DYNAMIC BEHAVIOR OF BED MATERIAL AND LOCAL SCOUR AROUND A CIRCULAR BRIDGE PIER UNDER WAVE AND CURRENT

Md. Faruque MIA[1], Akihiro TSUDA[1] and Hiroshi NAGO[2]

[1]Student Member of JSCE, Graduate Student, Graduate School of Natural Science & Technology, Okayama University (3-1-1, Tsushima-naka, Okayama 700-8530, Japan)
[2]Member of JSCE, Dr. of Eng., Professor, Dept. of Environmental & Civil Engineering, Okayama University (3-1-1, Tsushima-naka, Okayama 700-8530, Japan)

This study presents the dynamic behavior of bed material and local scour around a circular bridge pier under wave and current in a laboratory wave flume. Substantial bridge damages are considered to be occurred not only by the local scour but also by the dynamic instability of the bed material around the bridge pier under the persistent action by water waves. Observations were carried out on the local scour development under clear-water steady flow as well as under wave and current. Waves were generated from upstream side of bridge pier and from downstream side of bridge pier respectively. Observations were further carried out on the excessive pore-water pressure around a circular bridge pier. The results showed that the local scour depths found maximum in the downstream side of the pier for most of the cases under the coexistence of wave and current. The results also showed that the excessive pore-water pressure development decreased the effective stress of the bed material around the pier.

Key Words : *dynamic behavior, pore-water pressure, effective stress, local scour, bridge pier, wave flow*

1. INTRODUCTION

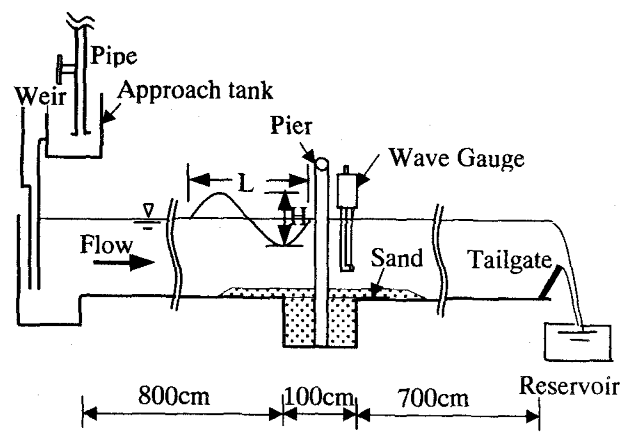
Many researchers (e.g., Breusers et al.[1]), Jain and Fischer[2]), Raudkivi[3]) and Melville and Sutherland[4])) have been developed numerous equations to predict scour at bridge piers, in clear-water as well as movable bed conditions. The equations were developed under laboratory experimental investigations mainly due to steady flow and are used widely in the design purpose. However, substantial bridge damages are so far reported due to floods with unsteady flow. A few number of studies (namely, Saito et al.[5]),. Kawata and Tsuchiya[6]) and Sumer et al.[7])) are found for scouring during unsteady flow. Some field data has reported by Palmer[8]). He measured the rate and magnitude of scour developed around obstructions exposed to oscillatory wave-induced flows. Das[9]) presented a few laboratory tests made on local scour around vertical cylinders in an oscillating flume. Kawata and Tsuchiya[6]) made similar experiments in real waves and further in waves and current. Herbich et al.[10]) has made extensive study on local scour around piles in waves and current. All of their investigations were limited to local scour measurement only, however, dynamic behavior of bed material around the bridge pier is also an important concern for damaging of bridges under the attack of flood waves. Nago[11]) investigated on the dynamic behavior of highly saturated sand bed under oscillating water pressure variation to find out the mechanism of the collapse of hydraulic structures during floods or storm waves. His study concluded that the sand will be removed easily by the flow tangential to the surface and the sand layer will be scoured successively, in the state of sand bed liquefaction. According to the researchers (Nago and Maeno[12]), O'Cornor and Clarke[13]), Sakai et al.[14]), Watson[15]) and Zen and Yamazaki[16])) sand bed around structures experienced under liquefaction due to oscillating water pressure is susceptible to erosion and the structure is liable to collapse. Mia and Nago[17]) stated that the equilibrium local scour becomes greater than that of the clear-water steady flow under the abrupt change of water pressure. Their investigation shows that the local scour is maximum at a stage when the effective stress reduces to zero, i.e.; when liquefaction occurs under the abrupt change of water pressure. The purpose of the present study is to investigate the local scour under wave and current. A series of laboratory scour tests was conducted around a bridge pier by generating waves from upstream of the pier as well from downstream of the pier to know the variation of scour results with time. Furthermore, in order to enlighten the underlying mechanisms responsible for the scour, a pore-water pressure measurement was made to know the effective stress condition of the bed layer around the bridge pier under wave and current.

2. EXPERIMENTAL SET UP

The experiments to study the wave-induced dynamic behavior of bed material and local scour around a bridge pier were conducted in a flume 1600cm long, 60cm wide and 40cm deep. Water was conveyed to the flume from an elevated tank by a pipe through an approach channel to measure the discharge by means of a sharp crested weir. The working section, 100cm long, 60cm wide and 57cm deep was located 800cm downstream from the entrance of the flume where the pier was located. This section was filled with the sediment of mean sand diameter 0.25mm below the bed level and the bed was flattened with the same size of the sediment used in the test section. Fig.1 shows the side view and plan view of the channel with working section. Fig.2 shows the location of sensors in the sand layer for pore-water pressure measurement in the sediment bed around the bridge pier. The pier was placed centrally and vertically in the working section. The valve was slowly adjusted without causing any disturbance to the bed material until the desired discharge was reached to the flume and the required depth was obtained by controlling the tailgate. When the desired flow conditions were established then the wave was added on to the steady flow using a plunger type wave generator. The scour depths were recorded with time in the front side of the pier as well as back side of the pier. The observations were performed for the conditions of steady flow, wave generated from upstream of the pier and wave generated from downstream of the pier.

The experimental conditions are summarized as:

(a) At first, steady flow conditions of clear-water were established and the scour depths (d_s) were recorded with time.
(b) The wave was added on to the steady flow from upstream side of the pier as well as from downstream side of the pier. The scour depths were recorded for the conditions.



(a) Side view of the flume

(b) Plan view of the flume

Fig.1 Schematic diagram of the experimental flume

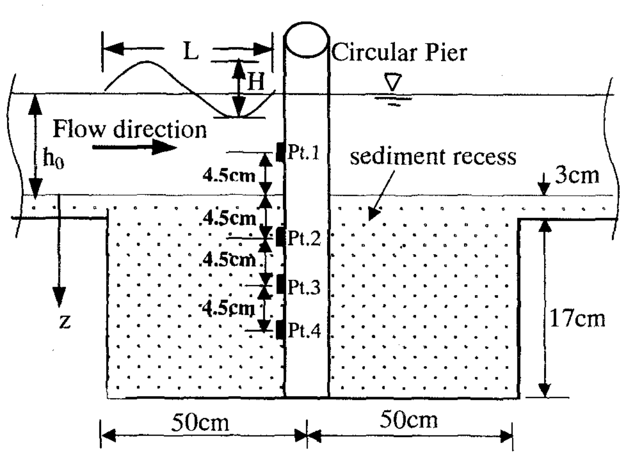


Fig.2 Location of pressure transducer

(c) Development of the excessive pore-water pressure was observed under wave pressure.
(d) In order to investigate the effect of wave strength on the development of pore-water pressure and local scour, the experiments were conducted with different wave heights.
(e) Uniform sediment was used with the mean sand diameter d_{50} = 0.25mm and the geometric standard deviation σ_g = 1.2. The porosity was assumed as 0.40.
(f) The size of the pier was used 6.0cm in diameter (10% of the flume width). This was selected as maximum as possible in size for ease of placement of the pressure transducers with considering minimum flow blockage effects.
(g) The flume bed slope was 1/500.

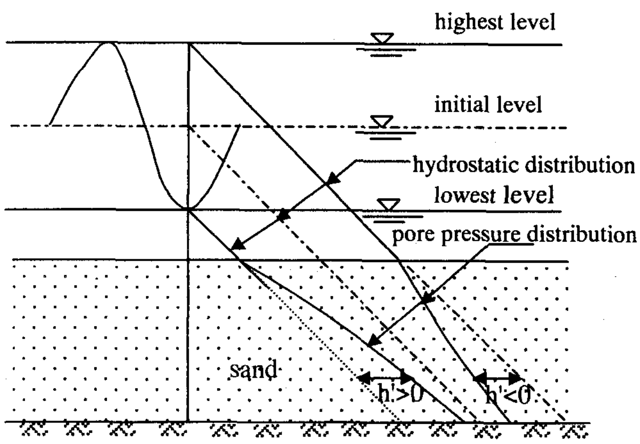


Fig.3 Definition sketch of pore water pressure

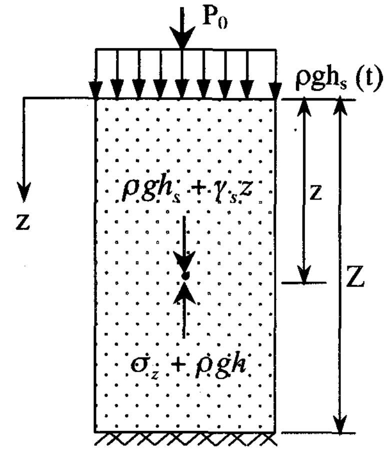


Fig.4 Sand layer under water pressure variation

3. PORE WATER PRESSURE AND LIQUEFACTION CRITERIA

When the water level is subjected to a rapid change from initial water level, a total stress variation is introduced in the underlying sediment bed. Fig.3 shows the concept of the pore pressure change from the initial state of the hydrostatic pressure in the sand bed. The sand bed may be weakened when the pore-water pressure becomes greater than the hydrostatic pressure (h'>0). The weakened sand near the surface will remove easily by the shear stress of flow and the scour around the structures placed in such conditions will progress much more.

The relation between the effective stress and the pore-water pressure can be equated to the downward acting force of water pressure variation and the weight of constituents of sand on the plane of contact of bed. Considering a sand layer at depth z of a saturated sand column of height Z as shown in Fig.4, it can be expressed that,

$$\sigma_z + \rho g h = \gamma_s z + \rho g h_s \tag{1}$$

The pore-water pressure $\rho g h$ and the weight of the sand column above the plane of contact $\gamma_s z$ can be expressed as follows:

$$\rho g h = \rho g \left(h_s + z + h'\right) \tag{2}$$

$$\gamma_s z = \rho_s g z (1-\lambda) + \rho g z \lambda_w \tag{3}$$

where, σ_z = effective stress; h = pore-water pressure in head (variation from hydrostatic pressure relative to mean water level); $\rho_s g$ = weight of unit volume of the individual sand grain; h_s = water pressure on bed surface; h' = excessive pore-water pressure; z = depth of the sand layer measured from top of the sand surface as datum; ρ_s = density of sand; ρ = density of water; g = gravity due to acceleration; λ_w = porosity of water part; and λ = porosity of the sand column ($\lambda = \lambda_w + \lambda_a$, λ_a = porosity of air part)

Substituting equations (2) and (3) into equation (1), and assuming $\lambda_w \cong \lambda$, the following relationship can be obtained:

$$\sigma_z + \rho g h' = \left(\rho_s - \rho\right) g z (1-\lambda) = \text{constant} \tag{4}$$

The non-dimensional effective stress σ_z' can be expressed as the form:

$$\sigma_z' = \frac{\sigma_z}{\left(\rho_s - \rho\right) g z (1-\lambda)} = 1 - \frac{\rho g h'}{\left(\rho_s - \rho\right) g z (1-\lambda)} \tag{5}$$

when σ_z' becomes zero, the sand layer above the depth z is in liquefied state.

4. RESULTS AND DISCUSSIONS

The experiments were performed for clear-water steady flow to observe the equilibrium local scour depth. Then waves were added onto the steady flow from upstream side of the pier as well as from downstream side of the pier to observe the wave effects on local scour over steady flow. The development of pore-water pressure was also measured around the pier under water pressure variations. Table 1 shows the summary of the experimental details. The 5th and 6th columns indicate the fully developed scour depth in the front

Table 1 Summary of experimental details.

Exp. No. (1)	Q (l/s) (2)	h_0 (cm) (3)	H (cm) (4)	d_s (cm) Front (5)	d_s (cm) Back (6)	
1	40	25	4	6.4	6.0	Wave from upstream of pier
2	40	25	5	6.7	7.0	
3	40	25	6	6.3	6.5	
4	45	27	4	5.3	5.0	
5	45	27	5	5.7	5.7	
6	45	27	6	6.2	6.1	
7	40	25	4	7.5	6.9	Wave from downstr-eam of pier
8	40	25	5	8.1	8.2	
9	40	25	6	7.4	7.5	
10	45	27	4	6.6	5.4	
11	45	27	5	7.0	7.6	
12	45	27	6	8.3	8.8	

side and in the back side of the pier respectively corresponding to each case. First, the scour data were collected for clear-water steady flow. Then, the wave was added on to the same condition of steady flow from the upstream end of the flume by using a plunger type wave generator. Again, the same observations were performed just adding the wave from downstream end of the flume. Fig.5 shows the graphical representations of scour depth development with time in the upstream side of the bridge pier for several cases studied. Some cases show that when waves are generated from upstream of the bridge, the development of scour depth is smaller than that of clear-water steady flow. Whereas some cases show that the scour depths with time are higher when waves are generated from downstream of the bridge pier. Fig.6 shows the graphical representations of scour depth with time measured in the downstream face of the pier for the same cases. Most of the cases show that the scour depths are greater when waves are generated from downstream end of the flume. The sediments in the near surface layer losses its shearing capacity due to the development of pore-water pressure as it decreases effective stress of the sand layer under the action of wave loading. As a result, when waves are generated from upstream of the pier some sediments enter into the scour hole from the upstream of the channel by the combined tangential velocity of wave and current which reduces the scour depth than that of steady flow. On the other hand, when waves are generated from downstream of bridge pier the tangential velocity of wave opposite to the current retards the loosen particles to enter inside the scour

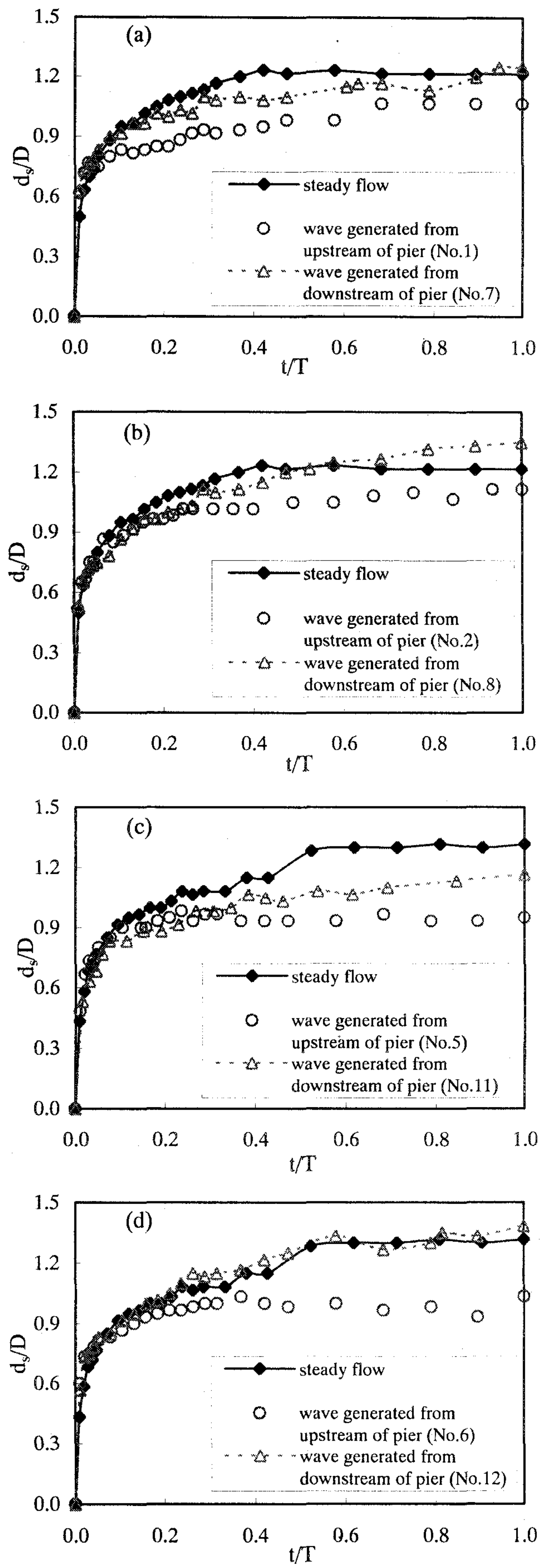


Fig.5 Scour depth with time in the upstream side of the pier

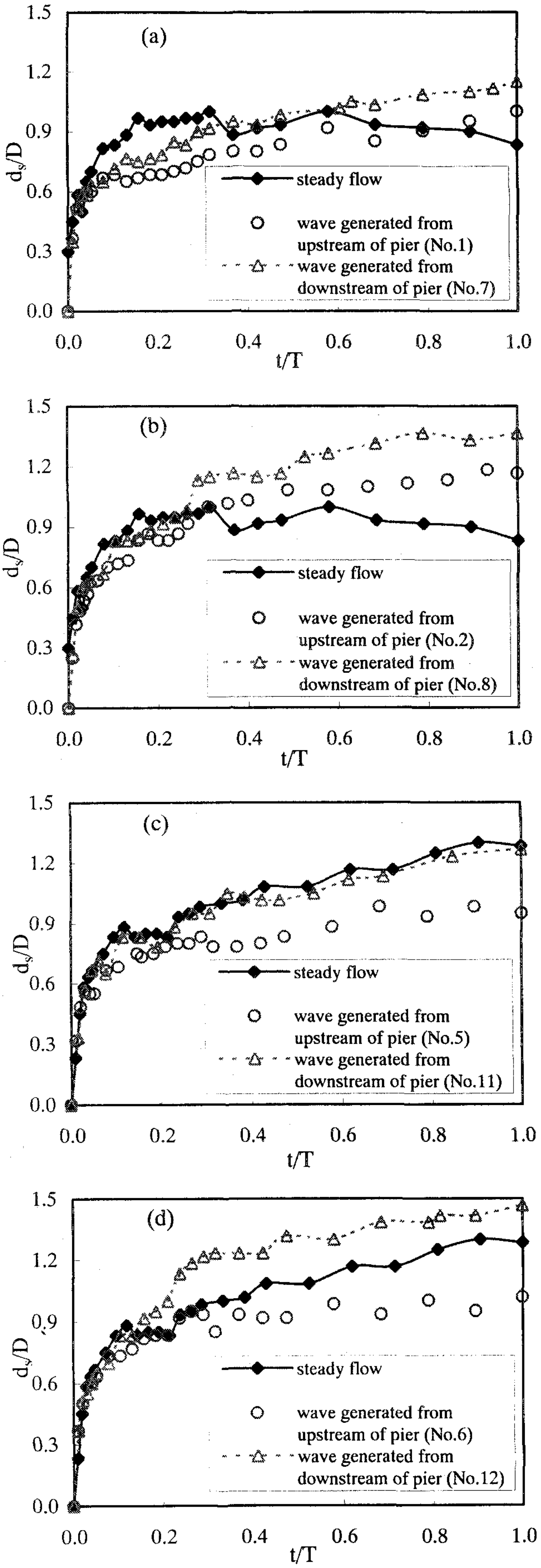


Fig.6 Scour depth with time in the downstream side of the pier

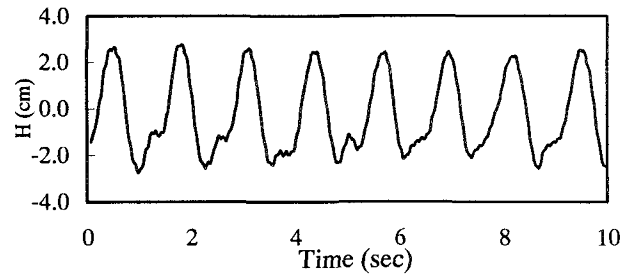


Fig.7 Profile of water surface variation

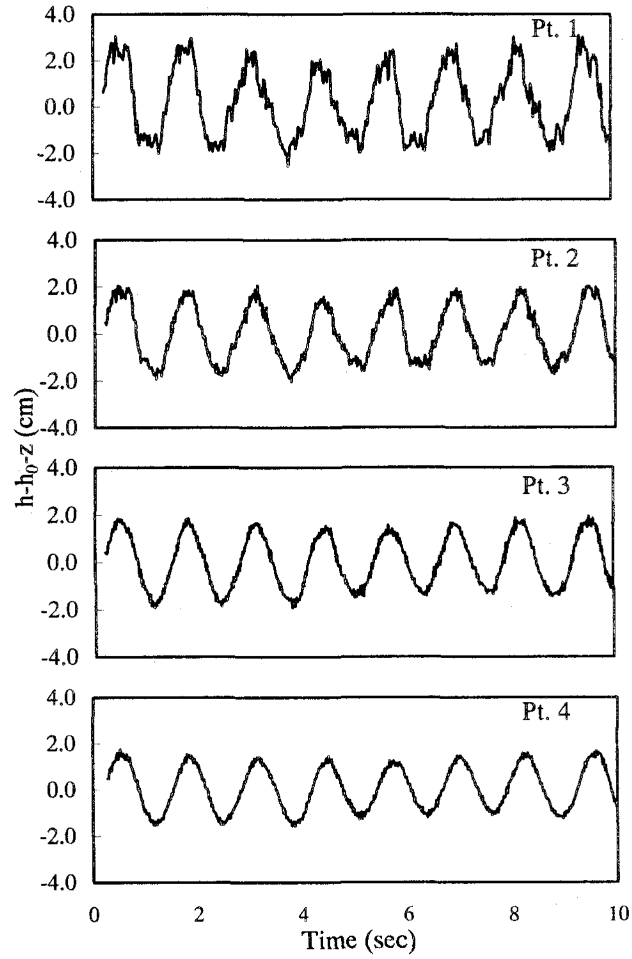


Fig.8 Time history of pore-water pressure at pier

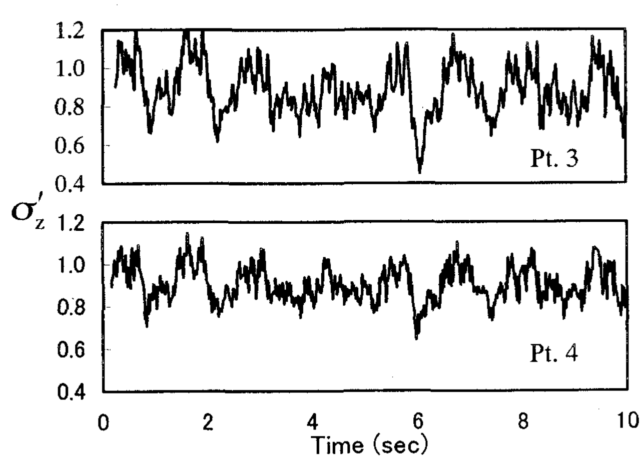


Fig.9 Non-dimensional variation of effective stress

hole. Also, the formation of horseshoe vortex by the waves at the downstream face of the pier accelerates the sediments to dislodge away from the scour hole. Therefore, scour depths are observed larger in some cases for waves generated from downstream side. In Fig. 6(a) and (b), scour depths are larger than that of steady flow in case of waves are generated from upstream side of the pier whereas these are smaller in Fig. 6(c) and (d). These differences depend on the flow intensity, wave strength and wave direction. The mehanism of dynamic behavior of sediments is discussed with Figs. 7 to 9. Fig.7 indicates the variation of wave profile for the wave height (H) of 5cm and time period 1 sec. In this case, the discharge was supplied 45 l/s and the mean depth was maintained 27cm. Fig.8 shows the time history of the change of pore-water pressure corresponding to each located points under water pressure variation. The pore-water pressure was recorded at a stage of scour depth 6cm. Therefore, Pt.2 was exposed in the water inside the scour hole. The effective stress condition of the bed material is calculated using Eq.5. If there is no development of excessive pore-water pressure, the last term of right hand side of Eq.5 will be equal to zero. That is, σ_z' =1 means the state that the effective stress at a depth z, σ_z , is balanced by the weight $(\rho_s-\rho)gz(1-\lambda)$. And this criterion states the stable condition of the bed materials. Fig.9 gives the non-dimensional effective stress condition at Pt.3 and Pt.4. The results show that the effective stress is reduced by a certain amount. A value for σ_z' smaller than 1 indicates the partial liquefaction of the sand layer. The sand layer such a condition near the surface can be considered to become weak and to be removed easily by the shear stress of water flow and the scour around the structures experienced this phenomenon will progress much more than that of the steady flow.

5. CONCLUSIONS

The following conclusions are drawn based on the maximum similarities of the experiments:

(1) The equilibrium local scour depth decreases due to adding of waves onto a steady flow from upstream side of the pier whereas it increases when waves are added from downstream side of the pier.

(2) The equilibrium scour depth shows larger in magnitude than that of steady flow at the back side of the pier especially when waves are generated from downstream side of the pier.

(3) The excessive pore-water pressure develops around the bridge pier under wave action and the sand layer decreases its effective stress up to a certain amount depending on the amplitude of the wave.

(4) Due to the formation of weaken sand bed under persistent action of wave flow, the sediments remove easily by the shear stress of water flow.

ACKNOWLEDGEMENT: This research was supported by a Grant-in-Aid for Scientific Research (B)(1) (2000, No.12450202) from the Japanese Ministry of Education, Science, Sports and Culture. The authors are grateful for this support.

REFERENCES

1) Breusers, H. N. C., Nicollet, G. and Shen, H. W.: Local scour around cylindrical piers, *J. Hydr. Res.* Vol.15(3), pp.211-252, 1977.
2) Jain, S. C. and Fischer, E. E.: Scour around circular bridge piers at high Froude numbers, No. FhwA-RD-79-104, 1979.
3) Raudkivi, A. J.: Functional trends of scour at bridge piers , *J. Hydr. Engrg., ASCE*, Vol.112, No.1, pp.1-13, 1986.
4) Melville, B. W. and Sutherland, A. J.: Design method of local scour at bridge piers, *J. Hydr. Engrg., ASCE*, Vol.114(10), pp.1210-1226, 1988.
5) Saito, E., Sata, S. and Shibayama, T.: Local scour around a large circular cylinder due to wave action, *Proc., 22nd Int. Conf., Coastal Engrg*, Delft, 1990.
6) Kawata, Y. and Tsuchiya, Y.: Local scour around cylindrical piles due to waves and currents combined, *Proc., 21st Int. Conf., Coastal Engrg*, 2, 1310-1322, 1988.
7) Sumer, B. M., Fredose, J. and Christiansen, N.: Scour around vertical pile in waves, *Proc., ASCE*, Vol.118(1), pp.15-31, 1992.
8) Palmer, H. D.: Wave-induced scour on the sea floor, *Proc. of the Civ. Engrg. in the Oceans II, ASCE*, pp.703-716, 1969.
9) Das, M. M.: A literature review on bed-load transport due to wave action and localized scour in non-cohesive sediments, *Final Report* HEL 21-6, University of California, Berkeley, Calif., 1970.
10) Herbich, J. B., Schiller, Jr. R. E., Dunlap, W. A. and Watanabe, R. K.: Seafloor Scour, Marcel Dekker, Inc., New York, N.Y., 1984.
11) Nago, H.: Liquefaction of highly saturated sand layer under oscillating water pressure, *Mem. of the School of Engrg., Okayama Univ.*, Japan, Vol.16(1), pp.91-104, 1981.
12) Nago, H. and Maeno, S.: Dynamic behavior of sand bed around structure under wave motion, *Mem. of the School of Engrg., Okayama Univ.*, Japan, Vol.21(1), pp.81-91, 1986.
13) O'Cornor, B. A. and Clarke, C. S. J.: The dishpan scour problem, *Proc., 3rd Indian Conf., Ocean Engrg.*, Bombay, Vol.2, J1-J12, 1986.
14) Sakai, T., Hatanaka, K. and Mase, H.: Wave-induced stresses in sea bed and its momentary liquefaction, *Proc., ASCE*, Vol.118, (WW2), pp.202-206, 1992.
15) Watson, T. N.: Scour in the North Sea, *J. Petroleum Technology*, 26(3), 1979.
16) Zen, K. and Yamazaki, H.: Wave-induced liquefaction in a permeable sea bed." *Rep. of the Port and Harbour*, Res. Inst., Japan, Vol.6, pp.155-192, 1993.
17) Mia, M. F. and Nago, H.: Prediction of bed liquefaction and local scour around a bridge pier under abrupt water pressure change, *Proc., International Symp., Scour of Foundations*, Melbourne, Australia, pp.23-37, 2000.

(Received October 1, 2001)