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LOCAL SCOUR AROUND A SUBMERGED CYLINDRICAL PIER

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Laboratory experiments were conducted on local scour and bed evolution around a cylindrical pier. Not only with a traditional non-submerged pier, but some cases with a submerged pier were explored. Experiments were carried out in both static and dynamic scouring conditions. Shape of a scouring hole around the pier, as well as backwater caused by the pier, is of particular interest.

The shape of the scouring hole in the submerged conditions is similar to that in the non-submerged condition, thus the maximum scour depth appears in vicinal front of the pier. The maximum scour depth reduces as the height of the pier decreases. A refined equation for estimating the maximum scour depth including the effect of variable pier height is proposed and shows good performance in the range tested here. Backwater in the upstream is not so noteworthy in the submerged cases compared with traditional piers.

Key Words : *cylindrical pier, local scour, bed evolution, backwater, submerged pier, embayment*

1. INTRODUCTION

It is well known that shallow areas formed along a river reach, such as bars, embayments and backwaters, have an important function for fishes and shellfishes, because these areas provide habitats necessary for their spawning and growing up (Ogawa, 2004). In Japan lots of such areas have been destroyed during last several decades, by straightening, widening and deepening the channel for improving conveyance capacity (Kawai, 2004). However, from around the end of the last century, restoration and rehabilitation of shallow and stagnant areas were attempted, in contrast to the river management in the aforementioned previous time. For this purpose, for example, spur dykes have again been installed (Muto et al, 2005). This aims to produce a preferable habitat by utilising an interaction between the structure and hydro-morphological processes. In other words hydraulic structures can be adopted for environmental restoration / rehabilitation if they are constructed and allocated in a suitable manner.

While shallow and mild-sloped areas are disappeared due to the channel improvement described above, nowadays scour holes formed around a pier are only the place providing good and precious habitat in many rivers. In fact a lot of eggs and infant fishes can easily be found in a scour hole, especially located near a shore line. Yano (2003) reported that some kind of fishes such as *Biwia zezera* can only be seen and regenerating in a scour hole in the downstream of the Kizu River. This indicates that bridge piers, or pier-like structures, can be used as a tool for river environmental restoration / rehabilitation by adding morphological undulation on river geometry. The pier-like structures mean, for example, a left pier after a removed / renewed bridge, or a structure similar to a pier in its shape but its purpose not for transportation (without beam), rather, specially constructed for the ecological purpose. However, one of the problems of such structures is that they do not match river scenery owing to there artificial forms and, more importantly, they can be an obstacle to floods by acting as a roughness and by blocking drift woods. In order to avoid these defects one of the solutions can be shortening the structure up to being submerged in case of floods. Flow and bed evolution around a submerged pier-like structure has, however, not yet been explored. Thus effect of the structure as an environmental restoration tool is unknown.

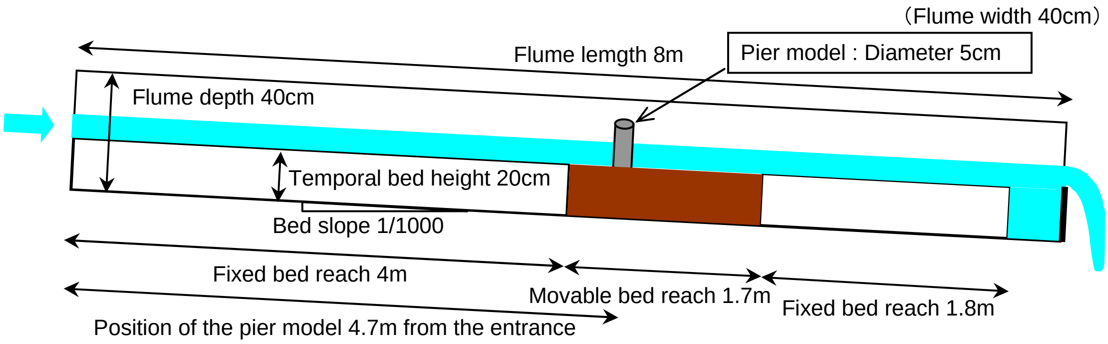

Fig.1 A schematic view of the experimental flume.

Table 1 Experimental cases and hydraulic conditions.

Case	Height of the pier T (cm)	Discharge Q (cm^3/s)	Uniform depth h (cm)	Velocity u (cm/s)	Friction Velocity u_* (cm/s)	Sediment Discharge Q_s (cc/min)	Reynolds Number Re	Froude Number Fr
S0	None	5,700	5.00	28.5	1.98	None	11,400	0.46
S1	7.5							
S2	3.5							
S3	2.5							
D0	None	10,000	7.00	35.7	2.25	65	18,500	0.50
D1	7.5							
D2	3.5							
D3	2.5							
Bed Material: Mean Diameter d_m=1.45mm, Specific gravity σ=1.9, Critical friction velocity u_{*c}=2.09cm/s Diameter of the pier D=5cm								

This paper reports on the results of laboratory experiments carried out on flow and local scour around a submerged cylindrical pier. The change of backwater effect as well as shape of the scour hole is studied. Then potential of the structure as an environmental restoration tool is evaluated.

2. EXPERIMENTAL SET-UP

The experiments were carried out at Ujigawa Hydraulics Laboratory, Kyoto University. A straight glass flume with a rectangular cross-section was used, whose dimensions are 8m long, 40cm wide and 40cm deep. The flume bed was temporary lifted up 20cm by installing plywood boards, from the entrance to 4m downstream, and from 5.7m to 7.5m. Bed material whose specific gravity of 1.9 and mean diameter of 1.45mm was filled in the middle part of the flume, from 4m to 5.7m, up to 20cm, fitted with the temporal wooden bed up- and downstream. A PVC model pier whose diameter of 5cm was located at 4.7m downstream of the flume entrance. **Figure 1** shows a schematic view of the flume set-up.

Table 1 shows experimental cases and hydraulic conditions. Three kinds of pier models with different length were studied. Two hydraulic conditions with different bed shear stresses and resultant sediment transport, namely static and dynamic bed, were tested.

A pointer gauge was used for measuring the water surface profile. The measurements were performed at the centre of the flume, every 10cm in the movable bed reach and 50cm in the fixed bed reaches. For bed configuration measurements a laser range finder whose accuracy of 0.05mm was adopted. The measurements were carried out in the movable bed reach, every 1cm in the lateral direction and 1 to 4cm according to variation of the bed in the streamwise direction.

3. RESULTS AND DISCUSSIONS

(1) Water surface profile

Figure 2 shows water surface profiles in the upstream of the model pier. The figure exhibits rises of the water surface due to backwater by a pier, comparing with the no-pier cases, Case S0 and D0. For the non-submerged cases, Case S1 and D1, the

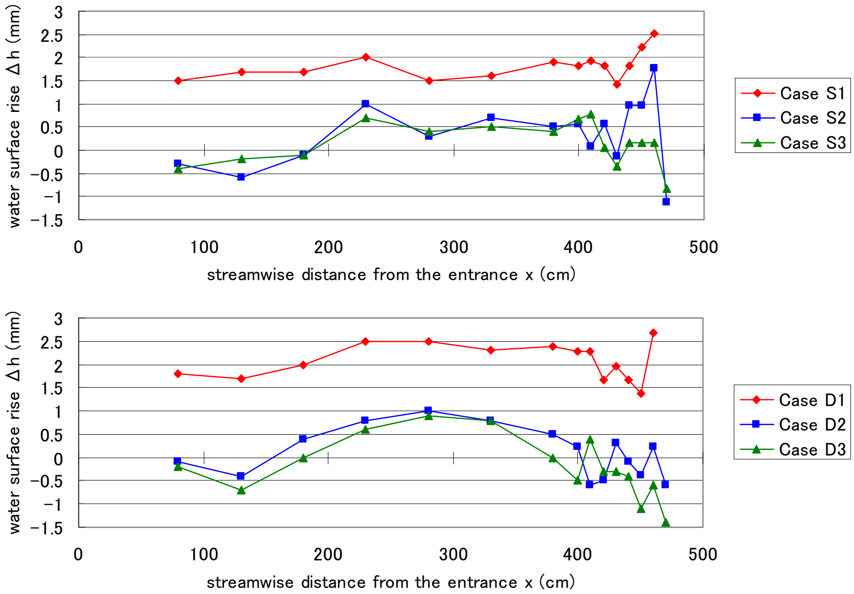

Fig.2 Water surface profiles in the upstream of the pier.

Table 2 The averaged water surface rise.

Case	Averaged water surface rise: mm (%)
S1	1.82 (3.6)
S2	0.45 (0.9)
S3	0.21 (0.4)
D1	2.08 (3.0)
D2	0.16 (0.2)
D3	-0.10 (-0.1)

backwater effect is quite clear. The maximum surface rise is observed right upstream of the pier, and the effect maintains up to the entrance with the value around 2mm. On the other hand, such a clear effect is not observed for the submerged cases except for Case S2, rather, the surface rise for these cases are as small as can be ignored. Only Case S2 shows the backwater effect, but that is fairly small compared with Case S1. **Table 2** shows the surface rises averaged over the distance shown in **Fig. 2**. For the non-submerged cases, Case S1 and D1, the averaged surface rises are about 2mm, 4% of the water depth. Whereas those are less than 0.5mm for the submerged cases. The height of the pier and the averaged surface rise seem to have a positive correlation for the submerged cases, but difference of the rises among the same hydraulic condition is about 0.25mm, which is almost the same as accuracy of the pointer gauge measurements, thus some more experiments should be necessary for confirming the correlation.

(2) Bed configuration

Figure 3 shows equilibrium bed configurations under the static scour condition. The figure shows the variation from the initial bed, erosion (-) and deposition (+). The shape of the scour hole for Case S1 is a typical one seen in a traditional research on local scouring by a pier. The scour hole develops concentrically around the pier, and shallow wings also extend diagonally in the downstream. The maximum scour depth appears in front of the pier. Some bed materials out of the hole are deposited behind the pier. The deposition as well as the scour wings reaches x/B=2.0, which is 16 times the diameter of the pier.

For the submerged cases, the shape of the scour hole is similar to that of the non-submerged case, however depth of the hole decreases and the affected area in the downstream also shrinks. As the height of the pier decreases the scouring area is reduced both in area and in depth. For Case S3 scouring occurs just in vicinity of the pier, so the wings and the deposition are not clear.

Owing to the lack of the information on detailed flow structure around the pier, hydraulic mechanism of the pier-height effect on scour depth and configuration cannot exactly be drawn at this stage. Nevertheless, it is deemed that the horse-shoe vortex formed in front of the pier changes its size and shape, by being released from the pressure restriction when the pier is submerged. Further investigations as to velocity distributions and surface profiles are necessary to check this conjecture.

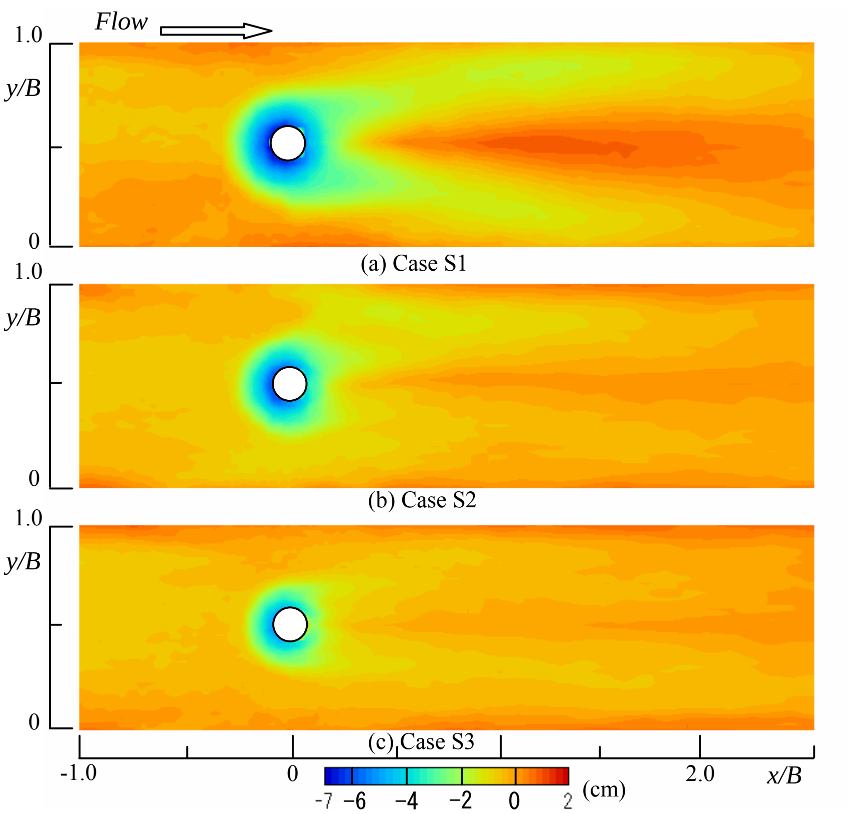

Fig.3 Equilibrium bed configurations under the static scour condition.

Table 3 The maximum scour depth.

Case	Water Depth h (cm)	Pier height T (cm)	Maximum scour depth Z (cm)	Z/D	h/D	Z/Z_0	T/h
S1	5.0	5.0	6.75	1.35	1.0	1	1
S2		3.5	6.00	1.20		0.89	0.7
S3		2.5	4.96	0.99		0.73	0.5
D1	7.0	7.0	7.38	1.48	1.4	1	1
D2		3.5	5.67	1.13		0.77	0.5
D3		2.5	4.81	0.96		0.65	0.36
Diameter of the pier D=5cm Z_0: Maximum scour depth in the non-submerged case, Case S1 and D1							

Equilibrium bed configurations under the dynamic scour condition, the shape of the scour hole and its variation according the pier height, are similar to those under the static scour condition shown in **Fig. 3**, thus are abbreviated here.

(3) Estimation for the maximum scour depth

The shape of the scour hole and bed evolution around a pier were examined in detail in the previous section. As a result, it is confirmed that the maximum scour depth appears in front of the first pier, irrespective of the pier height and scour condition. Summary of the maximum scour depth is shown in **Table 3**. The maximum scour depth is smaller in the submerged cases than in the non-submerged case. Among the submerged cases, in addition, the maximum scour depth is reduced as the height of the pier decreases.

Figure 4 shows the relation between the scour depth and the water depth normalised by the diameter of the pier. In the figure estimations for the maximum scour depth proposed by Laursen-Neill (1963), Cunha (1970) and Nakagawa & Suzuki (1974) are superimposed. Among the referred estimations, that

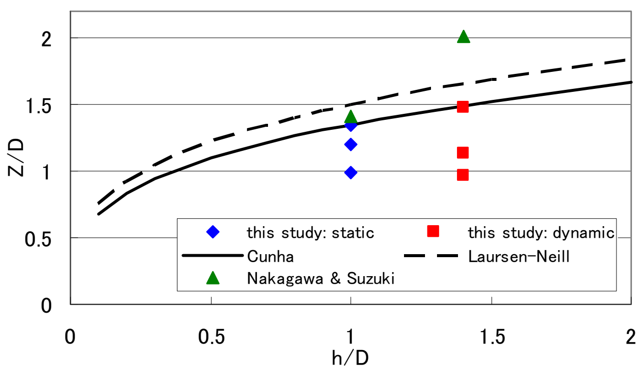

Fig.4 Relation between the scour depth and the water depth.

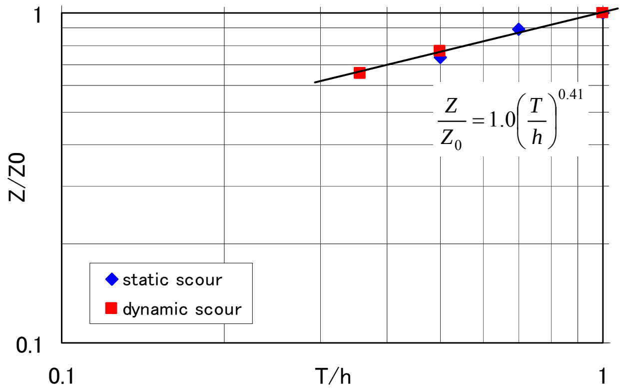

Fig.5 Relation between the scour depth and the pier height.

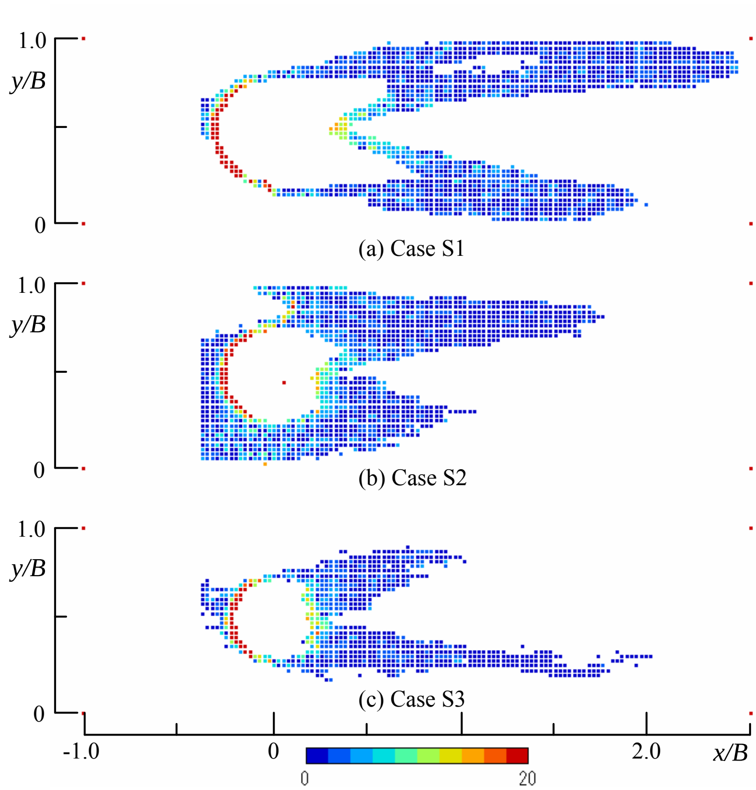

Fig.6 Distributions of local bed gradient in the streamwise direction in the scour hole where the depth from -0.5cm to -1.5cm.

by Cunha (1970) shows good agreement for the non-submerged cases, Case S1 and D1. However, but quite naturally, none of them can reasonably estimates for the submerged cases because they did not take the pier height into account as a parameter.

Figure 5 shows the relation between the scour depth and the pier height. In the figure the scour depth is normalised by that for the non-submerged case, and the pier height normalised by the water depth. It is clear that they have a strong correlation. The solid line drawn in the figure is the regression, which yields:

$$\frac{Z}{Z_0} = 1.0\left(\frac{T}{h}\right)^{0.41} \tag{1}$$

The equation for estimating the maximum scour depth proposed by Cunha (1970) is as follows:

$$\frac{Z_0}{D} = 1.35\left(\frac{h}{D}\right)^{0.3} \tag{2}$$

Consequently an equation for estimating the maximum scour depth for a submerged pier can be:

$$\frac{Z}{D} = 1.35\left(\frac{h}{D}\right)^{0.3}\left(\frac{T}{h}\right)^{0.41} \quad (3)$$

Equation (3) has an advantage that it is applicable both non-submerged and submerged cases, and that the form of equation is similar to that of Cunha's original equation.

(4) Evaluation of habitat change

In the foregoing sections it is shown that the size of the scour hole is reduced as the pier is submerged. This could mean that the habitat and the creatures living there are influenced a lot by altering the pier height. Nonetheless it was reported that all creatures do not distribute uniformly even in one closed space like a scour hole, but have their own preferences for living area, with small differences of water depth, flow velocity, bed material, etc. In addition they change the area depending on their life stage (Tetsukawa et al., 1979). Therefore the size reduction may not directly lead to deteriorating the habitat.

Yano (2003) reported that in case of *Biwia zezera* for spawning, necessary conditions are a shallow area submerged only during floods, but a steep sloped area such as cliff is not used even satisfying the prior condition. **Figure 6** shows distributions of local streamwise gradient in the scour hole of which the depth between -0.5cm and -1.5cm. Here the geometric similitude and the quantitative information regarding the preference of *Biwia zezera* is not clear, thus the following evaluation is only qualitative one. The area where the streamwise slope is less than 6 degree (blue coloured) is not so much reduced even the pier height decreases. This means that the habitat can possibly be maintained if the pier is changed to a submerged one.

4. CONCLUDING REMARKS

As shown in **Fig. 2** the backwater effect is almost negligible for the submerged pier, so the alteration of the pier considered here is deemed to have an advantage in flood managing. Further investigation will be necessary in the point of fluid dynamic force acting on such a pier. Change of the pier height largely influences the size of the scour hole as shown in **Fig. 3**. However, if quality of the habitat can at least be maintained, the size reduction can be compensated by increasing the location of the submerged pier. How the structure of ecology in a habitat is constituted, especially in relation to the hydro-morphological processes formed there, should also be clarified in more detail.

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REFERENCES

1) Veiga da Cunha, L. : Discussion to "Local scour around bridge piers" by Shen, H.W., Schneider, V.R. and Karaki, S., *Proc. ASCE*, HY8, pp.1742-1747, 1970.
2) Kawai, N. : Change of the environment in the Yodo River, *Research Report on Hydro-Morphological Management and Environmental Restoration / Rehabilitation in a River*, Foundation of River & Watershed Environment Management, pp.13-22, 2004. (in Japanese)
3) Muto, Y., Baba, Y. and Nakagawa, H. : Velocity Measurements in a Straight River with a Series of Goynes by a Ship-Mounted ADCP, *Proc. 31st IAHR Cong.*, Seoul, Korea, pp.455-465, 2005.
4) Nakagawa, H. and Suzuki, K. : *Annuals of D.P.R.I., Kyoto Univ.*, No.17B, pp. 725-751, 1974. (in Japanese)
5) Neill, C.R. : Measurements of bridge scour and bed changes in a flooding sand-bed-river, *Proc. ICE*, London, Vol.30, pp.415-436, 1963.
6) Ogawa, R. : Hydro-morphological conditions and behaviour of fishes in a stagnant area on a bar, *Research Report on Hydro-Morphological Management and Environmental Restoration / Rehabilitation in a River*, Foundation of River & Watershed Environment Management, pp.116-132, 2004. (in Japanese)
7) Tetsukawa, S., Matsuoka, K. and Tamura, T. : *The Yodo River - its nature and history* -, Shoraisha, pp.42-68, 1979. (in Japanese)
8) Yano, H. : Master's thesis, Osaka Kyoiku University, 2003. (in Japanese)