Flow Characteristics and Sediment Deposition Around a Pile-group Dike

Academic advisor: Professor Akihiro TOMINAGA

Obaidullah SAFIE

1. Introduction

Riverbank erosion and failure by water flow are the common problems in rivers that can sometimes greatly affect human life. Pile-group dikes as river training structures can be used for velocity control and sediment deposition along the bank to improve bank stability. Many pile-groups have been built along the banks of the Kiso River in Japan for several decades as river training structures to enhance navigability of the channel and control the bank erosion, as shown in Fig.1. No detailed explanation has been found in the literature on how these structures function. In order to study the effects of different pile-groups on the flow and sediment deposition, an experimental study was conducted.

2. Experimental procedures

Two types of experiments were conducted in order to study the flow characteristics and sediment deposition around pile-group dikes. Particle image velocimetry (PIV) method was used to study the flow characteristics. The flume was 7.5m long, 0.3m wide, and 0.4m high with a rectangular cross-section. Impermeable structure and permeable pile-groups were used in this study. The pile-groups were made of acrylic cylinders with diameter d of 0.5cm and height h_d of 5cm. Fig.2 shows the schematic view of the flume and the pile-groups layout. Different pile-group densities with two types of pile arrangement, namely in-line and staggered arrays were applied as noted in Table 1 and shown in Fig.2(a) and (b).

Length L and width W of the dikes were kept constant at 0.075m in all permeable and impermeable cases as shown in Fig.2. Therefore, all the cases had the same area. For each pile-group case, the number of piles was changed in the fixed area. For each case, the same number of piles per row and column $(n = m)$ hence the same face to face spacings of the piles in the x and y directions $(S_x = S_y)$ was kept. The number of piles was

Fig.1 Pile-group dikes along the Kiso River, Japan

Table 1 Pile-groups details

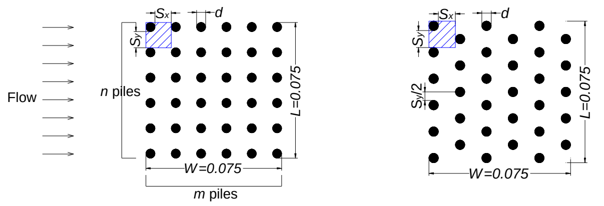
Case No.	Pile arrangement (row × column) $(n \times m)$	Case name	Number of piles N	Pile spacing S_x=S_y (cm)	Pile-group density λ (1/cm)
1	4 × 4 In-line	4L	16	1.83	0.092
2	4 × 4 Staggered	4S	14	1.83	0.092
3	5 × 5 In-line	5L	25	1.25	0.163
4	5 × 5 Staggered	5S	23	1.25	0.163
5	6 × 6 In-line	6L	36	0.90	0.255
6	6 × 6 Staggered	6S	33	0.90	0.255
7	7 × 7 In-line	7L	49	0.67	0.365
8	7 × 7 Staggered	7S	46	0.67	0.365
9	8 × 8 In-line	8L	64	0.50	0.500
10	8 × 8 Staggered	8S	60	0.50	0.500
11	Impermeable	Imp	-	-	-
12	Undisturbed-flow	Und	-	-	-

$\lambda = d/(d+S_x)(d+S_y)$, d: pile diameter

Table 2 Experimental conditions

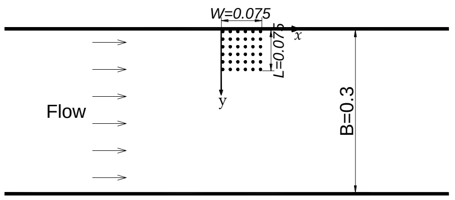
Parameter	PIV	Sediment deposition
Discharge Q (m^3/s)	0.0016	0.0038
Water depth h (m)	0.04	0.04
Mean velocity $U_0 (m/s)$	0.13	0.319
Froude number Fr	0.21	0.51
Channel slope S	0.001	0.00125
Sand mean diameter d_m (mm)	NA	0.09
Shear velocity / critical shear velocity (u_*/u_{*c})	NA	1.37
Manning coefficient n	0.01	0.01
Equilibrium state duration (h)	NA	6 to 14

Note: NA stands for not applicable.



(a) Case 8L

(b) Case 8S



(c) Plan view of the experimental flume

Fig.2 Pile-groups and experimental flume layout, unit in meter increasing from 4 to 8 piles to change from a low to high pile-group density. The pile-group density λ is defined as follows:

$$\lambda = \frac{d}{(d+S_x)\cdot(d+S_y)} \tag{1}$$

Where d is the pile diameter, S_x and S_y are the face-to-face spacings between the piles, which are defined in Fig.2. The details of pile-groups and the experimental conditions are shown in Table 1 and Table 2 respectively. The water depth h was set to 0.04m before installation of the Structure in the flume.

Velocity vectors were measured by PIV method in horizontal planes, and a commercial PIV software (FlowExpert by Katokoken) was used for analyses. For visualization of the flow, nylon resin particles with 80 microns in diameter and 1.02 in specific weight were used. A 3mm green laser light sheet was projected on horizontal $(x-y)$ planes. For each case, a total of seven layers were recorded from the bed to the surface with 5mm increment. The visual images were taken by a high-speed video camera with 200 frames in a second, and they were recorded as AVI files with 1024 x 1024 pixels. Time-averaged velocity vectors were obtained by processing 3200 successive images in 16 seconds.

The sediment deposition experiments were conducted in a fixed bed channel with similar cross-section as the PIV experiments. 8kg of sand was mixed in 250L of water. A part of sand was suspended, and the rest was transported as bed load during the experiment. The detailed conditions are noted in Table 2.

3. Results and discussion

3.1 Effect of pile-group density on the flow

Fig.3 shows the contours of time-averaged longitudinal velocity distribution normalized by the mean velocity (U/U_0) at a layer of z=2.0cm. The flow was from left to right according to these contours. The contours are for the in-line cases of 4L, 6L, 8L, and impermeable (case Imp) (first row) and staggered cases of 4S, 6S, and 8S (second row) respectively. Regardless of the type of pile arrangement, by increasing the pile-group density, the flow in the mainstream accelerated and that behind the pile-group decelerated. However, case Imp shows a return flow behind the structure.

3.2 Effect of pile arrangement on the flow

Changing the arrangement of piles from in-line to staggered caused further acceleration of the mainstream flow and deceleration behind the pile-group. On the other hand, staggered arrangements changed the flow behind the pile-group to a preferable pattern. For all the staggered cases, in a lateral section behind pile-group, the flow velocity is minimized near the bank and gradually increases toward the mainstream. In contrast, the in-line cases have not generated such a regular velocity change. They have a high velocity near the bank and decreases toward the mainstream up to the tip of the structure. Finally, the velocity reaches a minimum value behind the downstream tip of the structure.

The turbulence due to the installation of pile-group is entirely different for both types of pile arrangement. Fig.4 shows the contours of normalized Reynolds stress

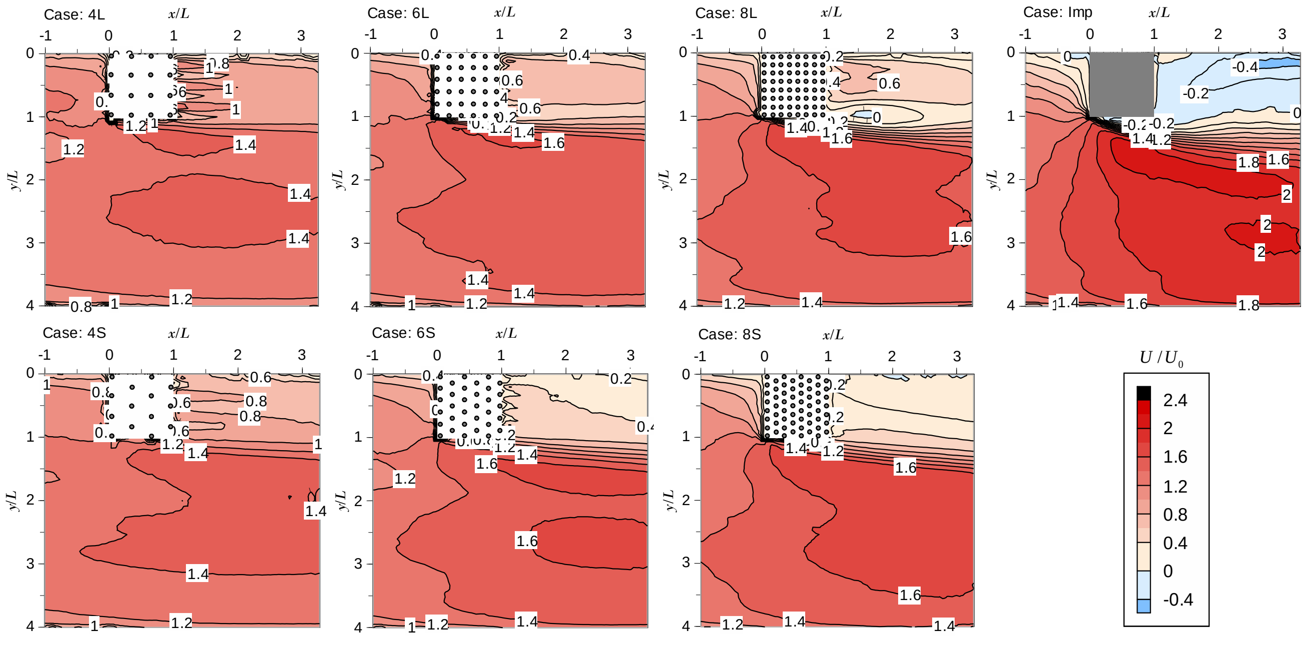


Fig.3 Contours of longitudinal velocity distribution at z=2.0cm, in-line cases (up) and staggered cases (down)

$-\overline{uv}/U^2$ at z=2.0cm for the cases of 8L and 8S. A region of high Reynolds stress appears at the downstream of the pile-group in the in-line case whereas the staggered case does not show such strong turbulence.

The bed shear stress shows a similar pattern to the flow velocity. Fig.5 shows the contours of bed shear stress (τ_b/τ_{b0}) normalized by the bed shear stress of case NoM (no structure). Staggered case 8S shows smaller bed shear stress behind the structure. In contrast, the in-line case 8L has higher bed shear stress. Both, the high velocity and the bed shear stress behind in-line pile-groups can affect the sediment deposition in the region.

Fig.6 summarizes the velocity (U_{bank}/U_0) averaged in the area near the protected bank downstream of the pile-group for each case. Each point represents the average velocity for one case. The red triangles denote the in-line cases from 4L to 8L and the green circles signify the staggered cases from 4S to 8S from left to right. The horizontal axis represents the pile-group density, so the number of piles increases from left to right. The vertical axis is the longitudinal velocity that is normalized by the mean velocity. The values were obtained by averaging the velocities in a region defined by $(1 < x/L \leq 3.2)$, $(y/L = 0.27)$ and vertically from the bed to the surface for each case. The plot indicates that the velocity reduction in the vicinity of the protected bank is directly proportional to the pile-group density. Staggered pile-group cases reduced the velocity significantly more than the in-line cases.

The flow structures around the pile-groups were well simulated by a 2D numerical model.

3.3 Effects of pile-group density and pile arrangement on the sediment deposition

Fig.7 shows the contours of sediment deposition which are normalized by the water depth h. It includes cases of 6L, 8L, 6S, 8S, Imp, and NoM. The flow was from left to right according to these contours. Installation of a structure enhanced deposition along the bank and decreased in the mainstream. By increasing the pile-group density the amount of deposition increases behind the structure, while decreases in the mainstream. In all the pile-group cases the peak amount of the deposition occurred along the bank, while it located far from the bank in the case Imp. Additionally, pile-group cases show wider deposition than the impermeable structure.

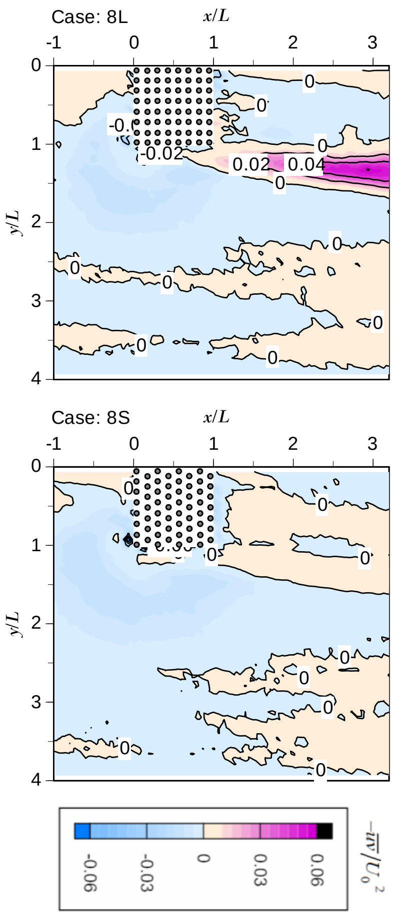


Fig.4 Contours of Reynolds stress distribution at z=2.0cm

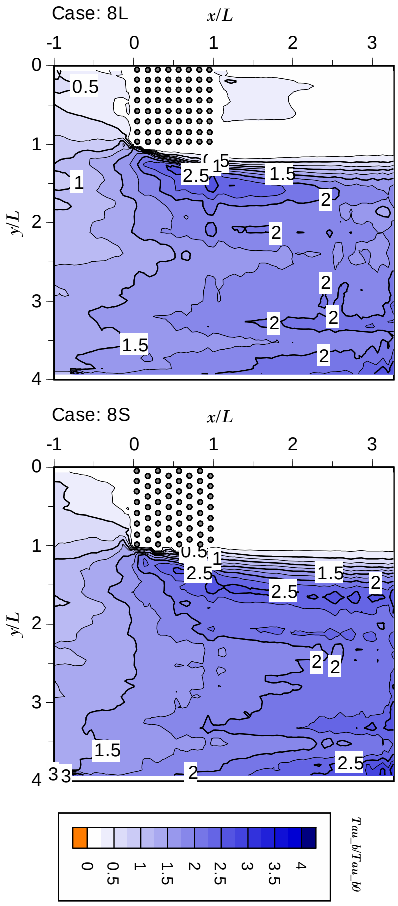
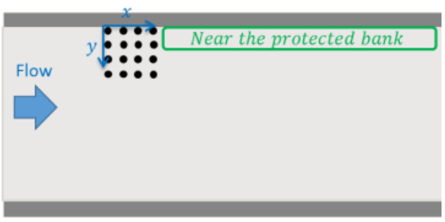
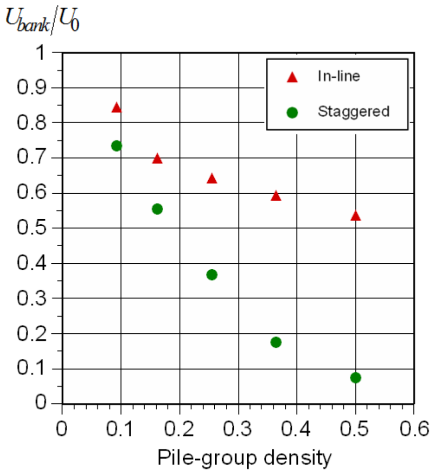


Fig.5 Contours of bed shear stress distribution



(a) Definition of the considered area near the bank



(b) Average longitudinal velocity near the bank normalized by the mean velocity

Fig.6 Average longitudinal velocity near the bank

Fig.8 summarizes the average-deposition height behind the structure in all the cases. It is normalized by the case NoM. The blue bars stand for staggered cases (*S_back*), and the red bars represent the in-line cases (*L_back*). Each staggered case shows more deposition compared to the in-line case. All the pile-group cases except cases 4L, 4S, and 5L show more deposition than the case Imp.

From an economic point of view, a lower pile-group density in staggered arrays can perform like a higher pile-group density of in-line arrangement. This, in turn, can reduce the number of piles to almost half in most cases. Considering cases 5S and 7L, the value of average velocity near the bank (U_{bank}/U_0) is 0.55 for the case 5S and 0.59 for the case 7L as shown in Fig.6(b). Similarly, as for the deposition, case 5S has a value of 2.83 while for the case 7L it is 2.64 as shown in Fig.8. In other words, if the arrangement is changed from in-line to staggered, 23 piles can perform better than 49 piles.

4. Conclusions

Effects of pile-group density and pile arrangement on the flow characteristics and sediment deposition around pile-group dikes were investigated experimentally. The Pile-groups were proved to be effective structures for velocity reduction and sediment deposition along the bank, which in turn, both can increase the riverbank stability.

Flow structure and sediment deposition changed significantly by changing the arrangement of piles from in-line to staggered arrays. For the purpose of bank protection, staggered arrangement performs better than an in-line array.

The magnitudes of flow velocity and sediment deposition along the bank can be controlled by changing the pile-group density. In contrast, it is not possible with the impermeable structure.

Economically, in order to obtain a certain velocity and deposition near the bank, changing the arrangement from in-line to staggered arrays significantly reduces the number of piles. Use of staggered arrays can reduce the number of piles to almost half.

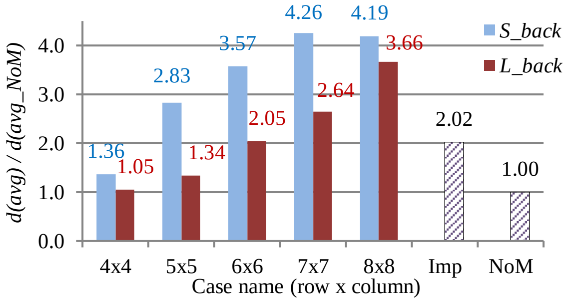


Fig.8 Average-deposition height behind the structure

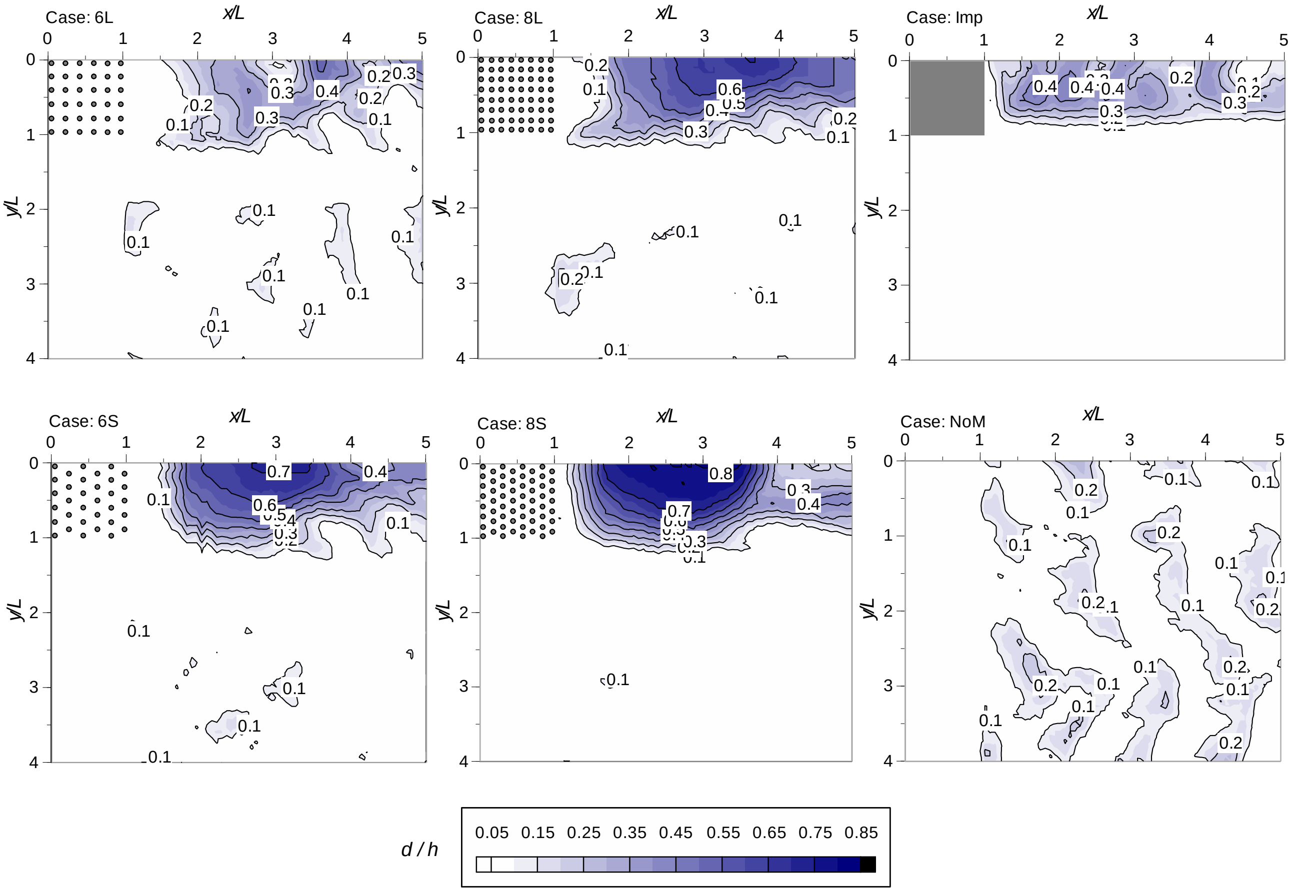


Fig.7 Average deposition-height normalized by water depth *h*