Flow control by pile-group groynes used for riverbank instability management

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Abstract. Smooth reduction of velocity from the mainstream to the bank is a desirable attempt when using a groyne for riverbank protection purpose. This can be achieved by applying modifications to groyne permeability or layout. In this study, the effects of different pile-group groynes on the flow deceleration were investigated experimentally. Different aspects including pile density, arrangement, row spacing and effects on the long downstream were considered. The results show that the pile arrangement pattern is an important factor on the control of flow magnitude and pattern behind a pile-group groyne. A gradual and smooth velocity reduction from the mainstream to the bank can be obtained by changing the arrangement of piles in a pile-group groyne.

1. Introduction

Riverbanks are constantly being eroded away by water flow, which can lead to riverbank failure and significant impacts on human life. Therefore, the use of groynes as sustainable riverbank management strategy for bank instability has been attracted attention from the long years ago. A groyne is a hydraulic structure that extends from a bank of the channel into the flow and controls the direction and velocity of the flow.

A permeable pile-group groyne reduces the velocity in the downstream and can improve the stability of the bank [1]. Many pile-group groynes have been built along the banks of the Kiso and Yahagi Rivers in Japan for several decades to control the riverbank erosion along the bank, an example of the Kiso River is shown in Photo 1.

The advantages of a permeable groyne over impermeable one in terms of the flow and morphology around the structure are often demonstrated in the literature [2-7]. Specifically, gradual deceleration of velocity from mainstream to the bank [8], reducing local scour around structure [6] and enhancement of sediment deposition for further stabilization and reclamation of the eroded banks [9-11] are the main advantages of permeable spur dikes that are founded in the literature.

A pile groyne, which consists of one single row of piles, is proven useful for velocity reduction along the bank [12-16]. However, there are very few studies on flow and bed characteristics around a pile-group groyne consisting of multiple rows of piles in a group. Ikeda et al. [10] reported flow retardation along the bank behind a pile-group dike. However, the study considered one type of pile density in one pattern of pile arrangement. Recently, Safie and Tominaga [17, 18] studied the effects of pile density and arrangement on flow characteristics. The results indicate that a pile-group with a staggered arrangement of piles demonstrated better performance than an in-line arrangement. The staggered arrangement shows lower velocity along the bank than the in-line arrays.
Obviously, the number of piles in a group and the pattern of arrangement of piles in the group affect the flow and bed characteristics. Nevertheless, the effects of pile density and arrangement on the flow around pile-group groynes with various pile arrangements are not studied sufficiently. Furthermore, the effects are unclear in long downstream distance. Herein, flow structure around pile-group groynes are investigated to study the effects of pile density, arrangement and row spacing on the flow. A series of experiments were conducted on different pile-group groynes. The main purpose is to evaluate the performance of various pile-group groynes on the flow control around structure to obtain a smooth flow deceleration that directly affects the riverbank stability.

2. Material and methods

2.1. Experimental conditions and laboratory flume

The experimental flume was 7.5m long, 0.3m wide and 0.4m high with a rectangular cross-section. Table 1 notes the experimental conditions. The pile-groups were studied attached to the sidewall, as shown in Figure 1.

| Parameter                  | Value        |
|----------------------------|--------------|
| Discharge $Q$ (m$^3$/s)    | 0.00187      |
| Water depth $h$ (m)        | 0.04         |
| Mean velocity $U_m$ (m/s)  | 0.156        |
| Froude number Fr           | 0.25         |

The pile-groups were made of acrylic cylinders with diameter $d$ of 0.5cm and height $h_d$ of 5cm. The details of pile-groups to study various aspects are noted as below.

2.2. Pile-groups to study the effect of pile arrangement

The Four patterns of pile arrangements were considered as shown in table 2. The length $L$ and width $W$ of the pile-groups (which are noted in Figure 2) were kept constant at 0.075m in all the four cases. All the pile-groups contained almost the same number of piles, which is equivalent to $7 \times 7$ piles on each side, but they are used in different arrangements in each pattern.
Table 2. Four patterns of pile arrangements.

| Case name | L1     | L2     | S1     | S2     |
|-----------|--------|--------|--------|--------|
| Total number of piles | 49     | 46     | 50     | 46     |

2.3. Pile-groups to study the effect of pile density
To study the effects of pile density (number of piles in a group), two patterns of pile arrangements that are L1 and S2 were picked up based on the results of the above four patterns (L1, L2, S1, and S2). The length L and width W of the pile-groups (which are noted in Figure 2) were kept constant at 0.075m in all the cases. For each pile-group, 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 spacing of the piles in the x and y directions (Sx = Sy) was kept, details are noted in table 3. The number of piles was increasing from 4×4 to 8×8 piles to change from a low to high pile density. The pile density \( \lambda \) is defined as follows:

\[
\lambda = \frac{d_p}{(d_p + S_x) \cdot (d_p + S_y)}
\]

Where, \( d_p \) is the pile diameter, \( S_x \) and \( S_y \) are the face-to-face spacing between the piles, which are defined in table 3. A total of 11 experiments that included 10 pile-group cases and one experiment when no structure was installed in the channel (Case NoS), were conducted, as noted in table 3. Case NoS was considered to capture the changes in the flow that occurred after the structure was installed in the channel.

Table 3. Details of pile-groups with various pile densities (number of piles).

| Case No. | Number of piles (row × column) \((n × m)\) | Pattern | Case name | Total number of piles | Pile spacing \(S_x = S_y\) (cm) | Pile density \(\lambda\) (1/cm) | Pattern |
|----------|------------------------------------------|---------|-----------|----------------------|-------------------------------|-------------------------------|---------|
| 1        | 4×4                                     | L1      | 4×4L1     | 16                   | 1.83                          | 0.092                         |         |
| 2        | 5×5                                     | L1      | 5×5L1     | 25                   | 1.25                          | 0.163                         |         |
| 3        | 6×6                                     | L1      | 6×6L1     | 36                   | 0.90                          | 0.255                         |         |
| 4        | 7×7                                     | L1      | 7×7L1     | 49                   | 0.67                          | 0.365                         |         |
| 5        | 8×8                                     | L1      | 8×8L1     | 64                   | 0.50                          | 0.500                         |         |
| 6        | 4×4                                     | S2      | 4×4S2     | 14                   | 1.83                          | 0.092                         |         |
| 7        | 5×5                                     | S2      | 5×5S2     | 23                   | 1.25                          | 0.163                         |         |
| 8        | 6×6                                     | S2      | 6×6S2     | 33                   | 0.90                          | 0.255                         |         |
| 9        | 7×7                                     | S2      | 7×7S2     | 46                   | 0.67                          | 0.365                         |         |
| 10       | 8×8                                     | S2      | 8×8S2     | 60                   | 0.50                          | 0.500                         |         |
| 11       | No structure                            | NoS     | -         | -                    | -                             | -                             |         |

2.4. Pile-groups to study the affected long downstream distance
Two cases that are 7×7L1 and 7×7S2 are picked up among the all 11 cases in table 3 to study the effects of pile-groups in long downstream distance.
2.5. Pile-groups to study the effect of row spacing
Three types of row spacing were considered for the same number of piles with two different pile arrangements, patterns L1 and S2. The details are noted in Table 4.

2.6. Velocity measurement technique
Velocity vectors were measured by Particle Image Velocimetry (PIV) method in horizontal planes. 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, seven layers were recorded from the bed to the surface with 5mm increments. A high-speed video camera took the visual images with 200 frames in a second, and they were recorded as Audio Video Interleaved (AVI) files with 1024 x 1024 pixels. Time-averaged velocity vectors were obtained by processing 3200 successive images in 16 seconds.

### Table 4. Details of various row spacing.

| Case No. | Number of piles (row × column) | Pattern | Length $L$ (cm) | Width $W$ (cm) | Case name | Pattern |
|----------|--------------------------------|---------|----------------|---------------|-----------|---------|
| 1        | 7×5                            | L1      | 7.5            | 4.5           | L1(45)    |         |
| 2        | 7×5                            | L1      | 7.5            | 6.0           | L1(60)    |         |
| 3        | 7×5                            | L1      | 7.5            | 7.5           | L1(75)    |         |
| 4        | 7×5                            | S2      | 7.5            | 4.5           | S2(45)    |         |
| 5        | 7×5                            | S2      | 7.5            | 6.0           | S2(60)    |         |
| 6        | 7×5                            | S2      | 7.5            | 7.5           | S2(75)    |         |

3. Results and discussion
Flow characteristics were studied from the bed to the water surface. The changes in the flow velocity and planar flow structures were small in the vertical direction downstream of the pile-groups. Therefore, the mid-height layer ($z = 2.0\text{cm}$ from bed) is selected to show the results in the present study.

3.1. Effect of pile arrangement
Figure 3 shows the longitudinal velocity contours for different pile arrangements, which are normalized by the mean velocity ($U / U_m$). Figure 3 shows that the flow deceleration behind the pile-groups is directly related to the number of obstacles that are placed directly against the flow in each pattern (or the projection of the pile-group on the y-axis). Therefore, the Cases L1 and L2 show higher velocities than the Cases S1 and S2 behind the structure. Case S2 has the maximum piles directly against the flow (13 piles); therefore, it shows the minimum velocity in the downstream of the pile-group among the all other cases. Case S2 shows a negative velocity attached to the bank in Figure 3.
Besides the velocity magnitude, the flow pattern also changed to a favorable type in the Case S2, as shown in the velocity profiles in Figure 4, which are plotted at section $x/L = 1.0$. Cases L1, L2, and S1 show higher velocities near the bank and decrease toward the mainstream up to the tip of the structure. On the other hand, Case S2 gradually decreased the velocity from the maximum in the mainstream to a minimum near the bank.

Among the four patterns (L1, L2, S1, and S2), the first two patterns (Cases L1, and L2) show almost similar behavior with each other, however the Case S2 shows completely different and smooth velocity reduction. Therefore, the Cases L2 and S1 will be excluded from the next results and only the Cases L1 and S2 will be considered for comparison.

3.2. Effect of pile density

Figure 5 shows the contours of longitudinal velocity for different pile densities with two patterns of pile arrangements, L1 and S2. In both patterns of pile arrangements, by increasing the pile density, the flow in the mainstream accelerated and that behind the pile-group decelerated.
Figure 5. Contours of longitudinal velocity for different pile arrangements.

Figure 6 shows the velocity profiles at section $x / L = 1.0$ for different pile densities. Based on Figure 6, all the pile-groups including the low pile densities reduced the velocity behind the pile-group when compared with the no structure condition, Case NoS.

Regarding the pile arrangement, each case with S2 pattern shows lower velocity behind the structure than the case with L1 pattern that has the same pile density, as shown in Figure 6. Additionally, changing the arrangement of the piles from L1 to S2 pattern caused a gradual deceleration of the velocity from the mainstream to the bank, as shown in Figure 6.

Figure 6. Velocity profiles @ $x / L = 1.0$ for different pile densities, L1 (left) and S2 (right) patterns.

3.3. Effect of pile-groups in long downstream distance

It is worth specifying how far the velocity reduction effect of a pile-group groyne is maintained in the downstream. Figure 7 shows the effects of pile-group groynes 7x7L1 and 7x7S2 on the flow in a long downstream distance. Figure 7 shows that the flow in the far downstream of the pile-group groynes did not attack the bank like a typical impermeable groyne.
As the flow moves downstream, the width of the shear layer increases and the case 7x7L1 shows much wider shear layer than the case 7x7S2. The width between bands 1 and 1.5 is wider at far downstream (at section x/L=13.5) of the Case 7x7L1 compared to the Case 7x7S2, as shown in Figure 7. Therefore, it is inferred that the slow velocity in the downstream of the Case 7x7S2 tends to be maintained for a greater distance than the Case 7x7L1.

3.4. Effect of row spacing

Figure 8 shows the velocity contours for different row spacing with two pile arrangements, L1 and S2. By increasing the row spacing, the velocity behind the pile-group decreases in the L1 pattern, but increases in the S2 pattern. Case L1(45) shows higher velocity than the Case L1(75) behind the pile-group. On the other hand, it is the opposite in the S2 pattern as Case S2(45) shows negative velocity attached to the bank, which disappeared in the Case S2(75). The velocity profiles at section x/L = 1.0, which is shown is Figure 9, also shows that Case L1(45) has the maximum and the Case S2(45) has the minimum velocities near the bank.

Figure 7. Contours of longitudinal velocity for long downstream distance.
4. Conclusions

Effects of pile-group groynes on the flow velocity reduction for improvement of riverbank protection were investigated experimentally. Different aspects including pile density, arrangement, row spacing and effects on the long downstream were considered. In all the cases, the flow penetrated to the pile-group and discharged from the structure with reduced velocity. The velocity magnitude behind the pile-group can be controlled by changing the pile density. Regarding the flow pattern, pile arrangement pattern S2 created a gradual and smooth velocity reduction from the mainstream to the bank compared to the all other patterns. Additionally, the retarded velocity maintained up to a far downstream in the Case S2 compared to the Case L1. The row spacing had an opposite effect on the flow deceleration of the two arrangement patterns, L1 and S2. Small row spacing created the maximum velocity in the L1 pattern, but the minimum velocity in the S2 pattern. In order to explain the mechanism of the flow change and generation of different flow patterns behind the pile-groups, the flow path width and angle inside the pile-groups can be significantly important, which requires detailed investigations in the future.

5. References

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