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EFFECT OF LIQUEFACTION ON LOCAL SCOUR AROUND A CIRCULAR BRIDGE PIER UNDER SUDDEN WATER PRESSURE DROP

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This paper presents experimental results carried out in a laboratory channel to investigate the effect of bed liquefaction on local scour development around circular bridge pier under sudden water pressure variation. Many hydraulic structures collapse due to scouring under sudden attack of flood flows or storm waves. During such a natural conditions, the water level rises abnormally above its initial level and then decreases to its original level. This phenomenon creates abrupt change of water pressure variation near the structures and cause to failure due to scouring. Considering such a real occurrence in the hydraulic engineering field, this paper deals with the distribution of pore water pressure, effective stresses, velocity distribution and local scour around a circular bridge pier. The results show that the sediment bed is liquefied by an increase of excess pore water pressure under sudden water pressure variation and that the equilibrium local scour increases considerably than that of clear-water steady flow at the bridge pier.

Key Words : *bed liquefaction, pore water pressure, effective stress, local scour, bridge pier, water pressure variation*

1. INTRODUCTION

Many researchers have attempted to develop the equations for the prediction of maximum local scour depth for steady flow. Most of the theories were developed considering the scouring parameters as fluid, flow, bed materials and the geometry of the pier. The main factors for the analysis of local scour are flow velocity, flow depth, sediment size, sediment gradation, pier shape, and pier alignment considered by Melville and Sutherland[1)], U.S. Department of Transportation[2)], Hancu[3)], Laursen and Toch[4)], Shen et al.[5)] Breusers et al.[6)], and Jain and Fischer[7)]. The equations developed considering these factors have been used widely in the design purpose. However, during most floods, the streambed is live and the flood flow is unsteady with an abrupt rise of water level. A few number of studies are attempted for scouring during unsteady by Saito et al.[8)], Kawata and Tsuchiya[9)], and Sumer et al.[10)]. Major structures collapse due to scouring during the rapid decrease of flood water level. Since a sharp rise and sudden decrease of water level occur, the flow changes sub-critical to super-critical state. This phenomenon occurs sudden change of water pressure variation near the structures and the development of liquefaction into the sand bed by an increase of excess pore water pressure which is susceptible to erosion and liable to the failure of structures. Over the past 30 years, a numerous laboratory investigations of local scour around structure have been reported in the hydraulic engineering literature. Nevertheless, there is no unifying theory to use with confidence for safe and economic design yet. There is considerable uncertainty in the use of the various existing scour depth formulae to predict scour in the field settings. Nago[11)] investigated the mechanism of the dynamic behavior of sand bed under oscillating water pressure variation with a view of the collapse of hydraulic structures. He studied the influence of the properties of the oscillating water pressure and the sand layer on the characteristics of the liquefaction for the explanation of the local scouring mechanism. The pressures due to the surface waves are transmitted into the sand bed and they give rise to horizontal and vertical pressure gradients, which encourage liquefaction, by Zen and Yamakazi[12). Nago and Maeno[13) stated that the strength of the sand bed decreases notably and the unstable zone will occur during the crest or the trough being in front of the structures. Sakai et al.[14) suggested that an important mechanism that makes the bed surface layers more susceptible to erosion is bed liquefaction. According to Zen and Yamakazi[12), liquefaction is considered to be important for estimating scour at, and hence the stability of, coastal structures (Scour at marine structures[15)). A bed is in liquefied state when the effective stress of it becomes zero (Nago[11)). This has two effects: (1) it removes the capacity of the bed to support a normal load (zero bearing capacity) and (2) it makes the bed much more susceptible to erosion by waves and currents because of the reduced intergranular friction. Mia and Nago[16) mentioned that the failure of structures during flood flows due to scouring can be considered close relation to the dynamic behavior of bed material around the structures under abrupt change of water pressure. Under variation in the water pressure normal to the surface of the sand bed, the pore pressure changes with time, and excess pore pressure occurs. An increase in the excess pore pressure produces a decrease in the effective stress of the bed material (Nago and Maeno[17)). In the state of sand bed liquefaction, it is expected that the liquefied sand will remove easily by the flow tangential to the surface, and the sand layer will be scoured successively (Nago[11)). Therefore, the determination of the dynamic mechanism of this decrease in the effective stress, that is, formation of liquefaction, is considered to be very important for the design of hydraulic structures under variation in water pressure. An extensive scour around the marine structures such as platforms, bridges, subsea templates and so on may reduce its stability due to the action of waves and currents, thus leading to its failure. In this study, we discussed the fundamental characteristics of the pore water pressure distribution, decrease in the effective stress, that is, liquefaction and their effect in the development of local scour around a circular bridge pier under sudden water pressure variation using a laboratory model. The factor "effect of bed liquefaction" can be a very important mechanism for the estimation of local scour and design of hydraulic structures against failure of scour.

2. EXPERIMENTAL SET UP

The experiments to study the effect of bed liquefaction on the local scour around a circular bridge pier model were conducted in a flume 1600cm long, 60cm wide and 40cm deep, located in the Hydraulics Laboratory of Okayama University, Japan. Fig.1 shows the side view and top view of the channel with working section. 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 flow rate in the flume was adjusted by controlling a valve in the pipe. Then the corresponding head over the sharp crested weir was measured for the supplied discharge value. The depth of water was being changed by controlling the tailgate. 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 particle size 0.25mm below the bed level and the bed was flattened with the same size of the sediment used in the test section. Before the start of the experiments for the variation of scour depth measurement with time, the working section and the bed was made level. The pier was placed centrally and vertically in the working section. Then the leveled area around the pier was covered with 3-mm thick acrylic sheet. 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. The steady flow conditions were adjusted slowly at least by 5 minutes. When the expected flow conditions were established the acrylic sheet was removed very carefully that ensures no scouring occurred around the pier due to this operation. The scour depths

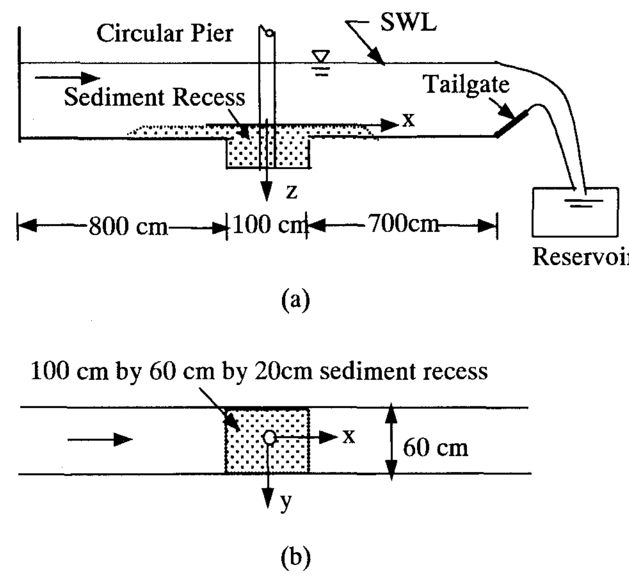

Fig.1 Channel bed: (a) side view, (b) top view

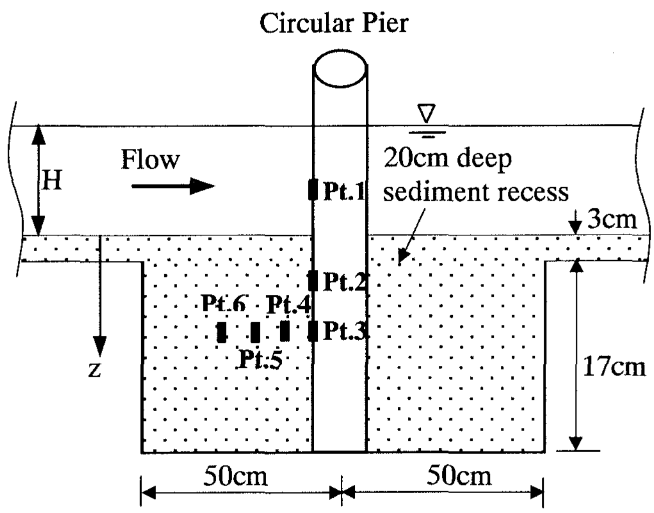

Fig. 2 Location of sensors for pore pressure observation

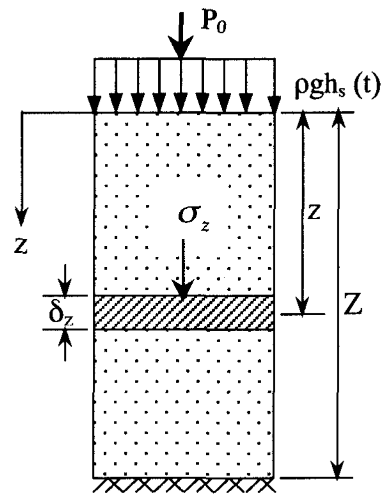

Fig.3 Sand layer under water pressure variation

were recorded from a reading scale attached to the wall of the pier relative to the initial bed against time. Six transducers were connected to the amplifier to record the digital data of pore pressure around the bridge pier. Three transducers were set directly to the wall of the pier vertically at a distance of 4.5cm apart and the rest three were set horizontally at a distance of 3cm apart each at a depth of 9cm from the top of the sediment recess (Fig.2). The average of at least 9,000 samples processed by a computerized data acquisition system at 50 Hz was taken by a digital recorder at each measured point.

The experimental conditions that were maintained in the laboratory can be summarized as following steps:

(a) At first, steady flow conditions of clear-water were established and the scour depths (d_s) were recorded against time.

(b) To investigate the effect of pore pressure and the effective stress in the bed material around the pier, the depth of flow was risen relative to the normal depth.

(c) The sudden drops were allowed at a stage when the equilibrium local scour around the pier was almost reached.

(d) In order to investigate the effect of pressure drop size, the experiments were conducted with sudden pressure drops of different variations.

(e) Excess local scour over clear-water steady flow was observed and data for pore water pressure were recorded.

(f) Uniform bed materials were used with the mean particle size of 0.25 mm and the porosity was assumed as 0.40.

(g) The size of the pier was used 6.0 cm in diameter (D).

(h) Bed materials were placed as a 3-cm thick layer in the flume bed with a bed slope of 0.002.

3. EQUATIONS FOR EFFECTIVE STRESS AND LIQUEFACTION CONDITION

The pore pressure and the effective stress in the sand bed can be analyzed by the method used to analyze ground water problems in an elastic acquifer. Here, the experimental explanation of the sand bed behavior under water pressure variation is expressed by using the following equations. A saturated sand column of height Z is shown in Fig.3 under water pressure variation.

Considering a sand layer at depth z, 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 (Nago[11]). That is,

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

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 : variation of water pressure acting on the surface of the bed relative to the initial water level

h' : excess 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

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 $\lambda_w \cong \lambda$,

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

Thus, the liquefaction state can be expressed by:

$$\frac{\sigma_z}{(\rho_s-\rho)gz(1-\lambda)} = 1 - \frac{\rho g h'}{(\rho_s-\rho)gz(1-\lambda)} = 0 \quad (5)$$

4. EXPERIMENTAL DETAILS AND SCENARIO OF THE OCCURRENCE OF SCOUR

Table1 shows the experimental details. The Shields diagram was used to determine critical shear velocity, u_{*c}, against mean grain size, d_{50}. The relation between critical shear velocity and mean grain size can be expressed as:

$$u_{*c} = 0.03 d_{50}^{1/2} \quad (6)$$

where, u_{*c} is in m/s, and d_{50} is in mm.

Critical shear velocity can be converted into critical mean flow velocity (U_c) by using the following logarithmic expression of the velocity profile:

$$\frac{U_c}{u_{*c}} = 5.75 \log\left(5.53 \frac{h_0}{d_{50}}\right) \quad (7)$$

where, h_0 = flow depth.

Fig.4 is the schematic phases for the scenario of the occurrence of scour under sudden pressure drop around bridge pier. Each of the experiments were run for clear-water steady flow to confirm the maximum equilibrium local scour depth and then water level was risen from the initial stage to a high stage. When equilibrium scour depth was reached, water level was allowed to drop from the high stage to the initial stage. The scour depth and pore water pressure measurements were recorded carefully during the application of sudden pressure drop. The

Table 1 Experimental details

Ex. No. (1)	Depth (h_0) (cm) (2)	U/U_c (3)	Before drop (d_s) (cm) (4)	Pressure drop ($H-h_0$) (cm) (5)	Increased (d_s) (%) (6)
P1	20	1.060	7.1	10	9.9
			7.4	15	12.2
P2	20	0.928	7.1	10	9.9
			7.3	15	9.6
P3	20	0.795	6.5	15	16.9
P4	15	0.914	7.3	10	9.6
			7.2	15	13.9
P5	16	0.850	6.6	11	13.6
			6.8	15	17.6
P6	15	0.914	7.2	12	13.9
			7.2	16	16.7

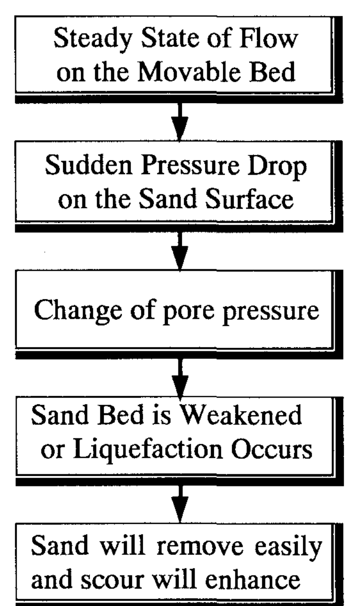

Fig.4 Scenario of the occurrence of scour under sudden pressure drop

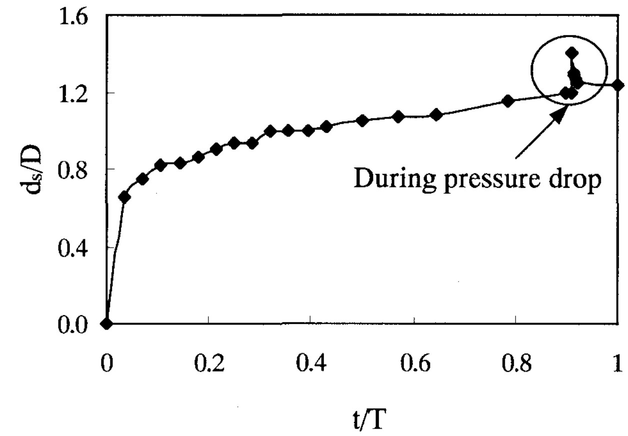

Fig.5 Variation of scour depth with time

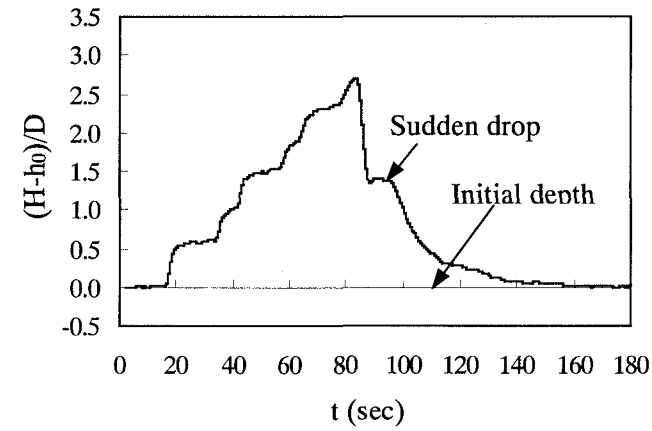

Fig.7 Variation of water surface profile

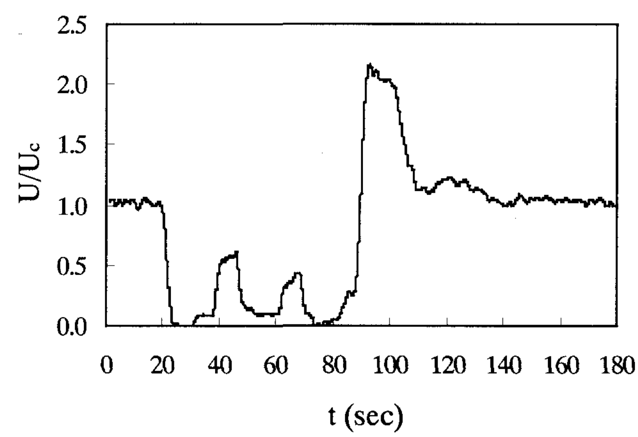

Fig. 6 Ratio of U/Uc with time

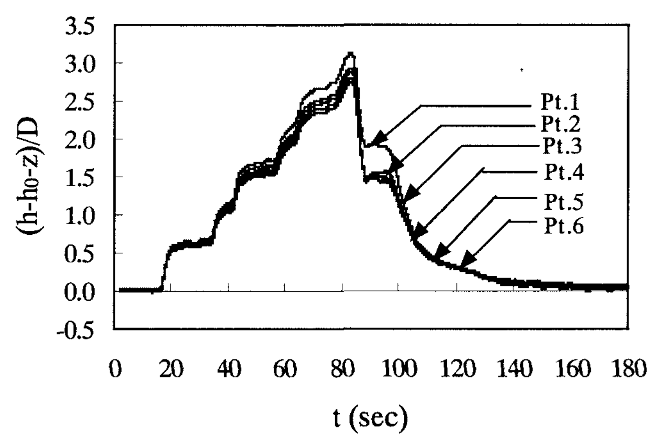

Fig.8 Pore water pressure variation

increased scour depths due to the corresponding sudden hydraulic drops have been shown in the Table1.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

The results for the phenomenon of 16cm sudden hydraulic drop for experiment no. P6 has chosen for the discussion. The experiments for the other conditions also show the similar results. Fig.5 is the scour depth variation with time for clear-water steady flow and the position of the circle expresses the excess development of the scour depth to that of the steady flow for the sudden drop of water pressure. This is happened due to introduce of the excess pore water pressure and the formation of liquefaction into the sand surface. Fig.6 represents the ratio of mean velocity (U) to the mean critical velocity (U_c) with time. Fig.7 shows water surface variation relative to the initial water level (h_0) of steady flow with time. Fig.8 expresses the time history of the distribution of pore water pressure at each level of sand surface considered. The observed velocity distribution (Fig.6) showed that the ratio of mean velocity to the critical velocity, U/U_c , was maintained about 1.0 for steady flow, that is, clear-water scour condition. This ratio (U/U_c) is the measure of flow intensity and the initiation of the sediment particles whether it moves or not. For $U/U_c>1$ indicates the live-bed scour condition. The velocity was decreased to about zero for the rise of water level, this rise of water level was created by applying a wooden plate at the end of the channel near the tailgate. Again, approach velocity increased as large as twice of the mean velocity during the hydraulic drop, that is, live-bed scour condition occurred because of $U/U_c>1$. Due to this formation of live-bed condition, sediments entered into the scour hole and an equilibrium scour depth is attained when the flow returned to its initial approach velocity condition after the application of pressure drop. But, it was observed a larger depth of local scour than clear-water equilibrium scour depth for a while even the bed was in live-bed scour condition.

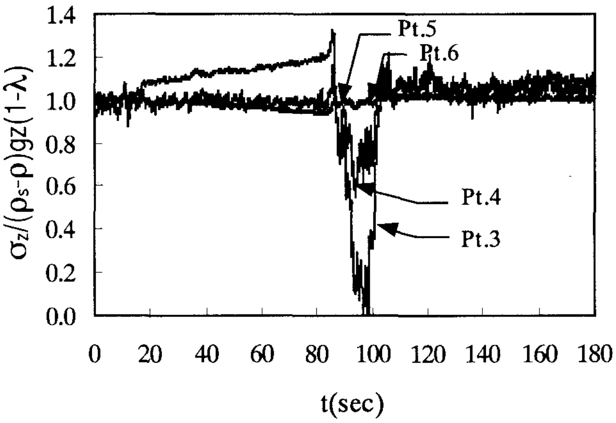

Fig.9 Effective stress

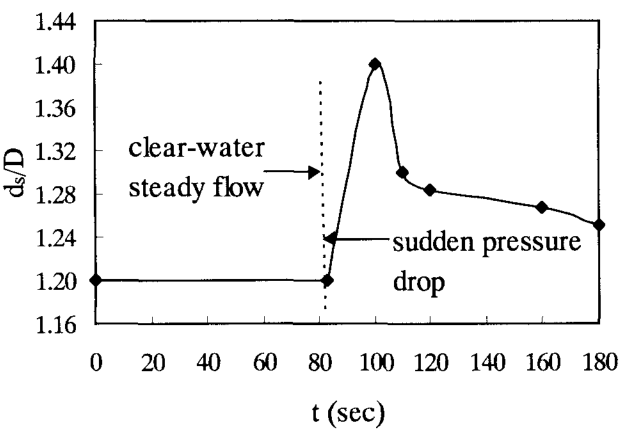

Fig.10 Variation of excess scour development with time

Fig.9 represents the effective stresses. The near surface level of Pt.3 indicates that the effective stress decreased to zero; that is, the layer is fully liquefied, and susceptible to scour depth enhancement. The layer of the sand surface of Pt.4 also indicates a factor of effective stress less than 1, that is, partial liquefaction, which is set just 3 cm away upstream of the pier. The results assure lack of stability of the bed layer around the pier. Fig.10 represents the quick enhances of local scour depths to that of steady flows at the same time of effective stress being reduced.

6. CONCLUSIONS

The effective stress in the near surface layer was reduced to zero, that is, the sand layer was fully liquefied, by the application of sudden pressure drop and as a result, a quick removal of sediment transported. The scour depth around the pier was increased by about 10%-18% for the cases studied than that of clear-water equilibrium local scour depth.

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