CHAPTER 195

# Fundamental Characteristics of a New Wave Absorbing System Using Sand Liquefaction

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**Abstract**
When a sand bed is liquefied due to a high pore pressure gradient, it significantly reduces the height of waves passing over it. This study investigates the fundamental characteristics of a liquefied sand bed including the wave damping effect.

## 1. INTRODUCTION

Two types of sand liquefaction exist. The first is a well-known phenomenon that occurs during an earthquake, namely, the generation of excess pore pressure caused by the shear deformation of sand, while the second is so-called quick sand or boiling of sand, which is generated by the upward pore pressure gradient of seepage flow in sand. A pore pressure gradient can also be generated by waves, and this causes sinking or settlement of sea structures such as block mound breakwaters.

The primary objective of the present study is to elucidate the fundamental features of a liquefied sand bed. One of its most impressive ones is the wave damping effect; i.e., when a sand bed is liquefied, the sand moves due to wave action and consumes wave energy, which results in generating this unique effect.

A series of model experiments were carried out to investigate the fundamental characteristics of liquefied sand and the wave-damping effect, with this report describing the results of the experiments and some theoretical considerations.

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## 2. SAND LIQUEFACTION SYSTEM AND EXPERIMENTAL PROCEDURES

### Sand Liquefaction System

Figure 1 shows the newly developed sand liquefaction system which is comprised of a sand bed and horizontal pipes buried at its bottom. Water is pumped into the pipes to increase the pore pressure in the sand bed and cause so-called boiling of the sand. Basically, a kind of and liquefaction takes place since the sand behaves like a liquid.

When this phenomenon occurs, the shear modulus of the liquefied sand is significantly decreased, and a large movement of sand occurs due to wave action. Consequently, wave energy is consumed by the resultant friction generated between sand particles during their wave-induced movement.

### Experimental Setup

The experiments were conducted in a small wave flume ( 30 m x 1 m x 0.5 m). Six cylindrical pipes with an inner diameter of 13 mm and a length of 4 m were horizontally installed at the bottom of the sand bed. Holes were drilled in them to supply water into the sand bed. The pore pressure is changed by adjusting the flow valves.

Two sand bed heights of $h_S$= 20 and 40 cm were tested. During the experiments, we measured pore pressure, flow rate from the pipes, wave height, and sand movement.

Four types of tests were conducted:
1) Permeability tests
2) Scouring tests
3) Block-sinking tests
4) Wave damping tests

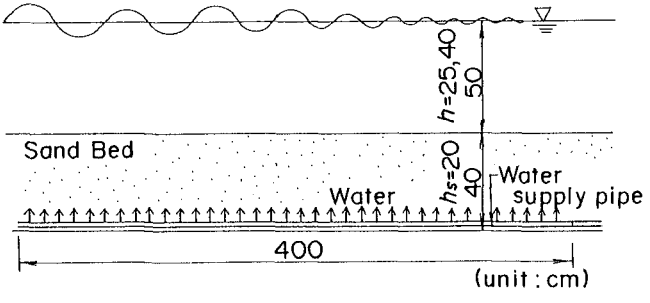


Fig. 1 Diagram of the Wave-Absorbing System

## 3. EXPERIMENTAL RESULTS

### Hydraulic Gradient and Liquefaction

Figure 2 shows the results of the permeability tests, and also the results of a typical permeability test done by Yoshimi (1975). The x-axis is seepage flow rate, while the y-axis is the hydraulic gradient.

In Yoshimi's ordinary permeability test, the proportionality remains until the hydraulic gradient, i, reaches the critical hydraulic gradient, $i_{cr}$, and then even though the seepage flow rate is increased, the hydraulic gradient slightly decreases. This phenomenon in sand is usually called "boiling" or "quick sand." The proportionality of the seepage flow rate with respect to the hydraulic gradient determines the permeability, which is 0.038 cm/s in Yoshimi's test.

Here, however, the proportionality vanishes when the hydraulic gradient is greater than about 0.5, that is, partial boiling is caused by the nonuniform distribution of seepage flow produced by supplying water through the pipes. In this case, the permeability of the sand bed is 0.14 cm/s.

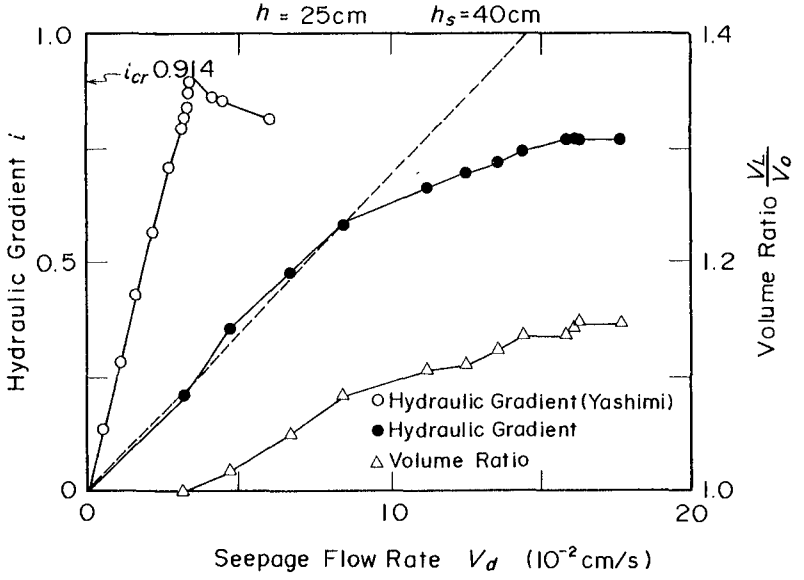


Fig. 2 Results of Permeability Tests

Ripples and Leveled Sand Surface

A typical feature of a liquefied sand bed is its level surface. It is well known that a sand bed surface normally forms sand ripples due to wave action, whereas a liquefied sand bed always stays level.

Figure 3 shows photographs of these two sand surfaces: ripples in a non-liquefied sand bed and no ripples in a liquefied sand bed. Even if a trench is dug in the liquefied sand surface, it is soon back-filled by the leveling movement.

Scouring of Sand Bed by Rapid Water Flow

A liquefied sand bed may easily suffer scouring due to rapid water flow over its surface. We therefore directed a water jet at the surface of an ordinary non-liquefied and liquefied sand bed, with Fig. 4 showing the resultant scouring of the liquefied sand bed due to the water jet from the nozzle, shown on the left above the bed. The sand particles are lifted up as indicated. It should be noted that the scoured location is back-filled quickly by the leveling behavior of the liquefied sand, and that the lifting of the sand particles continues.

Sand particles in the non-liquefied sand bed were lifted-up similarly to those in the liquefied sand bed and it becomes small after the sand bed was scoured to a certain depth. This is the significant difference between ordinary and liquefied sand beds.

Our results suggest a difference exists in the scouring mechanism. However, we cannot confirm that a liquefied sand bed suffers scouring more easily in comparison with ordinary beds.

Sinking of Blocks/Caisson Breakwater

Figure 5 shows a photo of sinking concrete blocks caused by liquefied sand. The blocks appear stable in the upper photo, while in the lower ones, they sink after water is pumped into the pipes.

Figure 6 shows the sinking speed of a concrete block as a function of the hydraulic gradient i for three water supply methods: constant flow, one-side oscillatory flow, and two-side oscillatory flow. Note that sinking rapidly occurs for each method when the hydraulic gradient is greater than about 0.5.

Sand liquefaction induced by wave action is believed to be a major reason causing the blocks to sink or settle

Fig. 3 Leveling of Sand Surface

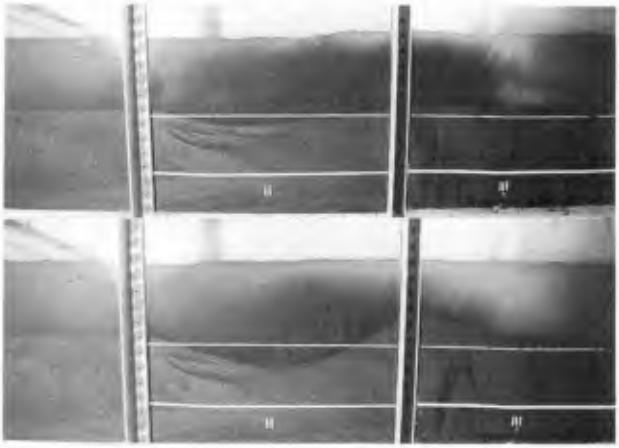

Fig. 4 Scouring of a Liquefied Sand Bed

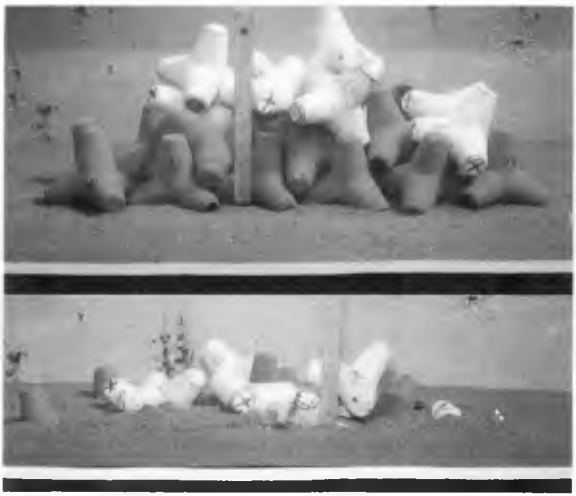

Fig. 5 Sinking of Blocks

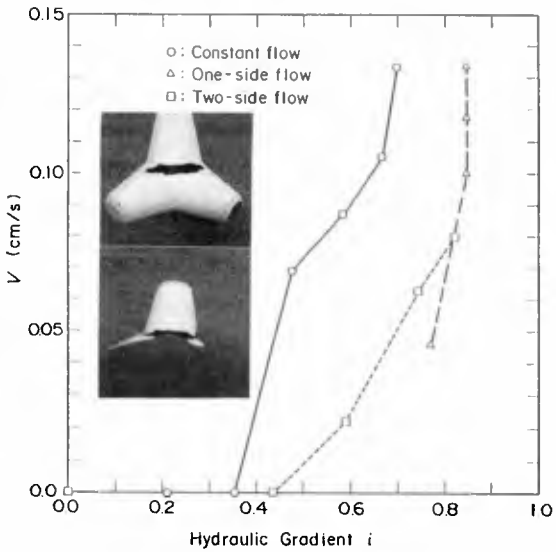


Fig. 6 Sinking Speed of a Concrete Block

(Nago (1981), Maeno (1985), Sakai (1992), Zen (1993), Iwagaki (1993)). It is believed that such sinking happens when the pore pressure gradient due to a wave exceeds the critical hydraulic gradient. However, this is not the case, because sinking occurs even when the hydraulic gradient is around 0.5.

Figure 7 shows the settlement of a caisson breakwater into a sand bed after pore water was supplied from its bottom. Although the caisson was expected to quickly sink due to its heavy weight, instead it remained relatively stable. The sand under the caisson is actually not liquefied, although other parts are. Consequently, the toe of the rubble mound begins sinking first.

Due to the caisson weight, the effective stress of the sand under it increases and prevents liquefaction. Wave-induced liquefaction is usually determined by considering the pore pressure gradient dp/dz. However, instead of employing this parameter, it is presumably better to apply Mohr-Coulomb failure criteria including the effective stress.

Of particular interest, the toe settlement occurring in the mounds of prototype composite breakwaters is very similar to the photographed settlement behavior. This

phenomenon was considered to be a result of scouring damage due to wave-induced water particle velocity. However, wave-induced liquefaction might be another reason for this type of damage, and therefore, proper to countermeasures should be taken to mitigate this effect.

It should also be noted that the rubble mound plays an important role in preventing caisson sinking. Actually, owing to the rubble foundation, prototype caissons of composite breakwaters have never suffered from a failure like that shown in Fig. 7. The importance of the rubble mound foundation should be emphasized in the design of sea structures, however, its function has not been fully clarified.

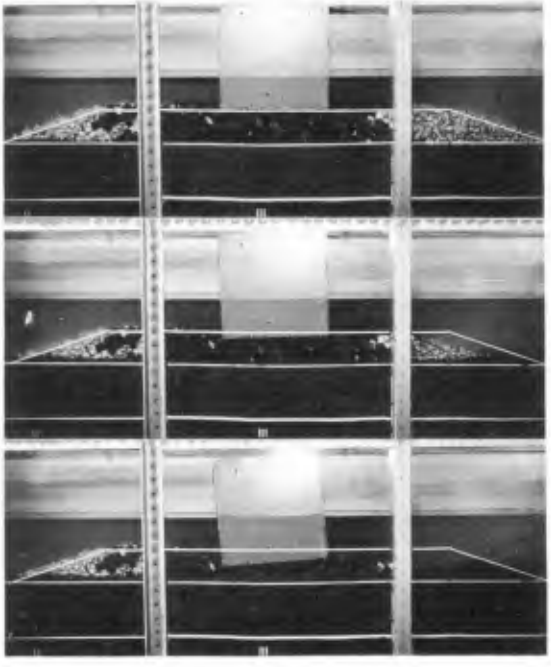

Fig. 7 Settlement of a Caisson Breakwater

## 4. WAVE DAMPING DUE TO SAND LIQUEFACTION

Wave Damping

Wave damping due to soft clay movement is generally known to be high (Yamamoto and Takahashi, 1985). On the other hand, that due to sand movement is much less because of its high shear modulus, though when liquefaction occurs, the sand becomes soft and induces high damping similar to soft clay.

Typical wave records obtained during model experiments are shown in Fig. 8. The sand bed was 40-cm-thick and regular waves with a 1-s period were applied in 25-cm-deep water. As indicated, these wave records were taken at the offshore side, the center of the sand bed, and harbor side. A record of the oscillations of the sand bed surface is also shown.

Note that wave damping clearly occurs after the water supply is started. The wave at harbor side is very small, and its height is reduced by more than 75%. In this case, the sand surface oscillates with an amplitude that is 6% of the incident wave amplitude, having a phase difference of approximately 50°.

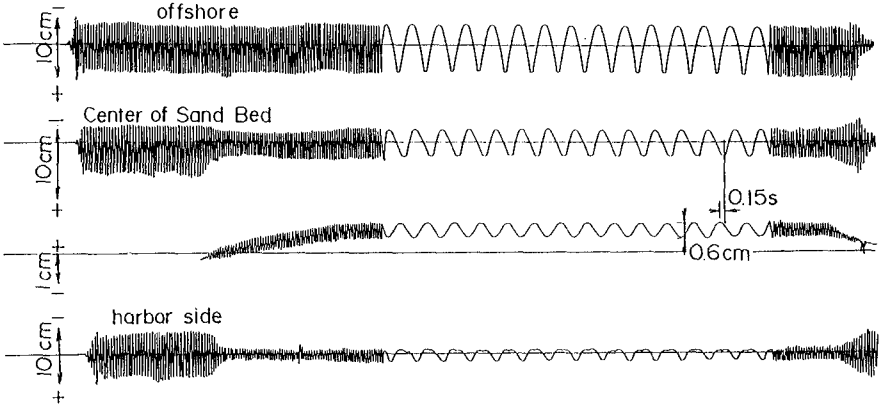


Fig. 8 Typical Wave Damping Record

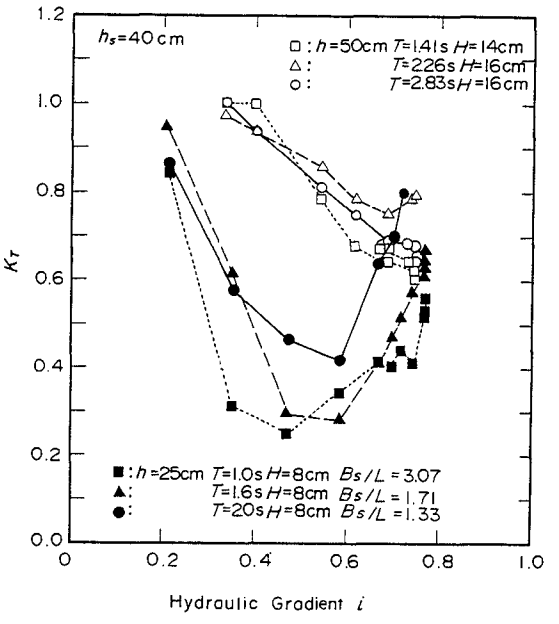


Fig. 9 Wave Transmission Coefficient ($h_S$ = 40 cm)

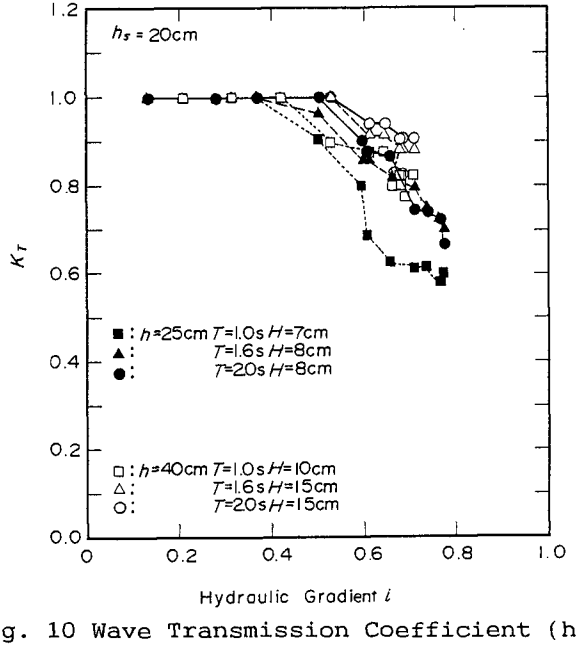


Fig. 10 Wave Transmission Coefficient ($h_S$ = 20 cm)

In Fig. 9, the wave transmission coefficient $K_t$ is plotted as a function of the hydraulic gradient i for three wave conditions and two water depths, where $K_t$ becomes very small when i is around 0.5 at h = 25 cm. However, when h = 50 cm, it is not so small, i.e., the damping is slight. Figure 10 is a corresponding graph in which the sand thickness $h_s$ is 20 cm. Note that wave damping is comparatively much less.

These results indicate that wave damping is large when the soil thickness is deep and the water depth is shallow. It is also apparent that wave damping is large when the sand is partially, not fully liquefied.

Wave Action on a Liquefied Sand Bed

Figure 11 shows the half amplitude of pore pressure due to wave action when h = 25 cm and $h_s$ = 40 cm. The pore pressure increases with an increase in the pressure of the water supplied from the bottom of the sand bed. Due to liquefaction, wave pressure penetrates deeper into the soil.

Figure 12 is a graph showing the amplitude of vertical oscillations of the sand, which increases with an increase in the hydraulic gradient, being about 10% that of the wave height at i = 0.5. Such large movement was not usually expected.

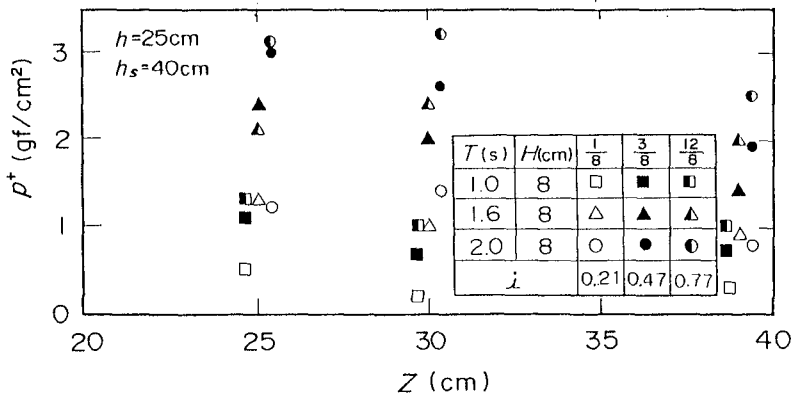


Fig. 11 Amplitude of Wave-Induced Pore Pressure Variation

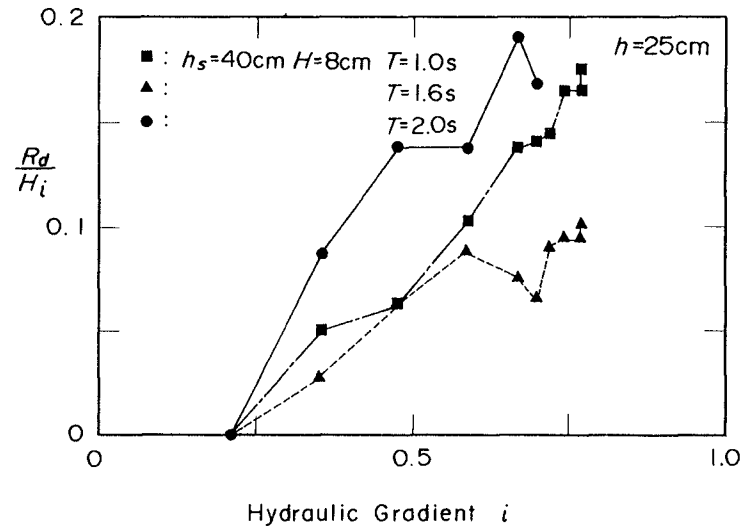


Fig. 12 Amplitude of Sand Movement

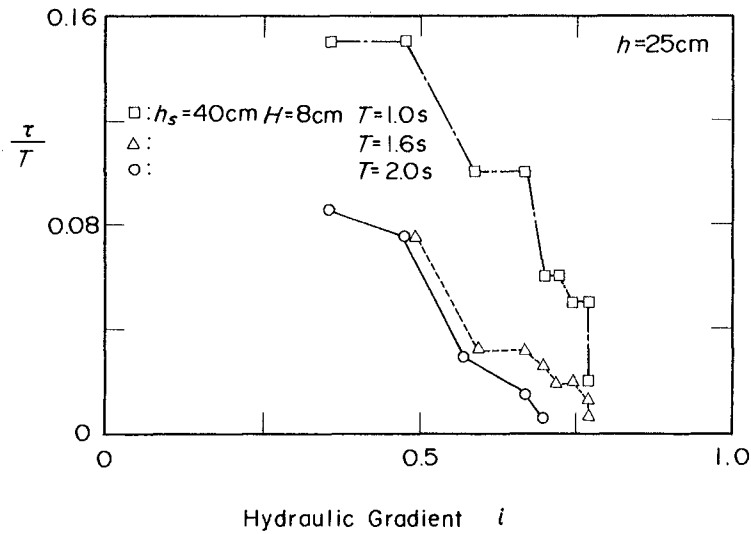


Fig. 13 Phase of Sand Movement

Figure 13 shows the phase of the sand oscillations, which is actually ahead of the wave profile. As the hydraulic gradient increases, the phase difference approaches closer to zero, being about 10% of the wave period when i = 0.5. Obviously these differences in amplitude and phase are closely related to damping of wave energy in a liquefied sand bed.

As will be discussed, wave damping is large when the sand movement is large and its phase difference is close to $90^{o}$. As the wave pressure on the sea bed increases, the sand movement increases and the phase difference approaches close to $0^{o}$. However, wave damping reaches maximum at a phase difference of $90^{o}$, vice $0^{o}$.

## 5. WAVE DAMPING THEORY

### Biot's Equation

Wave damping in a soil bed has been extensively studied. Application of linear wave theory in conjunction with Biot's theory for soil motion (Biot, 1962) is generally considered useful for describing wave damping in a sea bed, even during the occurrence of sand liquefaction.

Figure 14 illustrates the phenomena of wave damping and soil motion, where $U_z(0)$, which is expressed as a complex number, is the amplitude of soil oscillations at the surface. In wave damping theory, the amplitude and phase of $U_z(0)$ determine wave damping.

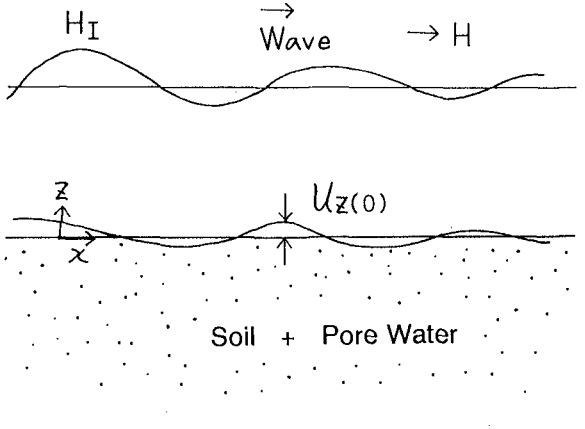


Fig. 14 Wave Damping and Soil Motion

Biot's theory, being is widely used to describe a sand bed filled with water, employs the equations of motion of the sand and pore fluid (see Yamamoto and Takahashi, 1985).

Linear Wave Damping Coefficient

Wave damping on a sea bed can be defined as follows using the linear wave damping coefficient $D_f$:

$$K_t = H/H_I = \mathrm{Exp}\ (D_f\ x) \qquad (1)$$

where $K_t$ is wave transmission coefficient, H the wave height at distance x, and $H_I$ the incident wave height.

$D_f$ for an infinitely deep soil bed can be defined by the imaginary part of the complex amplitude of the vertical oscillation of sand at the surface, and therefore, it can be expressed using (see Yamamoto and Takahashi, 1985):

$$D_f = \rho_f\ g\ \delta^*/(2G^*\ \cosh^2 k_o h\ (1+ 2\ k_o h\ /\sinh 2k_o h)) \qquad (2)$$

where $\rho_f$ is the density of water, g the acceleration of gravity, $k_o$ the wave number, h the water depth, $G^*$ the representative shear modulus, and $\delta^*$ the equivalent damping factor.

It should be realized that $G^*$ and $\delta^*$ are difficult to evaluate. Using the typical wave record in Fig. 8, for example, $D_f$ is 0.35 $m^{-1}$ and the value of $G^*/\delta^*$ is 2700 $N/m^2$. If it is assumed that $\delta^*$ ranges from 0.1 to 100, then $G^*$s ranges from 27 to 27,000 $N/m^2$. However, this value is quite small, and consequently, these parameters should be investigated further.

## 6. CONCLUDING REMARKS

Our major conclusions are as follows:

1) The fundamental characteristics of a liquefied sand bed were experimentally studied, and it was shown that partial liquefaction occurs when pore water is supplied from pipes located at the bottom of sand bed. It was also found that blocks will sink into a sand bed even when a small hydraulic gradient is present. Effective stress analysis using Mohr-Coulomb failure criteria is considered to be better than pore pressure gradient analysis in determining whether a sinking failure will occur.

2) Wave damping due to a liquefied sand bed can be

significant, even at a hydraulic gradient as low as about 0.5. When the water depth is shallow and the sand bed thickness is deep, then wave damping is large. Wave damping can be expressed by Biot's equation using the linear wave damping coefficient.

Our new wave-absorbing system can be employed as a wave barrier designed to produce a calm sea area, and may be especially suitable for damping waves at a harbor entrance. The necessary electrical power for system operation can be supplied from a land-based power generation station or possibly wave power converters. Further work will be directed at researching practical system application.

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