EXPERIMENTAL ANALYSIS OF WAVE-INDUCED LIQUEFACTION IN A FINE SANDBED

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Abstract

A series of experiments were conducted to examine wave-induced liquefaction in a loosely packed fine sandbed, which was specifically used to ensure the presence of residual excess pore pressure. Also observed was the compaction of a liquefied sandbed in response to cyclic wave loading; a phenomenon thought to reduce the possibility of liquefaction. In addition, pore water was supplied from the bottom of the sandbed such that the effect of underground water pressure on liquefaction could be clarified.

1. INTRODUCTION

Wave actions are known to produce the phenomenon of sand liquefaction. One type of sand liquefaction is caused by seepage flow due to differences in water pressure, which typically occurs in the vicinity of a sheet pile (Figure 1), although it can also be caused by waves generating a pore pressure gradient in the sandbed. Such behavior is termed as "momentary wave liquefaction," and has been simulated by Zen *et al.* (1990) using a fluctuating pressure-type liquefaction test apparatus. Another type of liquefaction occurs during an earthquake (Figure 2), where in this case, pore pressure builds up due to shear stress in the sandbed such that the residual pore pressure produces liquefaction. Foda *et al.* (1991) simulated this behavior using a wave flume experiment, while Sekiguchi *et al.* (1995) did so using a centrifuge experiment.

Due to the unusual nature of sand boiling, which can cause devastating failure of coastal breakwaters, elucidating its mechanisms is a key task in breakwater design processes. This led to the present study that describes the results of experiments in which the following phenomena were observed: (1) liquefaction behavior of a loosely packed, fine sandbed due to residual excess pore pressure, (2)

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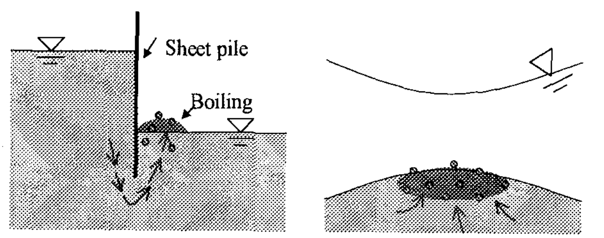
compaction behavior of a fine sandbed due to cyclic wave loading, (3) the softening effect of a fine sandbed due to large standing waves, and (4) liquefaction behavior due to bottom-supplied feedwater.

2.EXPERIMENTAL SETUP

A large wave flume (105 m × 0.8 m)(Figure 3) was used to generate sand liquefaction. Water depth was changed from 0.35 to 1.0 m. The sandbed, which consisted of a mixture of silt and fine sand, was 6.0 m long and 1.0 m deep (Fig. 4). A feedwater system supplied water to the bottom of the sandbed, being used to produce an initially loose sandbed condition and to generate seepage flow liquefaction. The 50% sieve diameter of fine sand was 0.08 mm. We measured water surface displacement and pore pressure in the sandbed. Regular waves were mainly applied to sandbed without a structure, although a caisson was installed in order to investigate a standing wave condition.

The sandbed is equipped with a feedwater system to supply water from the bottom of the sandbed; a system used to produce an initially loose sandbed condition, and to generate seepage flow liquefaction.



Piping failure of sheet pile Momentary liquefaction by waves

Figure 1 Diagrams showing causes of momentary wave liquefaction.

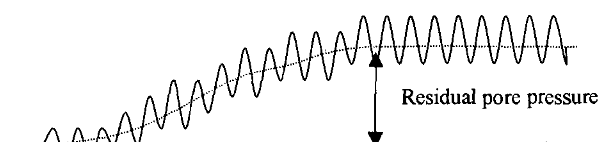


Figure 2 Liquefaction due to residual excess pore pressure.

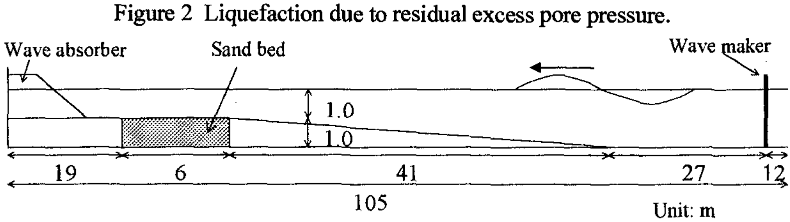


Figure 3 Cross sectional diagram of employed wave flume.

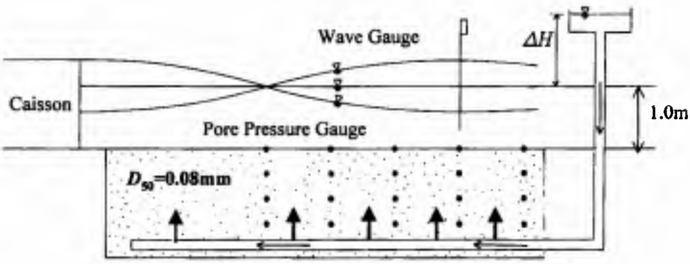


Figure 4 Sandbed model showing measurement locations.

3. EXPERIMENTAL RESULTS

Loose Sand under Progressive Waves

As can be seen in Photo 1, very loose sand behaves like a thick liquid. At the same time, the motion of the sand induces wave breaking and damping. Figure 5 shows typical pore pressures generated in the sandbed, where after just several waves the pore pressure oscillates and rapidly increases due to the wave-induced residual pore pressure. The magnitude of this pressure corresponds to the submerged weight of the sand.

Photo 1 Effect of progressive waves on a loose sandbed.

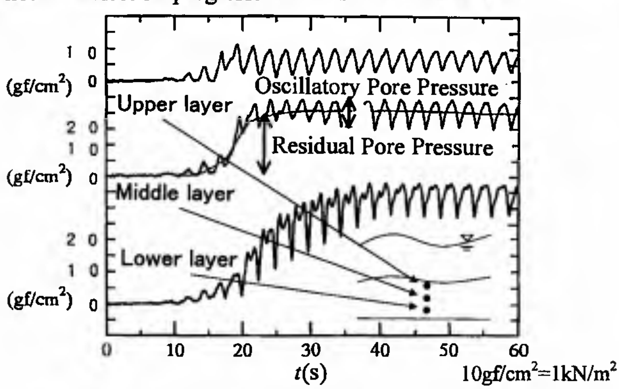


Figure 5 Pore pressure profile in a loose sandbed hit by progressive waves.

In the case of a loosely deposited sandbed (Fig. 6), the weight of sand is supported by both the pore water and the skeleton structure of the sandbed. Thus, when a wave acts on the bed, the sand skeleton structure breaks due to the shear stress such that only the pore water remains for supporting the sand's weight which corresponds to the increase in residual pressure.

It should be noted that this phenomenon only occurs when the permeability of the sand is low, *i.e.*, if permeability is high, such as in a coarse sandbed, the excess pore pressure easily escapes and the increase in residual pore pressure never occurs. Immediately after wave loading, sand boiling occurs (Photo 2) due to the excess pore water being squeezed out from the sandbed up to the sandbed surface. Such boiling is produced by residual pore pressure and lasts 2–3 min.

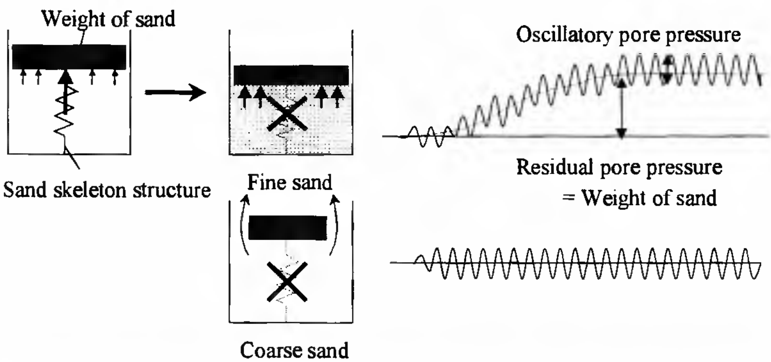


Figure 6 Diagram representing residual pore pressure

Photo 2 Sand boiling phenomenon.

Compaction Due To Cyclic Wave Loading

Because substantial settlement was observed in a fine sandbed, we investigated this compaction effect using series of cyclic loading tests in which a group of monochromatic waves was applied at 10-min intervals (figure 7). Wave period T was 2.08 s, wave height H was 48.8 cm, and each group consisted of 37 waves.

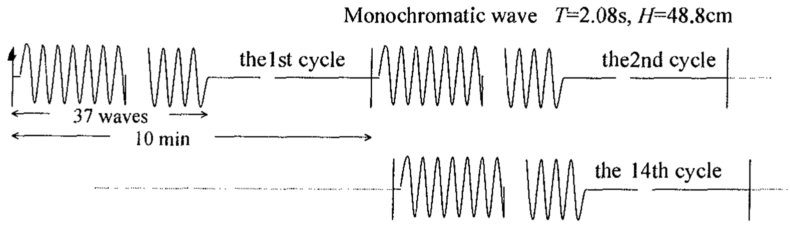


Figure 7 Applied cyclic loading scenario.

Figure 8(a) shows sandbed settlement after applying cyclic loading, where the effect of boiling forces the pore water out of the sandbed such that cyclic wave loading causes the bed to gradually settle. In fact, after the 14th loading, total settlement reaches about 13 cm; a substantial decrease in bed thickness.

Due to the presence of a loose sandbed during the 1st cyclic loading, sand particle motion is very large and vertical displacement is about 9 cm (Fig. 8(b)). However, the ensuing compaction effect with each loading subsequently reduces sand motion such that the 14th loading produces a displacement of only 0.3 mm, after which sand particle movement is not reduced by further loading, although sand ripples do appear such a compacted sandbed.

The compaction effect due to cyclic loading also leads to a reduction in residual pore pressure. Figure 8(b) shows the residual pore pressure P_r at different heights in the sandbed, where P_r gradually decreases such that after the 14th loading it vanishes.

Figure 9(a) shows the oscillatory component of pore pressure produced by 1st-loading water surface oscillations, where pore pressures have nearly the same amplitude and show no time lag. This result indicates that loose sand behaves like a thick liquid. At the 4th loading (Fig. 9(b)), however, a very sharp negative peak appears in the pore pressure, being is due to the "diletancy" effect which will be explained later. At the 14th loading (Fig. 9(c)), it is obvious that pore pressure decreases with respect to the depth of the sandbed, and that a significant time lag is present; an effect produced by compaction of the sandbed.

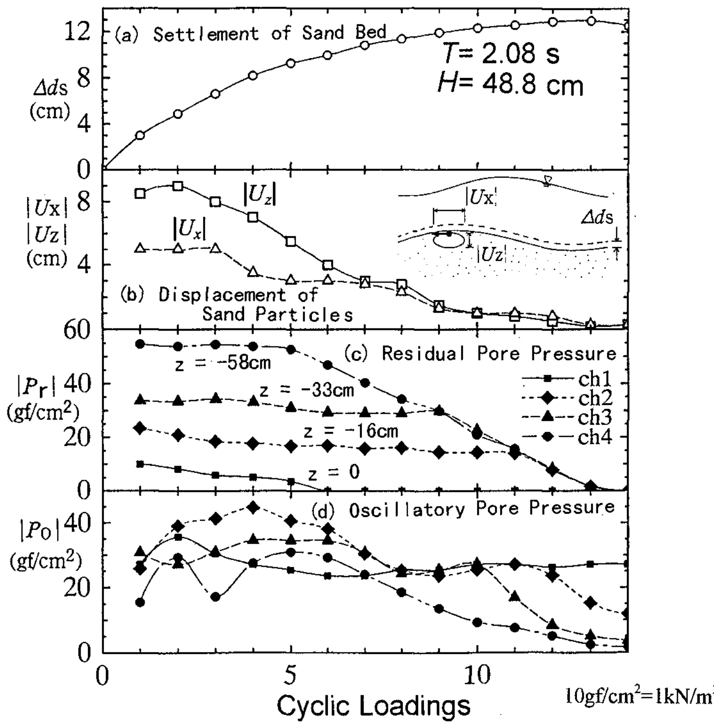


Figure 8 Compaction effect due to cyclic wave loading.

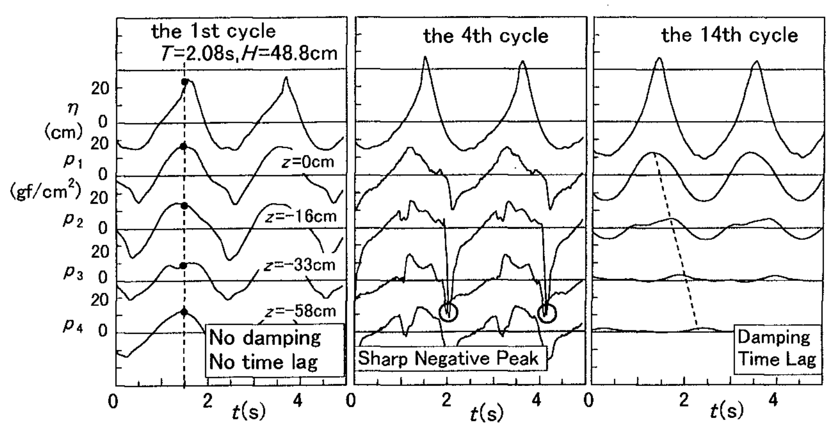


Figure 9 Profile of oscillatory pore pressure.

Sand Particle Motion after Compacted

Figure 10 shows the amplitude of sand particle motion after the sandbed is compacted, where only those waves larger than a certain height produce visible movement of the sand particles. In this case, large long-period waves acting on the sandbed increase sand particle motion and generate a large shear strain which in general results in the sand having small shear modulus. In other words, larger waves soften the sandbed.

When feedwater is applied from the bottom of the sandbed, the amplitude of the sand particle motion becomes much larger. That is, a 200-cm water head makes the sandbed boil and the amplitude of sand particle movement reaches 5 cm.

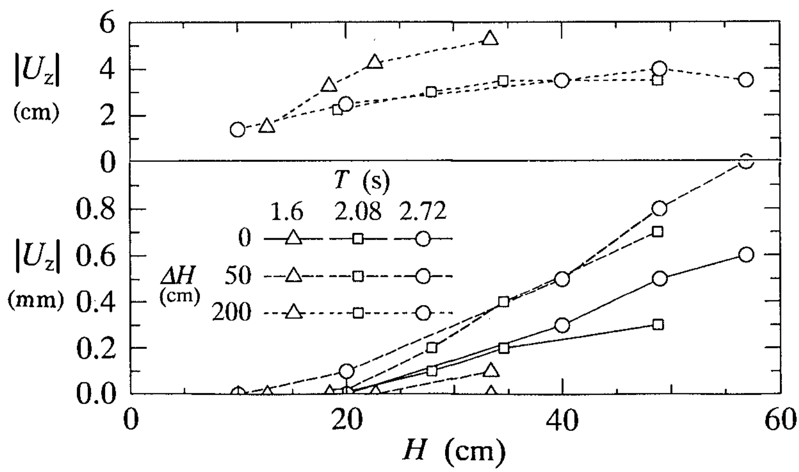


Figure 10 Sand particle movement after sandbed compaction.

Effect of Preceding Loading

Another interesting phenomena that occurred is re-liquefaction of the compacted sandbed. Figure 11 shows the change in residual pore pressure due to cyclic loading, where for smaller waves ($T = 1.6$ s, $H = 12.7$ cm) liquefaction does not occur until the 5th loading and residual pore pressure diminishes. However, after applying larger waves at the 11th loading, liquefaction reappears; a behavior we call "re-liquefaction."

Re-liquefaction probably occurs due to compaction by small waves being limited to near the sandbed surface, whereas the increase in shear stress produced by larger waves is sufficient to once again liquefy the bed. When larger waves were continually applied, the compaction expanded deep into the sandbed.

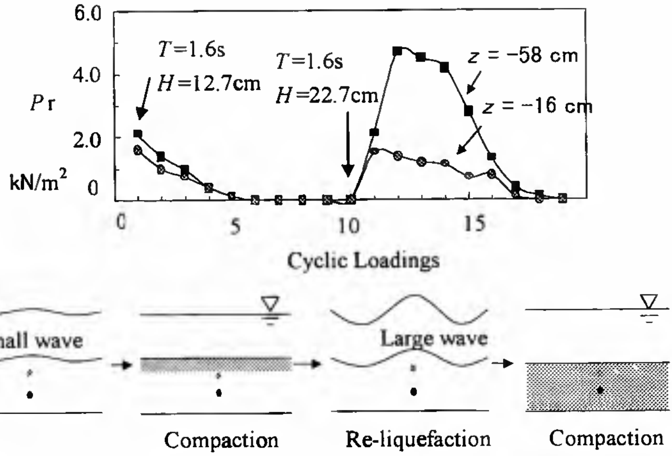


Figure 11 Effect of preceding loading (re-liquefaction).

<u>Loose Sand under Standing Wave</u>

Photo 3 shows a standing wave in front of a caisson model. When the sand bed is loose, it is easily liquefied due to the larger wave pressure compared to that by progressive waves. At the loop of standing wave, sand moves vertically in phase with the movement of surface water and at the node sand moves horizontally in phase with movement of water particles. On the other hand, for a compacted sandbed, its surface moves out of phase, that is lagging by 180 degrees.

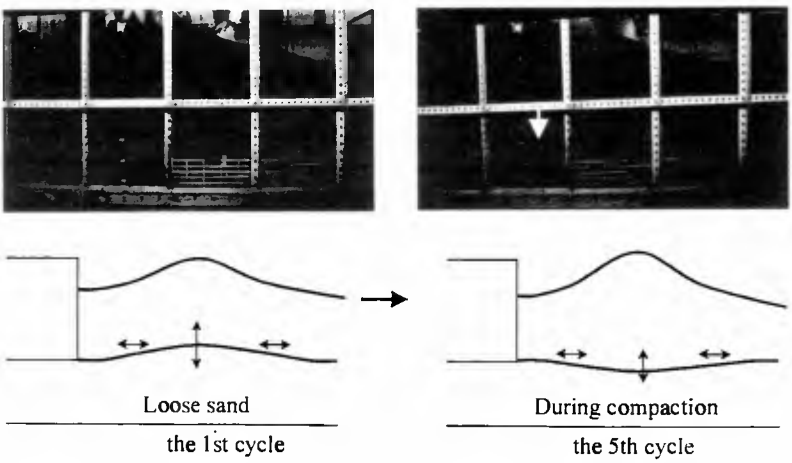


Photo 3 Applied standing wave.

Compaction due to Cyclic Wave Loading (Standing Wave Condition)

Figure 12 shows compaction of the sandbed under standing waves, where residual pore pressures are the same at the node and loop of the wave. On the other hand, oscillatory pore pressure is different. In particular, pore pressure at the node is quite large ($\approx 1.7w_0H$) from the 2nd–5th loading.

Figure 13 shows the oscillatory pore pressure profiles at the node of standing wave, where very sharp negative peaks appear. Since such peaks are not present at the loop of a standing wave, this indicates that they are caused by shear stress at the node of the wave. Such sharp negative pressure is surmised to be caused by the diletancy effect, *i.e.*, shear stress acting on the sand expands the volume of sand containing porous areas which in turn causes sharp negative peaks in pore pressure.

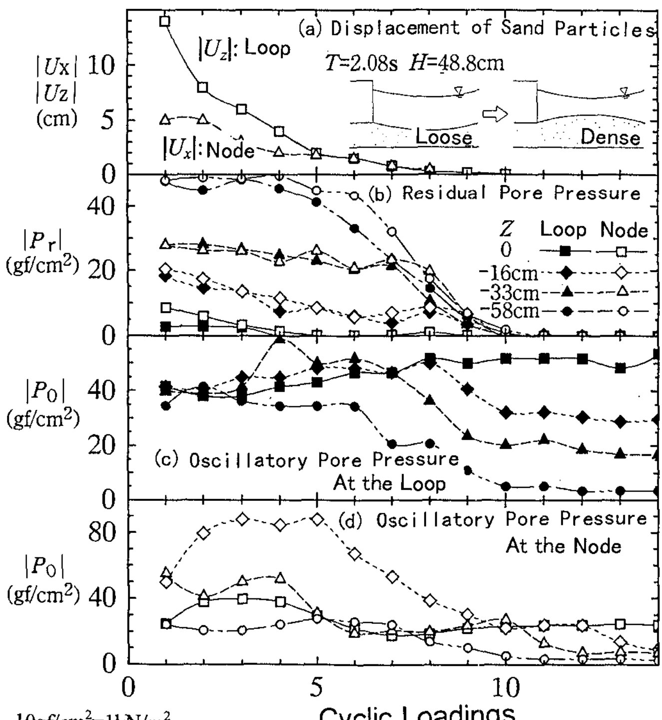


Figure 12 Compaction due to cyclic wave loading by standing waves.

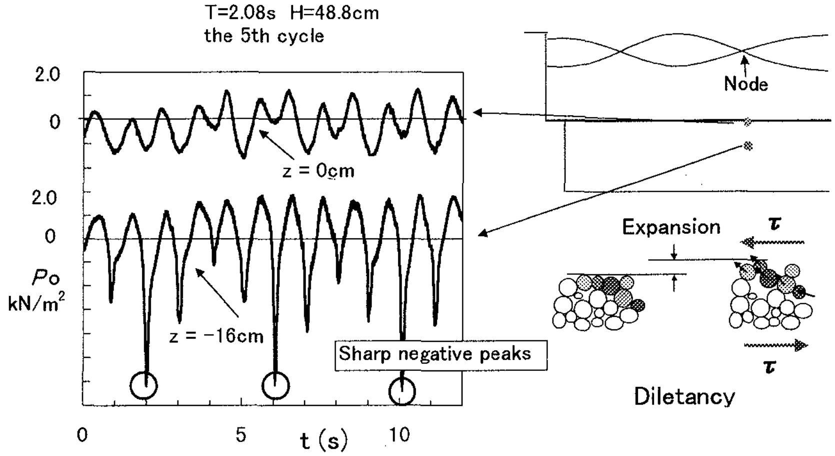


Figure 13 Pore pressure profiles at the node of standing wave at the 5th loading.

Softening Effect

Figure 14 (a)–(c) shows pore pressure profiles at the loop of a standing wave after it hits a fully compacted sandbed. For small waves (14(a)), the pore pressure lags out of phase and is damped out in the direction of sand bed depth; whereas for larger ones (Figure 14(b)), it penetrates deeper into the sand and is in phase. When feedwater is supplied (Figure 14(c)), this phenomena can be seen more clearly in that there is no lagging out of phase and no damping of pressure.

We call this phenomenon the "softening effect" because it exhibits the same characteristic as the shear modulus of soil. Namely, if the shear strain becomes large, the shear modulus of soil is reduced. Large shear strain is generated by strong wave pressure and amplified by upward seepage flow.

4. FEM SIMULATIONS

Using FEM in conjunction with Biot's equations (Park et al (1996)), pore pressure was numerically simulated for a standing wave (T = 2.08 s, H = 48.8 cm). Figure 15(a) shows results for compacted sand in which the strain is small with a large shear modulus G of 10000 kN/m^2, where in this case the oscillatory pore pressure lags out of phase and dampens out in the direction of sandbed depth. Figure 15(b) shows results for lower G = 1000 kN/m^2, a large wave, and feedwater being supplied, where due to the softening effect, pore water penetrates deeper into the sandbed and no time lag or damping occurs. Finally, Fig. 15(c) shows G = 10 kN/m^2 for loose sand, where it should be noted that such substantial lowering of G produces behavior similar to that observed in Fig. 15(b) with feedwater being supplied.

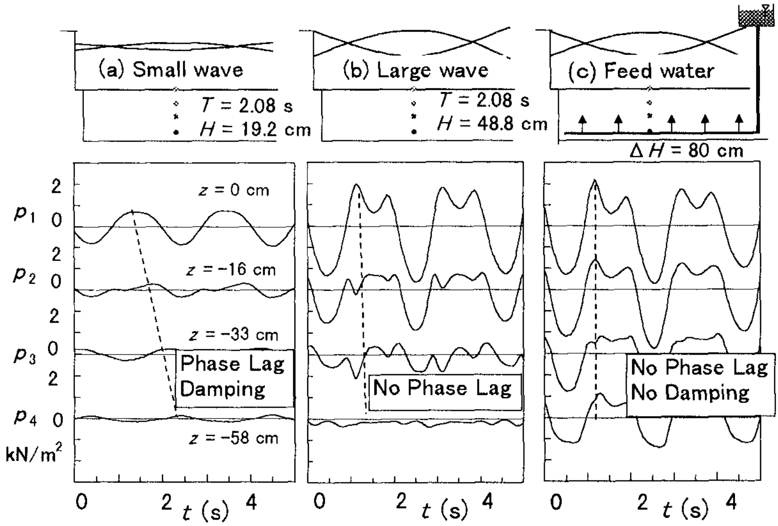


Figure 14 Pore pressure profile at the loop of a standing wave.

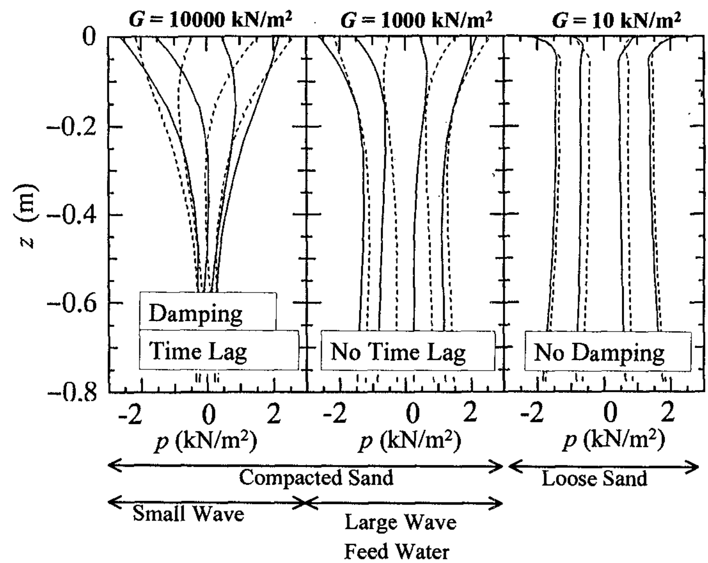


Figure 15 FEM simulation of pore pressure distribution along sandbed depth.

5. SUMMARY

Using model experiments, we observed the following phenomena:

1) When waves act on a loosely packed fine sandbed: (*i*) the skeleton structure of the sandbed easily breaks and it behaves like a thick liquid, and (*ii*) the internal pore pressure builds up within it, *i.e.*, sandbed liquefaction occurs due to the excess pore pressure.

2) Waves acting on a sandbed gradually squeeze out the excess pore pressure such that a compaction effects occurs.

3) For small waves, compaction is limited to near the sandbed surface. However, as the waves get larger, the sandbed is again liquefied and compaction substantially expands into deeper depths.

4) Once fully compacted, large waves produce large shear strain due to a corresponding decrease in the shear modulus, *i.e.*, a softening effect occurs allowing the pore pressure, which is in phase in the direction of sandbed depth, to penetrate deeper into the sandbed.

While it is important to gain experimental insights elucidating the effects of waves acting on a fine sandbed, our future work will be directed at developing methods to quantitatively evaluate the effects of such phenomena; as only in this manner can we assuredly prevent associated damage to coastal breakwaters.

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