EFFECTS OF PILE ARRANGEMENT ON THE FLOW AROUND A PILE-GROUP GROYNE

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When using a groyne for bank protection purposes, obtaining a smooth reduction of velocity from the mainstream to the bank with less turbulence around the structure is ideal. This can be achieved by applying modifications to groyne permeability or layout. Obviously, pile-arrangement type in a pile-group groyne significantly affects the downstream flow structure. However, these effects have not been sufficiently studied. In this study, the effects of different pile-group groynes on the flow characteristics were investigated experimentally. This research aimed to find an efficient design of pile arrangement in a pile-group groyne in order to produce a smooth flow reduction with low turbulence around the structure. Two types of pile arrangements, namely in-line and staggered arrays, were considered. The findings demonstrated that the staggered type caused a gradual deceleration of flow from the mainstream toward the bank, longer low-velocity field behind the structure, and drastic reduction in the turbulence around the structure when compared with the in-line type.

Key Words : permeable groyne, flow characteristics, turbulence, riverbank protection, flow control

1. INTRODUCTION

Control of riverbank erosion is of high importance, especially in the rivers that are close to infrastructures or those having a meandering tendency1), 2). One of the effective methods of protecting a bank is the construction of a series of groynes or spur dikes3). A groyne is a hydraulic structure that extends from a bank into the river to control the flow direction and velocity.

The presence of a groyne deflects the flow from the erodible banks. High resistance of an impermeable groyne to the flow causes increase in the upstream water level4), insufficient discharge capacity at high water stages, excessive acceleration of the mainstream, and pronounced scour hole around the tip of the groyne5)-10). Modifications to groyne permeability, structure, or alignment can suppress the unwanted effects of groynes7), 11), 12).

The high-velocity gradients at the groyne tip and the formation of turbulence structures along the shear layer are expected to contribute most to the exchange of mass and momentum and the erosion of bed material2), 13)-16). Therefore, modifications in the permeability and shape of groynes have been applied in the literature to reduce the velocity gradient, turbulence, or local scour near the groyne tip16), 17), 18). In terms of flow pattern and bed morphology around the structure, the advantages of a permeable groyne over an impermeable groyne, ranging from pile groynes19)-21) to bandal-like structures that consist of a pile row with upper impermeable part22), 23), are often reported in the literature12), 24). Specifically, gradual reduction of velocity from mainstream to the bank24), local scour reduction around the structure6), and enhancement of sediment deposition for further stabilization and reclamation of the eroded bank11), 25), 26) are the main advantages of permeable groynes that are reported in the literature.

A pile groyne, which consists of a single row of piles, has been proven useful for velocity reduction and limiting the erosion of banks and coast7)-29). In contrast with an impermeable groyne, Uijtewaal10) has reported reduction of the shear and turbulence intensity around a permeable pile groyne. However, a pile groyne with a single row of piles allows for relatively high permeability. Therefore, for sufficient flow control, applications of pile-group groynes that
combine multiple rows of piles within a group exist in rivers. Many pile-group groynes have been used along the Kiso and Yahagi Rivers in Japan for bank protection purposes. An example from the Kiso River is shown in Photo 1.

Compared to an impermeable groyne, the use of a pile-group groyne is expected to contribute to the reduction of excessive acceleration of the mainstream, avoiding severe local scour, weakening of the strong flow deviation and velocity gradient around the groyne head, and decreasing the resistance in flood levels, thus fulfilling most of the requirements formulated for a newly designed groyne\cite{10}. Ikeda et al.\cite{25} reported flow retardation and sediment deposition along the bank behind a pile-group groyne. The study considered one type of pile density in a staggered pile arrangement. Recently, Safie and Tominaga\cite{30, 31} have highlighted the effects of the pile arrangement within a pile-group groyne on the flow and bed characteristics. These authors found that a pile-group with a staggered arrangement of piles outperformed an in-line arrangement. The staggered arrangement shows lower velocity along the bank compared to the in-line arrays.

The number and type of arrangement of piles in the group affect the flow and turbulence characteristics and require more detailed investigations.

This study investigated the flow structure and turbulence around different pile-group groynes and a typical impermeable groyne. The study contained two main stages. First, the flow characteristics were studied in the vicinity of groynes to grasp the mechanism of the flow change by different arrangements of the piles in a group. Second, the changes in the flow were studied to far downstream (up to 14-times the groyne length) to determine the downstream distance that would be effectively affected by a groyne.

The principal aim of this research is, first and foremost, to obtain clear pictures of the flow produced by permeable pile-group groynes with different pile-arrangement types, thereby identifying a suitable pile-arrangement type for a smooth reduction of velocity from mainstream to the bank and suppressed turbulence around the structure. Second, the flow fields of the permeable pile-group groynes will be compared with the flow field in a typical impermeable one both near the structure and at far downstream. Third, to provide experimental data to test future numerical models.
2. MATERIAL AND METHODS

To study the flow structure and turbulence around groynes, experiments were conducted on different permeable pile-group groynes and a typically impermeable groyne. The particle image velocimetry (PIV) method was used to measure the velocities. The flume was 7.5m long, 0.3m wide, 0.4m deep, with a slope of 0.001 having a rectangular cross-section.

The pile-groups were made of acrylic cylinders with a diameter \(d_p\) of 0.5 cm and a height \(h_p\) of 5 cm. Length \(L\) and width \(W\) of the groynes were kept constant at 0.075 m in all permeable and impermeable cases, as shown in Fig.1. Consequently, the groynes in all the cases covered the same planar area. The number of piles was changed in the fixed area in each pile-group groyne and was defined as pile density. The same number of rows and columns \((n = m)\), hence the same face-to-face spacing between the piles in the \(x\) and \(y\) directions \(S_x = S_y\) was kept in each pile density; for instance, Fig.1 shows a 6×6 pile-group. The number of piles was increasing from 4×4 to 8×8 piles in the groups to change from a low to high pile density. The pile density is defined as follows:

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

where \(d_p\) is the pile diameter and \(S_x\) and \(S_y\) are the face-to-face spacing between the piles.

Additionally, two types of pile arrangements, namely in-line (L cases) and staggered (S cases) types, were applied for each pile density. In the in-line type, each pile after the first row was located exactly behind the first row; however, in the staggered arrangement, each pile was directly placed against the flow. As an example, the arrangement types for the 6×6 pile-group are shown in Fig.1. The groynes with the same pile-density but different pile arrangements have different projection areas on the \(y\)-axis, which depends on the number of piles that are placed directly against the flow, the details of all the cases are noted in Table 1.

The groynes were attached to one side of the channel. Figure 2 shows the schematic view of the groynes in the flume. The origin was selected to be the downstream edge of the groyne attached to the sidewall, as shown in Fig.2(a).

The flow conditions that are listed in Table 2 were selected to obtain a lower Froude number of 0.25 in order to suppress large fluctuation of water surface for flow visualization purpose. The experiments were conducted under a non-submerged clear water condition. The initial water-depth \(h\), measured just upstream of the groyne at \(x/L = -1\) with reference to Fig.2(a), was set to 0.04 m with the aid of a tailgate before installation of a structure in the flume. However, it changed around the structure after installation of each pile-group according to the pile density and arrangement. It rose to a maximum of 1.5 mm in the upstream of Case 8S.

The velocities were measured by the PIV method.

### Table 1 Details of the groynes.

| Case No. | Pile-group (row × column) \((n \times m)\) | Case name | Number of piles in a group | Pile spacing \(S_x = S_y\) (cm) | Groyne projection on \(y\)-axis (cm) | Pile density \(\lambda\) (1/cm) |
|----------|---------------------------------------------|-----------|-----------------------------|-------------------------------|----------------------------------|-------------------------------|
| 1        | 4×4 In-line \((n \times m)\)                | 4L        | 16                          | 1.83                          | 2.0                              | 0.092                         |
| 2        | 5×5 In-line                                 | 5L        | 25                          | 1.25                          | 2.5                              | 0.163                         |
| 3        | 6×6 In-line                                 | 6L        | 36                          | 0.90                          | 3.0                              | 0.255                         |
| 4        | 7×7 In-line                                 | 7L        | 49                          | 0.67                          | 3.5                              | 0.365                         |
| 5        | 8×8 In-line                                 | 8L        | 64                          | 0.50                          | 4.0                              | 0.500                         |
| 6        | 4×4 Staggered \((n \times m)\)              | 4S        | 14                          | 1.83                          | 3.5                              | 0.092                         |
| 7        | 5×5 Staggered                               | 5S        | 23                          | 1.25                          | 4.5                              | 0.163                         |
| 8        | 6×6 Staggered                               | 6S        | 33                          | 0.90                          | 5.5                              | 0.255                         |
| 9        | 7×7 Staggered                               | 7S        | 46                          | 0.67                          | 6.5                              | 0.365                         |
| 10       | 8×8 Staggered                               | 8S        | 60                          | 0.50                          | 7.5                              | 0.500                         |
| 11       | Impermeable                                 | Imp       | -                           | -                             | 7.5                              | -                             |
| 12       | No structure                                | NoS       | -                           | -                             | -                                | -                             |
For visualization of the flow, nylon resin particles (80 µm diameter and 1.02 in specific weight) were used. A 3 mm 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 a 5 mm increment. A high-speed video camera took the visual images at 200 frames per second, and they were recorded as Audio Video Interleaved (AVI) files with 1024 × 1024 pixels. Each pixel had a side dimension of 0.03 cm. Commercial PIV software (FlowExpert by Katokoken) was used for analyses. Time-averaged velocity vectors were obtained by processing 3200 successive images in 16 seconds. The averaging time of 16 s was confirmed to be sufficient to obtain steady time-average values by comparing with 50 s data.

For nomenclature purposes, each case name begins with a number indicating the number of rows and columns, combined with the letter L or S for in-line or staggered type, respectively. For instance, Case 6L represents a pile-group of 6×6 in-line, and Case 6S is named for the 6×6 staggered. The flow around an impermeable groyne that was named as Case Imp, and one experiment when no structure was installed in the channel, Case NoS, were also recorded, as noted in Table 1. Case NoS was considered to capture and compare the changes in the flow that occurred with the installation of a groyne in the channel.

3. RESULTS AND DISCUSSION

(1) Typical flow structure around a single impermeable groyne

In order to define the important expressions that will be used in the next sections, Fig.3 shows a simple typical flow structure that is caused by a single impermeable groyne, which was found in the previous studies32)-34). As depicted in Fig.3, the separated flow from the groyne tip eventually reaches the bank far downstream, called the reattachment point. The flow returns from the reattachment point and recirculates in the area behind the groyne. A large primary gyre occupies the greater part of the recirculation field, which is driven by the mainstream via an exchange of momentum through the interfacial mixing layer. The mixing layer is defined as the zone of gradual velocity change from a high velocity in the mainstream to a value close to zero in the recirculation field. There is a smaller counter-rotating secondary gyre in the upstream corner of the recirculation field, which gains momentum from the primary gyre10).

(2) Flow characteristics in the vicinity of the groynes

a) Vertical profiles of longitudinal velocity

In this study, flow characteristics are studied from the bed to the water surface. Figure 4 shows the vertical profiles of averaged longitudinal velocity \( U_w \), which is normalized by mean velocity \( U_m \). The velocity \( U_w \) is averaged behind the length \( L \) of the pile-group at the section \( x/L=1 \) and is defined by Equation (2).

| Table 2 Flow conditions. |
|---------------------------|
| Discharge \( Q \) (m³/s) | 0.00187 |
| Initial water depth \( h \) (m) | 0.040 |
| Mean velocity \( U_m \) (m/s) | 0.156 |
| Froude number \( F \) | 0.25 |
| Reynolds number \( Re \) | 6216 |

Fig.4 Vertical profiles of longitudinal velocities in the downstream of groyne at \( x/L=1 \): (a) in-line, (b) staggered cases.
where $U$ is the time-averaged longitudinal velocity and $z$ indicates the vertical direction. From Fig.4, it is clear that regardless of the type of pile arrangement, the presence of the piles reduced the bed shear effects, causing a milder velocity gradient over the vertical direction in comparison with the no structure condition (Case NoS), which is consistent with the findings of Ikeda et al.\(^2\)\(^5\). The deceleration of the bottom layer becomes more pronounced as the pile density becomes smaller. The impermeable groyne, Case Imp, shows a negative velocity that represents a return flow behind the structure. In Fig.4, the Case Imp shows almost zero velocity value near the bed. This does not represent a complete stagnant zone near the bed, but a zero value is caused by averaging the negative return flow near the sidewall and the positive flow near section $y/L = 1.0$.

Permeable pile groynes give rise to a rather uniform velocity profile in a non-submerged condition since the effect of the piles is present over the full water depth, which represents the rather two-dimensional nature of the flow\(^1\).\(^0\). The change in the flow velocity and planar flow structures was small in the vertical direction downstream of the pile group. Therefore, as a typical planar flow structure, a mid-height layer, $z/h = 0.5$ from the bed, is selected to show the results in the present study.

### b) Velocity contours and vector fields

Figure 5 shows the contours of longitudinal velocity ($U/U_m$) and Fig.6 shows the time-averaged velocity vectors ($U_r/U_m$), which are normalized by the mean velocity. $U_r$ is the resultant velocity in the horizontal ($x$-$y$) plane. The flow was from left to right in the represented figures. In contrast with the impermeable groyne, the momentum transfer by the water flowing through the permeable groynes prevented the formation of a recirculating flow\(^1\).\(^0\). Therefore, the permeability of pile-group groynes resulted in a unidirectional flow toward the downstream, as shown in the contours of Fig.5 and vectors in Fig.6. In both types of pile arrangements, by increasing the pile density, the number of obstacles increased against the flow, hence the flow in the mainstream accelerated, and that behind the pile-group decelerated.

In Figs.5 and 6, at the mainstream-face of the impermeable groyne (Case Imp), a return flow is noticed. This indicates that the flow separation started from the upstream edge of the impermeable
groyne, while the permeability of pile-group groynes suppressed a sudden separation of the flow from the upstream edge.

c) Average discharge behind groynes

Figure 7 shows the average discharge \( q_{\text{avg}} \) through the pile-groups just downstream of the structure. The average discharge \( q_{\text{avg}} \) was calculated from the velocity at the section \( x/L = 0.2 \) behind the length \( L \) of the pile-group that is defined by Equation (3).

\[
q_{\text{avg}} (x) = \int_0^L \int_0^h U(x, y, z) dydz
\]

In Fig.7, the average discharge \( q_{\text{avg}} \) is normalized by the discharge when no structure is installed in the channel \( q_{\text{avg \_NoS}} \) to enable a comparison of flow blockage rate by different pile densities and arrangements. All of the cases in Fig.7 show values lower than one. This shows that all of the pile-groups, including the low pile densities, are effective in discharge reduction in the downstream of the structure. The number and arrangement of the piles control the discharge through the structure. By increasing the pile density, the discharge reduces accordingly. Additionally, the piles in each row resist directly against the flow in the staggered type; therefore, the staggered arrangement shows a lower discharge than in the in-line type having the same pile density.

d) Average velocities near the bank and in the mainstream

The influence of the number and arrangement of piles on the velocity magnitude along the bank \( U_{\text{bank}} \) and in the mainstream \( U_{\text{main}} \) are shown in Fig.8. The averaged velocities along the bank and in the mainstream are normalized by the average velocity of Case NoS when no structure exists in the channel, \( U_{\text{bank \_NoS}} \) and \( U_{\text{main \_NoS}} \), respectively. The horizontal axis represents pile density; therefore, from left to right, the number of piles increases from \( 4 \times 4 \) to \( 8 \times 8 \). The vertical axis is the longitudinal velocity that is averaged in a specific volume from the bed to the surface over a specified area. Figure 8(c) shows a sketch of the areas for \( U_{\text{bank}} \) and \( U_{\text{main}} \). The \( U_{\text{bank}} \) was obtained by averaging the velocities in a volume defined by \( 0 < x/L \leq 2.0 \), \( 0.13 \leq y/L \leq 0.33 \) and vertically from the bed to the surface. The \( U_{\text{main}} \) was obtained by averaging the velocities in a volume defined by \( 0 < x/L \leq 2.0 \), \( 1.0 \leq y/L \leq 4.0 \) and vertically from the bed to the surface.

The plot in Fig.8(a) indicates that the velocity reduction near the bank \( U_{\text{bank}} \) is directly proportional to the pile density. Furthermore, the staggered
arrangement reduced the velocity significantly more than the in-line type, particularly in the high pile densities. By increasing the pile density, the gap between the values of in-line and staggered cases increases. In other words, the effect of pile arrangement on the flow along the bank becomes more significant in the high pile densities. On the other hand, Case Imp shows a negative velocity close to the bank, which corresponds to a return flow.

The average velocities in the mainstream \((U_{main})\) show a direct relationship between the mainstream acceleration and the pile density, as shown in Fig.8(b). However, all of the pile-group cases show significantly lower velocities in the mainstream compared to the Case Imp. The effect of pile-group structures on the acceleration of the mainstream tends to become identical for cases with high pile densities. That is, Case 7L with 8L and Case 7S with 8S have almost the same effects on the mainstream acceleration and the pile density, respectively.

Considering the number of piles in the two types of pile arrangements in a group, a lower pile density in the staggered type can perform similarly to a higher pile density in-line arrangement because each pile in each row is placed directly against the flow in the pile density of in-line arrangement because each pile in each row is placed directly against the flow in the pile arrangement. Therefore, a focus on the flow details around the structure is considered in Fig.10. The contours and vectors of longitudinal velocity \((U/L)\) in Fig.10(a) show the difference in the flow pattern. Figure 10(b) shows a schematic representation of the groyne inflow and outflow. To depict the most important differences between the in-line and staggered types, Fig.10(d) shows a schematic representation of the groyne inflow and outflow.

Two types of flow paths are introduced in Fig.10(d). Path1 and Path2 are sketched representa-
tively for the two types of flow paths to show that no obstacles exist along these paths. Path1 has a direction parallel to the mainstream, while Path2 is inclined to the mainstream. The normal spacing between two lines of a path is defined as path width. The widths of Path1 and Path2 are the opposite in two types of arrangements. Path1 is wider than Path2 in the in-line type; however, in the staggered arrangement, Path2 is wider than Path1. The widths of these paths governed the magnitude and direction of the outflow in the downstream. This is further explained below.

The existence of a structure enhances the deviation of the upstream flow. Therefore, the penetrating flow in the upstream of the pile-group shows two main types of flow-penetration angles to the pile-group. Near the bank, the flow penetrated the structure in a parallel direction with the mainstream, while near the tip, it inclined in an angle, as shown by the two large arrows just upstream of each pile-group in Fig.10(d). Considering the inflow angle and the path widths, in the in-line type, the flow penetrates a wider path (Path1) near the bank and a narrower path (Path2) near the tip. In contrast, it is the opposite in the staggered type. As a result, in a lateral section just downstream of the pile-group, the in-line type shows a higher velocity near the bank and lower velocity near the tip (Fig.10(a)). On the other hand, the staggered type shows a minimum velocity near the bank and increasing gradually to the mainstream. In other words, the magnitude of outflow is larger from the wider path. Therefore, the outflow leaves the in-line pile-group in the same direction as of the mainstream flow, while in the staggered type it is inclined from the bank towards the mainstream, as shown in Fig.10(c). It is clear from Fig.10(d) that the wider path direction controls the outflow direction in both types of arrangements.

**Fig.10** Detailed flow around groynes: (a) contours of longitudinal velocity; (b) contours of transverse velocity; (c) time-averaged velocity vectors; (d) schematized inflow and outflow of groynes.
In addition, Fig.10(c) shows different outflow velocity vectors attached to the mainstream side of the in-line and staggered pile-groups at section \(y/L=1\). The wider Path2 in the staggered type resulted in a faster outflow in the mainstream face of the pile-group compared to the in-line type. **Figure 11** shows the longitudinal velocity profile attached to the mainstream face of the pile-group at section \(y/L=1\). Three peaks of higher velocity can be noticed along the width of the staggered pile-group from \(-1\) to \(0\), which are the three outflows from Path2, as depicted by the arrows in **Fig.10(d)**. Additionally, Figs.9(a) and (b) show larger longitudinal and transverse velocities on the mainstream side (at \(y/L=1\)) of the staggered pile-group between every two successive piles compared to the in-line type, which indicates larger outflow on the mainstream-face of the staggered pile-group than that in the in-line type.

**f) Reynolds stress**

Besides the flow magnitude and structure, the downstream turbulence is also strongly influenced by the type of pile arrangement. **Figure 12** shows the contours of Reynolds stress \(-\overline{uv}/U_m^2\), where \(u\) and \(v\) are the velocity fluctuations in the longitudinal and transverse directions, respectively. **Figure 12** represents a dramatic difference in the turbulence between both types of pile arrangements. By increasing the pile density, a region of intense turbulence appeared in the downstream of the in-line type, whereas the staggered type did not generate such strong turbulence.

With reference to the velocity profiles in **Fig.9**, the in-line cases have a minimum velocity at the downstream behind the tip of the structure at \(y/L=1\), then there is a sudden jump to maximum velocity in the mainstream. Therefore, abrupt change in velocity from a minimum to a maximum value created a steep velocity-gradient and contributed to the generation of high turbulence along the shear layer in the in-line cases. On the other hand, staggered cases had a minimum velocity near the bank and increased gradually to the mainstream. As a result, the velocity increased smoothly from the bank to the mainstream and created a milder velocity-gradient than that in the in-line cases. Therefore, it prevented the generation of such a high turbulence region in the channel.
As seen in Fig.12, the low pile densities, Cases 5L and 5S, caused rather similar turbulence. Increasing the pile density, which resulted in increasing the velocity gradient along the shear layer, enhanced the turbulence in the in-line type; however, the increase in the velocity gradient did not affect the turbulence in the staggered type, and the turbulence remained suppressed in the downstream of the staggered type even in the high pile-densities. Therefore, the turbulence in the downstream of the staggered pile-groups cannot be explained from the shear in the mean flow field only. The detailed mechanism of the turbulence generation in the downstream of the pile-groups requires further investigations.

In the in-line cases, pile density controls the strength of the Reynolds stress in the downstream. The turbulence becomes stronger by increasing the pile density. Since, in the in-line cases, the difference between the value of the minimum-velocity behind the tip at y/L=1 and peak-velocity in the mainstream increases by increasing the pile-group density, in other words, the gradient becomes steeper by increasing the pile density. Therefore, the strength of the peak region of Reynolds stress increases accordingly. The high pile density in the in-line type shows a turbulence region similar to the impermeable structure (Case Imp). However, Case Imp shows maximum turbulence in that region.

(3) Long downstream distance influenced by the groynes

a) Velocity fields and turbulence

It is worth specifying how far the velocity reduction effect of a single pile-group groyne is maintained in the downstream. The effects of a single permeable and impermeable groyne on the flow and turbulence are shown in Fig.13. In Fig.13(a), the impermeable groyne shows a reattachment of the deviated flow at approximately x/L = 12. From that point, the flow returns to the upstream behind the structure. However, the permeability of pile-group groynes resulted in a unidirectional flow that was parallel to the main flow. The reattachment of the deviated flow to the bank is clearly visible in the vectors of Fig.13(c) in the impermeable groyne, while in the permeable groynes, the flow does not attack the bank.

Figure 13(b) reveals a large difference in the turbulence induced by the two types of pile arrangements along the mixing layer. The in-line type shows stronger turbulence in the upstream, which is dispersed in the far downstream, while the staggered type shows a dramatic reduction in the upstream turbulence and rather higher turbulence in the far downstream. The larger velocity gradient in the far downstream of the staggered type can contribute to the stronger turbulence in the region. The flow penetration into the permeable groynes influences the downstream turbulence generation and structure. Therefore, as mentioned in the previous section, the turbulence along the mixing layer in the permeable groynes cannot be explained from the shear in the mean flow field only. The detailed mechanism of the turbulence generation in the downstream of the pile-groups requires further detailed investigations.

The impermeable groyne generated significantly high turbulence compared to the permeable groynes. The turbulence in the Case Imp spread wider as it traveled downstream.

b) Longitudinal velocity profiles

The velocity profiles in Fig.14 represent a further analysis of the velocity gradient along the shear layer. Considering the velocity gradients in the upstream at section x/L = 0.1 and far downstream at x/L = 13 in Fig.14, the velocity profiles in the in-line type show a steep slope in the mixing layer in the upstream region that converts rapidly to a gentle slope in the downstream relative to the staggered type. In contrast, the staggered type shows a milder slope in the upstream that slowly flattens as it moves downstream in comparison with the in-line type. The velocity profiles in the impermeable groyne show maximum deformation from the upstream to the far downstream compared to the permeable groynes. Figure 14 shows a similarity in velocity profile trends for in-line and impermeable groynes. The above comparison reveals that the staggered arrangement maintains a larger velocity gradient to the far downstream. However, the in-line type shows a rapidly diffused flow in the mixing layer in comparison with the staggered type. The flattening of the velocity profiles along the mixing layer can be interpreted as the retarded-flow recovery downstream of the groyne. From the above comparison, it is inferred that the slow velocity in the downstream of the staggered type tends to be maintained for a greater distance than that in the in-line type. The change in the flow direction immediately behind the in-line and staggered pile-groups and the difference in the flow magnitudes in the far downstream of the two pile-group types can be clearly seen from the velocity vector fields in Fig.14.

c) Velocity gradient

Figure 15 shows the velocity gradient in the mixing layer at various sections starting from the downstream edge of the groyne x/L = 0.1 up to the far downstream section x/L=13. Each velocity gradient value in Fig.15 is the slope of a linear regression line that is obtained by plotting the maximum slope of longitudinal velocity in the lateral section.
In Fig. 15, the velocity gradient is high near the downstream tip of the structure at $x/L = 0.1$, which is due to the flow separation by the structure. Then, the gradient decreases gradually downstream with the widening of the mixing layer. The velocity gradient along the mixing layer can also be recognized from the distance between the contour lines in Fig. 13(a).

In the upstream, for instance, at section $x/L = 1$, the contour lines of Case 7L are tightly compressed along the mixing layer, as shown in Figs. 12(a) and 9(a). On the other hand, Case 7S stretches out the contours to the mainstream-side in that section.

Fig. 13 Flow and turbulence in a long downstream distance of a groyne: (a) contours of longitudinal velocity; (b) contours of Reynolds stress; (c) velocity vector fields.
Therefore, the in-line arrangement shows a high velocity-gradient along the deviated flow direction, but the staggered type represents a slightly expanded flow distribution along the flow separation line. However, the impermeable groyne shows the largest velocity gradient in the upstream.

At far downstream of the pile-group groynes, the width of the shear layer widens, becoming larger in the in-line arrangement relative to the staggered type, which shows an opposite feature compared to the upstream. The width between bands 1 and 1.5 is wider, far downstream of the in-line type compared to the staggered type in Fig.13(a) at section \( x/L = 13.5 \).

4. CONCLUSIONS

To improve riverbank protection, the effects of pile density and arrangement on the flow characteristics around pile-group groynes were investigated experimentally for velocity control along the bank. This research aimed at identifying an efficient design of pile arrangement in a pile-group groyne to produce a smooth flow reduction with low turbulence around the structure. The main conclusions from this study are as follows:

The velocity magnitude along the bank can be controlled by the pile density (number of piles in a group). It was found that the type of pile arrangement within a group significantly affected the flow magnitude, pattern, and turbulence parameters. The staggered type arrangement represented better improvements compared to the in-line type. The gradual reduction of velocity from the mainstream to the bank, the substantial decrease in turbulence around the structure, and preservation of the retarded flow to far downstream distance were the main favorable features of the staggered type. In addition, the in-line type showed a discharge that was parallel to the mainstream flow, while the staggered type guided the outflow inclined from the bank to the mainstream.

The mechanism of the flow change by different arrangements of piles in a group was also demonstrated with the existence of different flow paths within the group. From the type of flow paths within a pile-group, it was inferred that the width and direction of the paths were responsible for determining the magnitude and direction of the downstream flow.

A comparison of the two types of pile arrangements in a pile-group groyne expressed that the staggered arrays could reduce the number of piles to almost half in most cases. Therefore, the material, construction, and maintenance cost could be considerably decreased by using the staggered type.

Fig.14 Longitudinal velocity profiles in the lateral direction at different sections.

Fig.15 Velocity gradient behind the groyne at different sections.
A dual feature was revealed in the turbulence intensity of the most upstream and far downstream of a pile-group groyne by investigating long downstream distance affected by a single groyne. This feature was reversed in the in-line and staggered types; the turbulence was suppressed at the most upstream part of the staggered type compared to the in-line type, while it was the opposite in the far downstream region. From the above feature, it was inferred that the retarded velocity maintained a long distance in the staggered type compared to the in-line arrangement.

The establishment of a large recirculation zone, steep velocity gradient, and strong turbulence along the shear layer were the main dissimilarities among the impermeable and pile-group groynes.

This study revealed some unknown perspectives of the flow induced by pile-group groynes having different pile arrangements, which could be useful in practical engineering fields. However, the detailed mechanism of the turbulence generation, morphodynamic evolutions around the structure, and the effects of pile-group submergence require further investigation.

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