/P_s and P_{12}/P_s , and the Shields number for the various sand bed conditions. The critical value of the Shields number is almost 0.06 for all sand bed conditions.

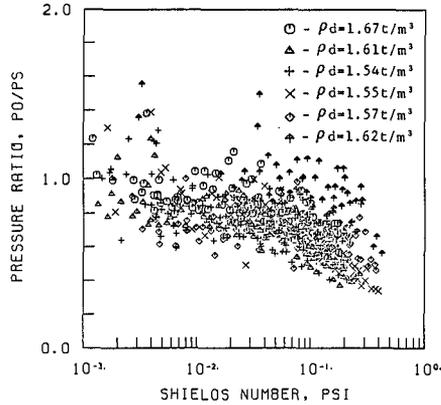
The Shields number is the key parameter in the empirical formulas of the ripple geometry such as the wave length and the wave steepness



(a) $\rho_d = 1.61 \text{ t/m}^3$



(b) $\rho_d = 1.55 \text{ t/m}^3$



(c) wave pressure for various bed conditions

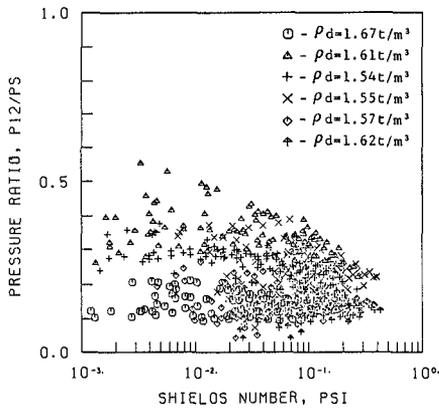
(d) pore pressure at $z=12\text{cm}$ for various bed conditions

Figure 4. Relationship between the Shields number and transmissivity

(e.g., Sakakiyama et al.,1986; Sato, Mitani and Watanabe,1988; Sato, Sugiura and Watanabe,1987). The empirical formulas for the concentration of suspended sediments near the bed surface have proposed in relation to the Shields number (e.g., Kawamata,1982). Kawamata(1982) showed that the concentration in a vortex layer on ripples depends on cubic the Shields number.

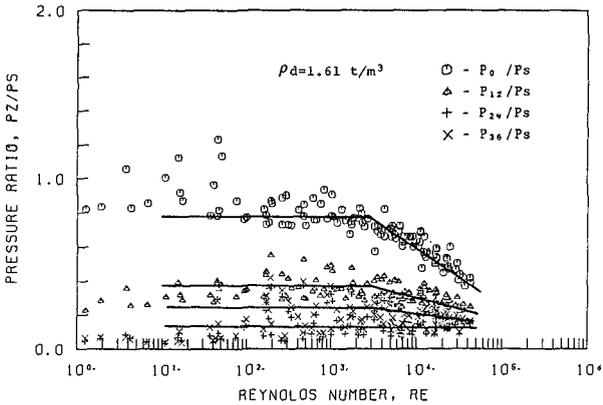
Therefore, examinations of the relationships between the transmissivities of pressures and the Shields number enable to obtain indirectly the relationships between the transmissivities and the ripple geometry and the concentration of suspended sediments. On the basis of the previous works, the wave length of ripple becomes small and the concentration of suspended sediments near the sand bed increases as the Shield number increases. Thus, the wave-induced pressures attenuates near the sand ripple, and the generation of wave pressures and

pore pressures are restricted. This inference is consistent with the experimental observation of the wave pressure propagation.

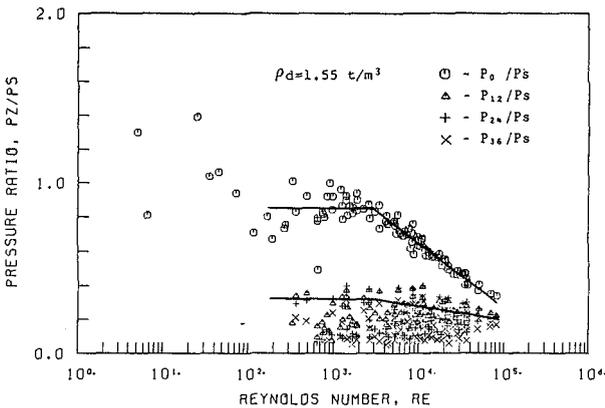
Relationship between Reynolds Number and Transmissivity

Figures 5(a) and 5(b) shows the relationship between the transmissivity of pressures and the Reynolds number. The transmissivity keeps constant until a critical Reynolds number of 3000.0, and then decreases as the Reynolds number increases. This tendency is most predominant in the wave pressure fluctuation. The reduction of transmissivity with the Reynolds number becomes slower as the depth below the mudline increases. The transmissivity of pore pressures is constant with the Reynolds number at the deep depth below the mudline.

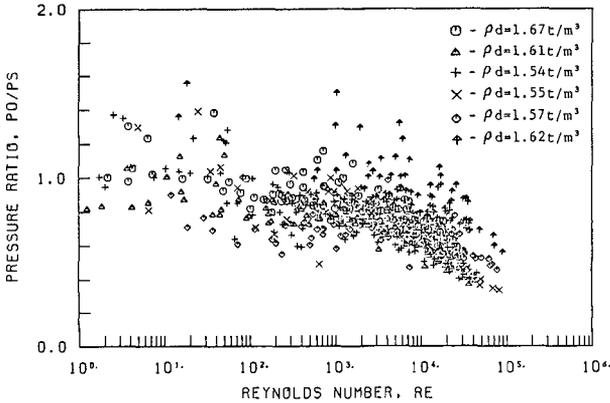
Figures 5(c) and 5(d) show the relationships between the transmissivities of pressures, P_0/P_s and P_{12}/P_s , and the Reynolds number for the various sand bed conditions. The critical value of the Reynolds number is almost 3000. for all sand bed conditions.



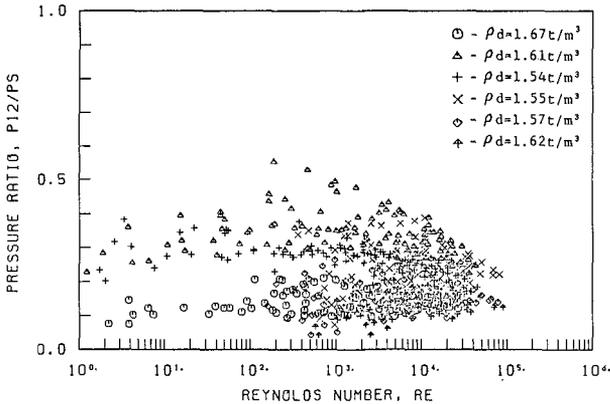
(a) $\rho_d=161 \text{ t/m}^3$



(b) $\rho_d=1.55 \text{ t/m}^3$



(c) wave pressure for various bed condition



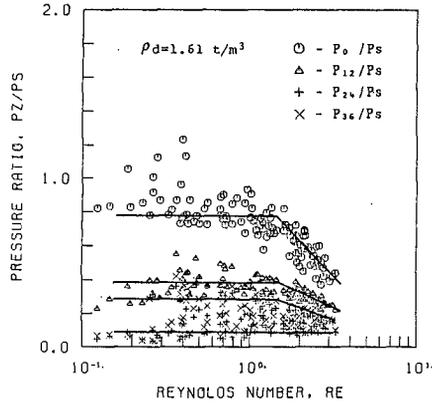
(d) pore pressure at z=12cm for various bed condition

Figure 5. Relationship between the Reynolds number and transmissivity

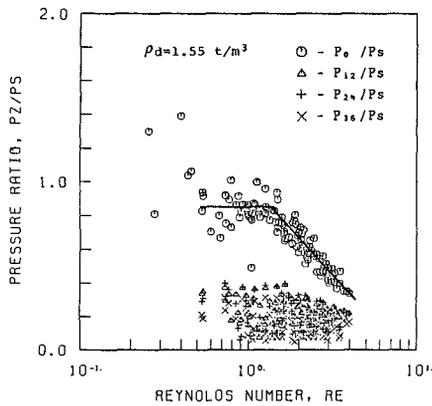
Relationship between Sediment Reynolds Number and Transmissivity

Figures 6(a) and 6(b) show the relationship between the transmissivity of pore pressures and the sediment Reynolds number. The transmissivity also keeps constant until a critical sediment Reynolds number of 1.5, and then decreases as the sediment Reynolds number increases. The gradient of the reduction is most steepest at the sand bed surface, and becomes gentle as the depth of sand bed increases. The transmissivity of pressures is regarded as a constant value at the deep depth of sand bed.

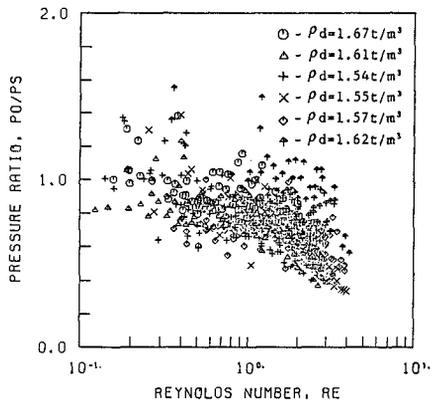
Figures 6(c) and 6(d) show the relationship between the transmissivities of pressure, P_0/P_s and P_{12}/P_s , and the Reynolds number for the various sand bed conditions. The transmissivities of pressure start to reduce at the critical sediment Reynolds number of almost 1.5 for all sand bed conditions.



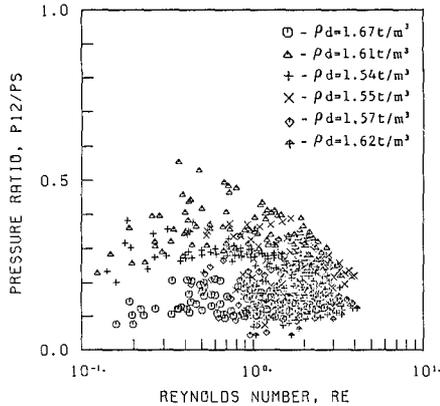
(a) $\rho_d = 1.61 \text{ t/m}^3$



(b) $\rho_d = 1.55 \text{ t/m}^3$



(c) wave pressure for various bed conditions



(d) pore pressure at $z=12\text{cm}$ for various bed conditions

Figure 6. Relationship between the sediment Reynolds number and transmissivity

The relationships between the transmissivities of pressures and the sediment Reynolds number are the same as those for the Reynolds number using the index of the orbital diameter of water particle instead of the median grain diameter. Since only a single sand is used in this experiments. The sediment Reynolds number should be examined, conducting additional experiments on the other sands that show any distributions of grain particle.

Sand Ripple Geometry and Transmissivity

All four parameters described above keep the transmissivities of pressures constant until a critical value of each parameter and linearly reduce them with increasing each parameter. This tendency is predominant in the dense sand bed and at the sand bed surface and becomes weaker as the depth of sand bed increases. This fact indicates that the damping characteristics of pressures change at a critical value of each parameter. Their critical values of each parameter are 1.5 for the sediment Reynolds number, 3000. for the Reynolds number, 0.06 for the Shields number and 300. for the dimensionless orbital diameter of water particle.

Riho, Watanabe and Horikawa (1981) proposed the following bed regime boundary of flat bed to rippled bed for both fine and coarse sands:

$$d_0'/d_m > 280 \text{ and } \psi > 0.1 \quad (11)$$

where d_0' = the orbital diameter of water particle in the finite amplitude wave action; d_m = the average grain diameter.

The critical values of both the dimensionless orbital diameter and the Shields number are in a good agreement with their bed regime boundary of flat bed to ripple bed. Since the ripple formation causes the complicated stream regimen such as vortex and increases the concentration of suspended sediments, the wave energy attenuates and decreases the rate of the wave pressure propagation into the sand bed. The damping characteristics of pressures are influenced by the energy losses near the interface between the water and the sand bed. Thus

examinations of the damping of pressures is a tool to investigate the complicated phenomena near the interface between the water and sand bed surface.

Recently, the criterion of ripple disappearance in the upper regime has been focused on and usually defined as the bed regime boundary of ripple bed to sheet flow. However, this study doesn't examine the other bed regime boundaries without flat bed to ripple bed in the relation to the damping characteristics of pressures in sand beds, since waves generated by wave tank is restricted in a narrow range of oscillatory flow velocity. If we conduct the laboratory experiment in water tunnel generating oscillatory flow and examine the damping characteristics of pore pressures in sand beds, we can obtain the bed regime boundary of ripple to sheet flow as well as that of flat to ripple. Since the wave pressure can easily propagate into the sand bed without damping based on the theoretical considerations, the transmissivity of pressures is inferred to change.

Therefore, the following bed regime boundaries can be determined by the damping characteristics of pore pressures: (a) no movement to flat bed; (b) flat bed to ripple bed; (c) ripple bed to sheet flow.

Boundary Layer in Sand Bed

Many types of instabilities of sand beds should be classified through their mechanisms. These mechanisms depend on their own bed conditions. For example, a bed condition is characterized by the composition and the constitution of sand beds, geotechnical properties of sediments, and so on. These bed conditions were discussed in our previous works (Maeno & Hasegawa, 1987b,c). The instability near the surface layer of sand beds is influenced by the effects of energy loss near the interface between the water and the sand bed. The interface between them includes the complicated factors as previously described. The boundary layer is assumed in the sediment, defining its thickness as the depth of the surface layer which depresses the wave-induced pore pressure. It is considered that the boundary layer has any contribution to cause the instabilities of sand beds such as the scour and the liquefaction.

In the boundary layer, the high erodibility may be caused, because its density is loosest; no solid skeleton in it is sufficiently composed; and it is considerably deformable. Thus, it is significant to investigate the correlation between the boundary layer thickness and the instability due to scour and erosion. The boundary layer is examined by laboratory experiments in a wave tank.

The elastic wave propagation theory predicts exponential attenuation of wave-induced pore pressures in a poro elastic media. This attenuation curve is valid for coarse sand beds (Yamamoto, 1977). However, the rapid attenuation curve is observed near the surface of fine sand beds (Maeno & Hasegawa, 1985b). Figure 7 shows the relationship between the damping ratio, P_z/P_0 , and the relative depth, z/D_s . This figure shows that the pore pressure is damped rapidly near the surface of a sand bed, and then is depressed slowly as the depth below the mudline increases.

The above experimental results indicate that there is a difference in mechanism of attenuation of pore pressure between near the surface and the inside of the sand bed. Since the surface layer of the sand bed is deformable; the soil skeleton in this layer is composed of the sand grains which are weakly combined with each other; wave-induced pore pressure easily squeezes out, and then attenuates greatly in the surface layer. The pore pressure, on the other hand, less attenuates

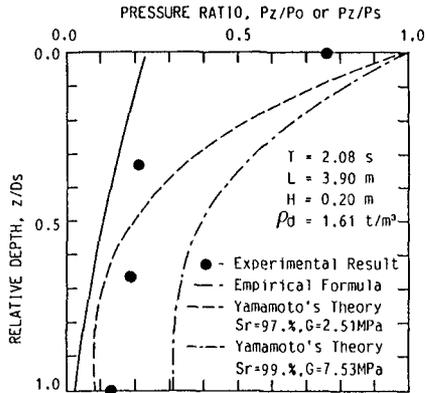


Figure 7. The relationship between the transmissivity of pressure and relative depth

in the sublayer below the surface layer, because the sublayer is relatively rigid and it is not easy for pore pressure to dissipate forward to bed surface. The above discussions suggest that the boundary layer may exist in the sand bed under wave loading. The boundary layer thickness should be predicted on the basis of laboratory experiments. Many difficulties, however, accompany these experiments. Those are the simultaneous measuring of pore pressures at various points, and the exact measuring near the surface of the bed. Since transducers disturb the flow of the pore fluid and the propagation of pressures in the beds, many miniature high quality transducers are required for these measurements. Overcoming these difficulties of laboratory experiments, the boundary layer thickness will be predicted experimentally. Moreover, the wave-induced instabilities near the surface layer will be classified based on these studies.

CONCLUSIONS

The following conclusions are obtained:

1. The energy losses near the interface between the sand bed and the water affect the wave-induced pore pressure in the surface layer of the sand bed. The effects of energy losses on the damping characteristics are examined in relation to the four dimensionless parameters: (1) the ratio of the orbital diameter of water particle to the sand grain diameter; (2) the Shields number; (3) the Reynolds number; (4) the sediment Reynolds number.
2. The transmissivity of pressure keeps constant until a critical value, and then decreases as all four dimensionless parameters increase. The rate of this reduction decreases as the depth below the mud line increases. The critical values are 300.0 for the orbital diameter, 0.06 for the Shields number, 3000.0 for the Reynolds number, and 1.5 for the sediment Reynolds number, respectively.
3. The critical values of both the dimensionless orbital diameter and the Shields number are in good agreement with Riho et al.(1981)'s bed regime boundary of flat bed to ripple bed. The flat bed to ripple bed

boundary is determined by the damping characteristics of wave-induced pore pressures. Experimental results suggest that it is possible to determine the other bed regime boundaries by the proposed method that examines the relationship between the damping characteristics of wave pressures and the group of intrinsic dimensionless parameters.

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