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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/110251

Vorgeschlagene Zitierweise/Suggested citation:
Jong, Jaehun; Tominaga, Akihiro (2008): Flow Structure and Sediment Trasport around Groynes in Compound Open Channels. In: Wang, Sam S. Y. (Hg.): ICHE 2008. Proceedings of the 8th International Conference on Hydro-Science and Engineering, September 9-12, 2008, Nagoya, Japan. Nagoya: Nagoya Hydraulic Research Institute for River Basin Management.

FLOW STRUCTURE AND SEDIMENT TRASPORT AROUND GROYNES IN COMPOUND OPEN CHANNELS

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ABSTRACT

The purpose of a groyne is to protect riverbank from erosion and to converge flow to the river axis. At the same time, it provides ecological environment for river shores. The flow structures around groynes and in the groyne area (embayment) are very complicated depending on the groyne length, flow depth and channel bed conditions. Groynes and embayment are often constructed in rivers with flood plains. The groynes on the flood plain may cause much scour and sand deposition by the flow interaction between main-channel and floodplain, superimposed on their obstruction and contraction effects. The flow structures around groynes on the floodplain are presumably different from those in a single main-channel. In order to investigate the flow structures around groynes in compound open channels, we performed experimental study by using Particle Image velocimetry (PIV). Velocities were measured in a compound open channel with setting groynes of different lengths on the flood plain. In addition, the secondary flow structures were clarified by synthesizing the velocity components in horizontal and vertical planes. The groynes on the flood plain deflected the main flow and produced 3-D flow structures around the groynes. These local flow features influenced the main channel flow and generated the strong secondary flows in the main channel.

Keywords: groyne, compound open channel, 3-D flow structure, PIV

1. INTRODUCTION

Recently, after frequent flood disasters, excavation of riverbed is implemented to increase river conveyance. In compound rivers, a part of flood plain is sometimes excavated to expand flow cross-sectional area. These improvement works make dry riverbeds or wetlands along riversides, and at the same time, provide good environment for ecology. Figure 1 shows a plan view of excavating area of the Ibi River. In this area, old groynes constructed about 100-years ago were exposed. These groynes are preserved from a historical point of view and these make embayment area in the flood plain of the right bank, as shown in Figure 1. The river width is about 250m and the length of the groyne is 60m to 90m. The height of the groyne is about 1.8m. This excavation of the flood plain makes three-stage flow, which is composed of a main channel, a flood plain and groyne field. After one year from the work, considerable sand deposition was observed behind the groynes and embayment area, as shown in Figure 1. In order to maintain and the function of groynes, on the flood plain, it is necessary to understand the flow structures in this complex river condition. The flow structures include typical flow patterns of compound open channel flows and local flows through groynes.

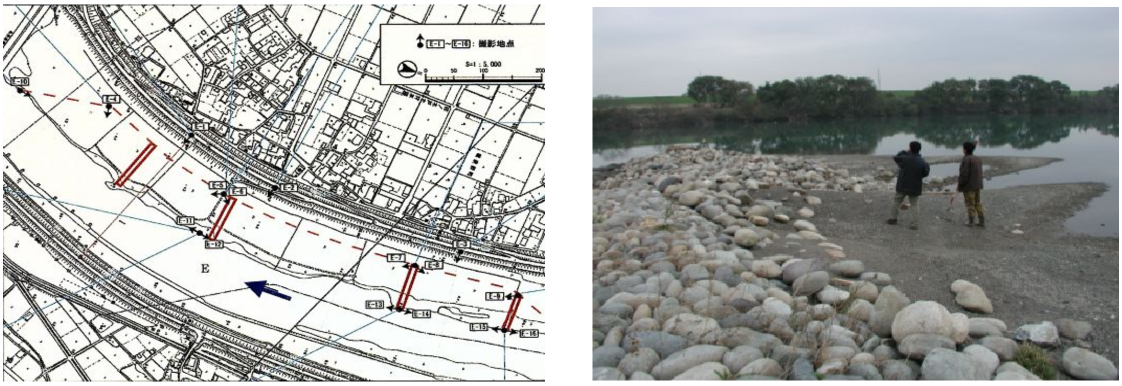

Figure 1 Groynes in compound open channel of the Ibi River, Ohgaki city in Japan
(Left: Excavating work in the Ibi River, Right: Groyne and downstream sediment)

In compound open channel flows, significant momentum exchange occurs laterally, causing deceleration in the main channel and acceleration on the flood plains. It is postulated that large-scale planform vortices, rotating about a vertical axis (Knight & Sellin, 1987), and streamwise secondary flows (Tominaga & Nezu, 1991) are the reason for the momentum transfer from the main channel to the flood plain. On the other hand, open channel flows with embayment or with groynes are characterized by separation vortices interacting with the main flow (McCoy et al., 2008). Weitbrecht et al. (2008) studied the mass exchange of dissolved tracer between the main channel and groyne field. As similar researches to groyne in compound open channel, the effects of abutments in compound channels were studied by Sturm (2006) and Melville et al. (2006). They measured velocity and scour depth around abutment in compound channels. In the case of submerged groynes, the vertical vortices caused by the side flow and transverse vortices caused by the top flow interact with each other and produce characteristic three-dimensional vortex structures (Tominaga et al., 2001; 2003).

In this study, we investigated three-dimensional flow structures around groynes and embayment zone in a compound open channel experimentally. We picked up the groyne length and water depth as design items and investigated their effects on the flow structures in the groyne zone by using PIV method. The analysis was focused on the secondary flow, which is closely related to the cause of groyne scour and the sand deposition in embayment zone. Combination of two-dimensional PIV analyses of vertical and horizontal sections could reproduce the time-averaged three-dimensional flow structures in groyne zones as demonstrated by Tominaga et al. (2001). The purpose of this study is to predict the influence of 3-D local flow around groynes on the flow structures in compound open channels.

2. EXPERIMENTAL SETUP AND METHOD

The experiments were conducted in an 8m long and 0.3m wide rectangular flume. The slope of the flume was set as 1/1000. A rectangular flood plain was set on the left-hand side of the flume. The flood plain was 0.2m wide and 0.02m high. The groyne zone was located 6.5m downstream from the channel entrance. The interval of two groynes was adjusted to 0.33m. The setup of groyne zone is shown in Figure 2. The groyne model is a rectangular solid with 0.02m in height and 0.005m in width. The length of groyne is in 0.2m in the case A and 0.1m in the case B. The discharge Q of series 1 and 2 was set as $0.0016\text{m}^3/\text{s}$ and $0.0008\text{m}^3/\text{s}$, and then water depth was set as 0.06m and 0.04m, respectively, by adjusting the downstream weir. These were presupposed that submerged and emerged conditions were established on the flood plain (see Figure 3). The cases A1 and B1 correspond to the high-

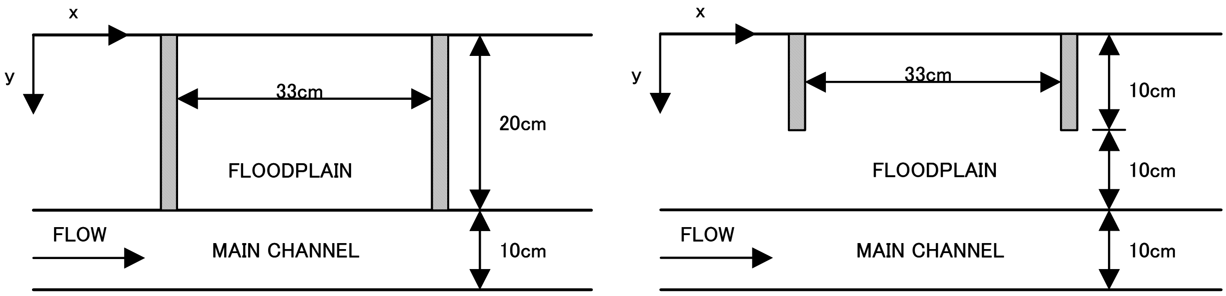

Figure 2 Plan view of the groyne field in compound channel

stage flow and groynes were submerged, whereas the case A2 and B2 correspond to the middle-stage flow and groynes were emerged. Groynes with different length were used to see the influence of the groyne length.

For visualizing the flow, the tracer of nylon resin particles with 50micron in diameter and 1.02 in specific weight were used. The argon laser light sheet with about 3mm thickness was projected on vertical (*x-z*) planes and horizontal (*x-y*) planes. The laser sheet was projected at every 10mm vertical sections from the left wall (10mm) to the right wall (270mm). In addition, the tip section of the short groyne (105mm) and the boundary section between flood plane and main channel (205mm) were added. The projection height for horizontal planes were 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55mm from the main-channel bottom in the case A1 and B1, 5, 10, 15, 20, 25, 30, 35mm in the case A2 and B2. Secondary flow velocity in the cross section could be reproduced by synthesizing vertical and horizontal velocities in each section. The visual images were taken by using high-speed video camera. The images were recorded in the hard disk of the computer as "TIFF'' files with 640x480 pixels. The velocity vectors were calculated by using ''VISIFLOW'' PIV system software (AEA Technology). The image area was changed in the entire size and responding to the mean velocity to realize the acceptable dynamic range. The resolution of the image analysis was 32x32 pixels and the overlap was 75%. Time-averaged velocity vectors were obtained by processing 3,200 successive images in 16s with a time interval of 1/200s.

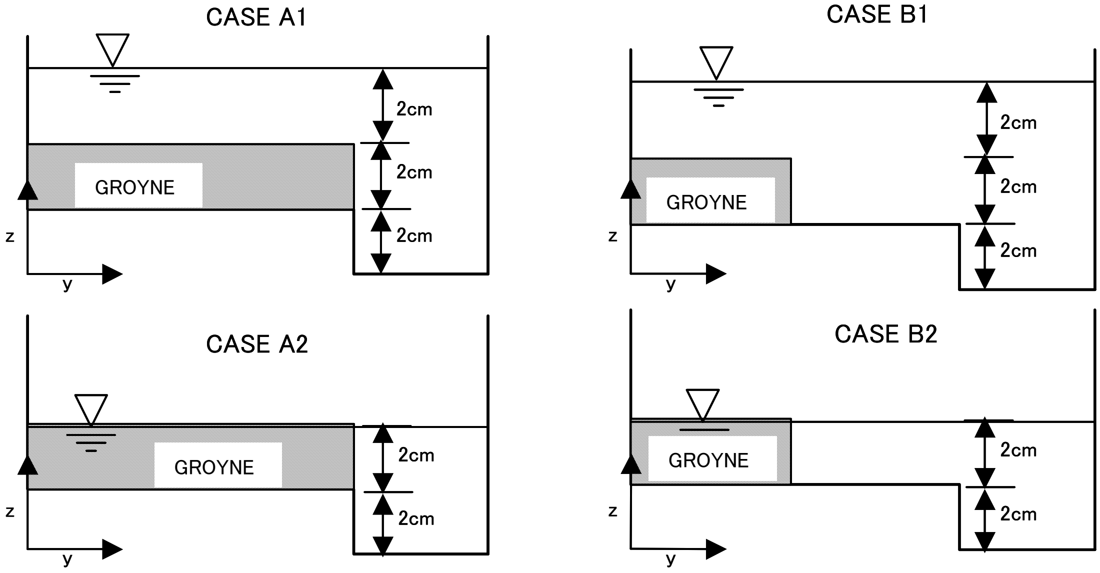

Figure 3 Cross-sectional views of the different experimental setups and cases

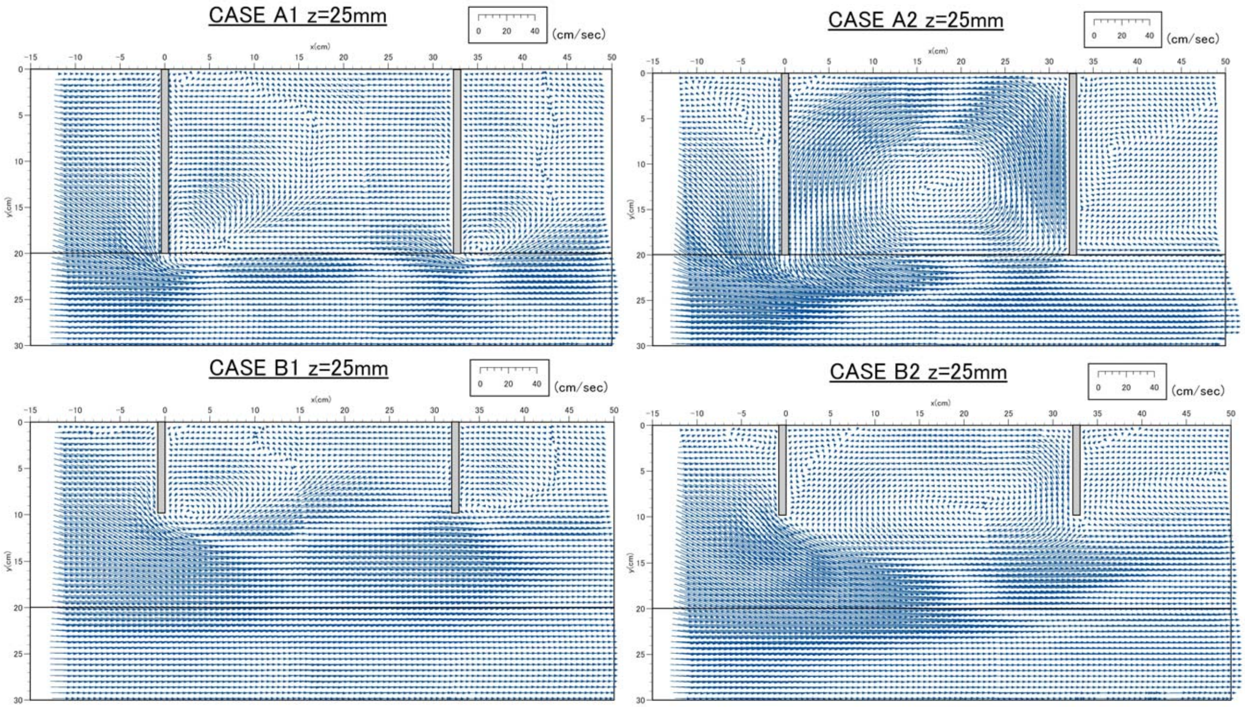

Figure 4 Velocity vectors in horizontal plane at z=25mm

3. ANALYSIS OF RESULTS

3.1 Time-averaged velocity vectors

Figure 4 shows the time-averaged velocity vectors for the horizontal plane of z=25mm. A significant deflection is observed from the tip of the first groyne in all cases. In the case A2, a large recirculation vortex is formed in the embayment area. In this case, the outflow behind the first groyne intensely influences the main channel flow. However, the deflected flow is restricted in the left-half of the main channel. This feature is specific to a compound channel flow with groyne on a flood plain. In the region behind the second groyne, no significant vortex is observed. In the case B2, the deflected flow develops far outward and affects the main-channel flow. This forms large-scale horizontal vortex reaching to the second groyne. Since the main-channel flow seems not to affect the local flow caused by the groynes, this structure shows a typical flow pattern of the groyne zone with the same aspect ratio. In the case of submerged groyne, a large-scale horizontal vortex is not produced but small-scale attached vortex appears just behind the tip of groyne. The vectors designate the interface between transverse vortex generated by the overtopping flow and the reattached flow in the embayment area. The distance from the groyne to the interface attains maximum at the middle of the groyne length and become small toward the sidewall and the main channel. This distance becomes smaller behind the second groyne. In the case A1, a small deflection is

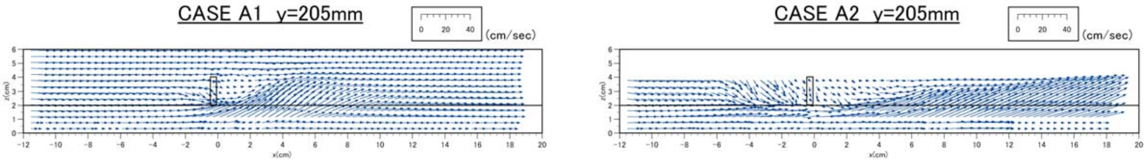

Figure 5 Velocity vectors in vertical planes of case A1 and A2 at y=205mm

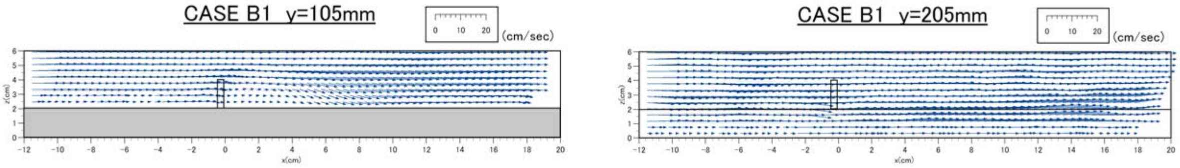

Figure 6 Velocity vectors in vertical planes of case B1 at y=105mm, y=205mm

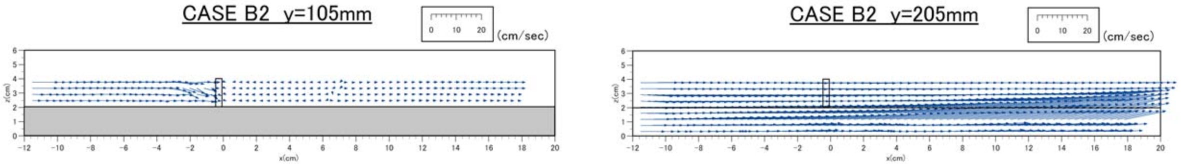

Figure 7 Velocity vector in vertical planes of case B2 at y=105mm, y=205mm

observed at the tip of the second groyne. In the case B1, the effects of the local flow on the main channel flow to be little.

Figure 5, 6 and 7 show the velocity vectors in vertical plane at the boundary between flood plain and main channel (y=205mm) and the tip of short groyne (y=105mm). In the case of long groynes, a strong upflow is produced just behind the first groyne. The upflow comes from the main channel water below the flood plain height. The upward velocity becomes maximum value at x=4cm to 6cm in the submerged case (A1), but it is still increasing toward the downstream region in the emerged case (A2). These significant upflow implies that a secondary flow was generated in the cross sections of compound open channels. In the case of short groyne, a similar upflow appears behind the first groyne at the boundary between main channel and flood plain, but its strength becomes smaller than the long groyne case. In the same manner as the case A2, the upflow increases while moving to the downstream (Figure 5 and 7). On the other hand, no upflow occurs at the tip section of short groyne, but a downflow

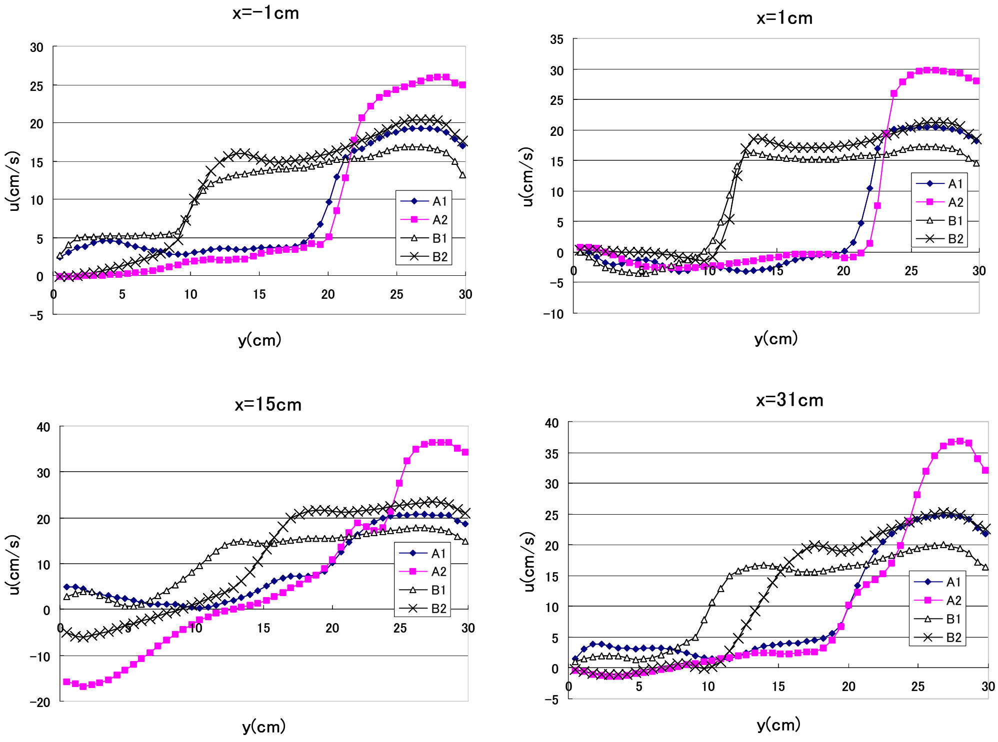

Figure 8 Velocity profiles of cross section at z=30mm of vertical plane
(Position of cross-section x=-1cm, 1cm, 15cm and 31cm)

is observed in the groyne zone of the emerged case.

3.2 Velocity profiles

Lateral distributions of the primary mean velocity are shown in Figure 8 at z=30mm for the longitudinal section of x=-1cm, 1cm, 15cm and 31cm. The contraction caused by the groyne raises the velocity in the residual area in the flood plain and the main channel. In addition, the higher velocity in the main channel relative to the velocity in the flood plain is characteristic of the compound open channels. Since the contraction effect is larger in the emerged case than the submerged case, the velocity in the outer area becomes higher in the emerged case. In the case of short groyne, the acceleration in the flood plain is noticeable. In the case B2, lateral shear layer moves toward the main channel. In the case A2, the velocity in the left-half part of the main channel is decelerated and the right half is accelerated in the downstream region.

3.3 Secondary flows

The flow structures in compound open channels are characterized by large shear layers generated by the difference of velocity between the main-channel flow and the flood-plain

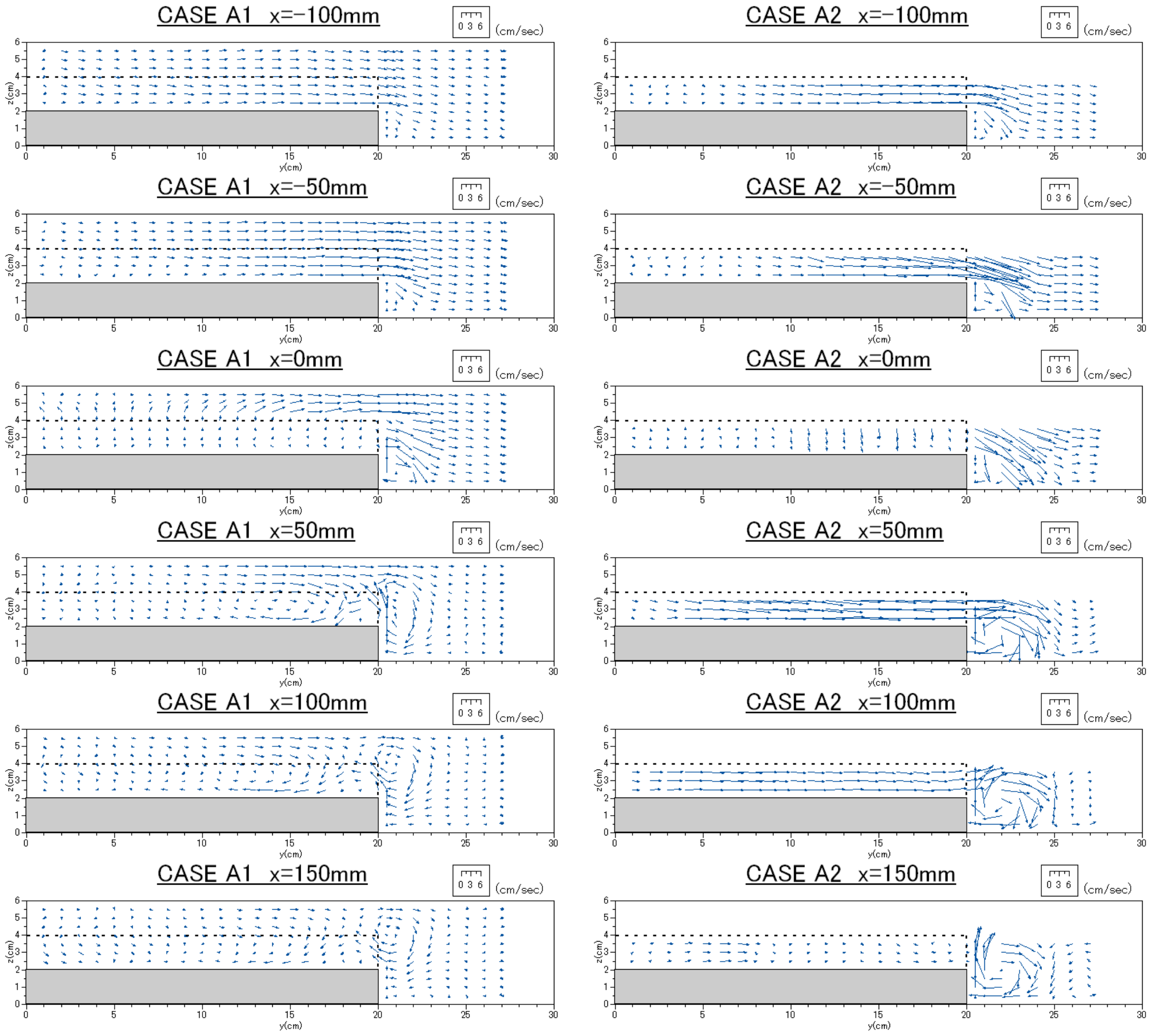

Figure 9 Secondary flow vectors of case A1 and A2

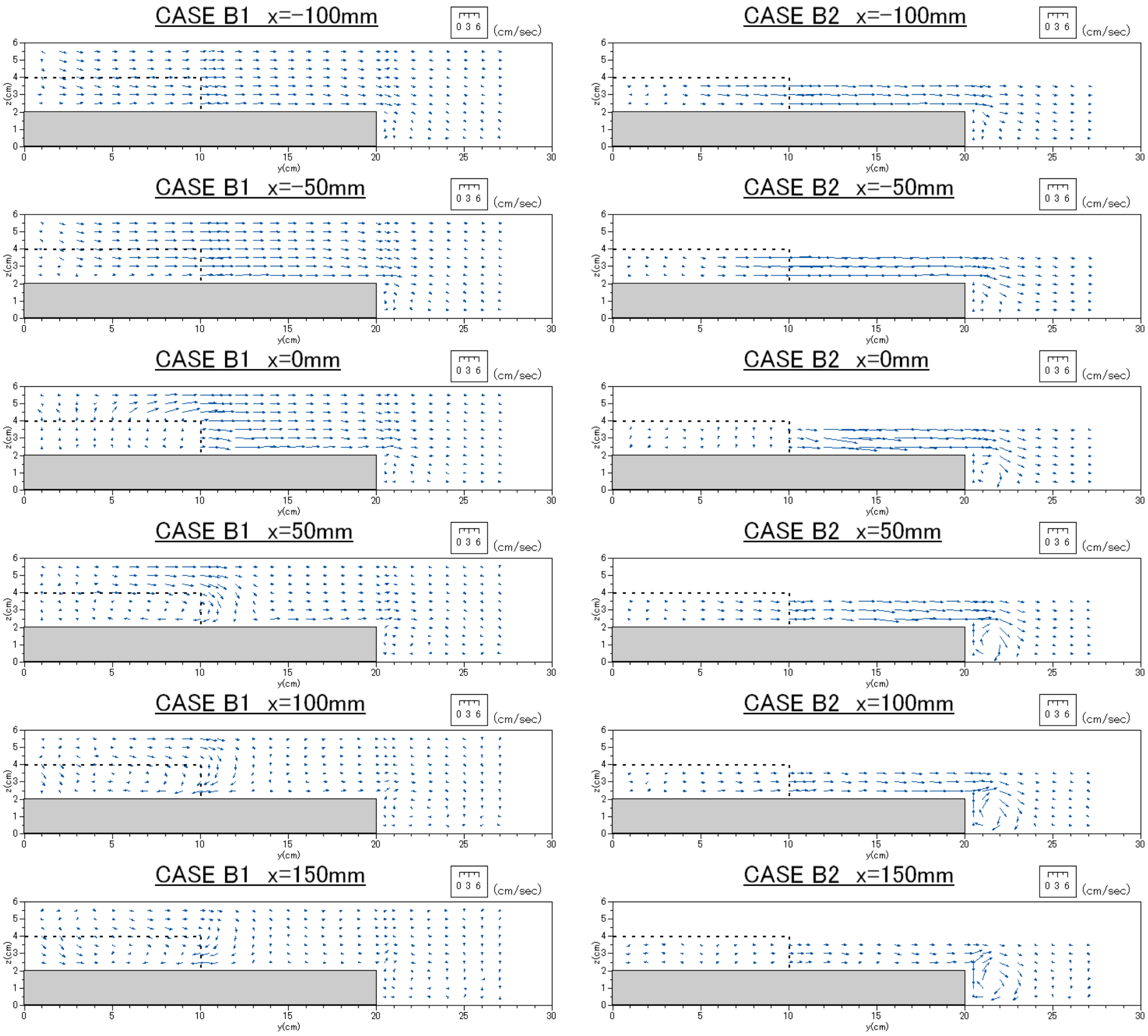

Figure 10 Secondary flows vector of case B1 and B2

flow. In this study, a similar flow was caused by the installation of groyne on the flood plain. The secondary flow structures were obtained by synthesizing the velocity data in horizontal and vertical sections. The secondary flow vectors are shown in Figure 9 and 10. In the case A2, the lateral flow toward the main channel angled by the first groyne intrudes into the main channel and generates the downflow. This downflow causes the longitudinal vortex attached on the flood plain wall. This longitudinal vortex develops in the region downstream the first groyne and it causes the strong upflow at the boundary between main channel and flood plain. In the case A1, the lateral flow caused by the groyne intrudes into the main channel from the upper level of the groyne top. This causes downflow in the main channel and generates the longitudinal vortex. However, this vortex is weaker and it exists in the upper region of the main channel in contrast to the case A2. In the downstream region behind the first groyne, another longitudinal vortex appears. This is also observed in the case B2 and this is considered to be a general feature in submerged groynes. In the case B2 a strong lateral flow angled by the first groyne remains on the outer area of the flood plain. This lateral flow also causes the similar longitudinal vortex as the case A2. In the case B1, the lateral flow on the outer flood plain becomes small, but it affects the main channel flow. In the downstream region where the lateral flow on the flood plain diminishes, weak secondary flow pattern characteristic of the compound channel is observed. It is demonstrated that the lateral flow on the flood plain causes the strong longitudinal vortex in the main channel. This swirling flow structure is liable to affect the sediment transport in compound open channels.

4 CONCLUSIONS

3-D flow structures around groyne in compound open channel were investigated experimentally, analyzing the time-averaged velocity of horizontal plane and vertical plane by using PIV. When groynes were installed on the floodplain, secondary flows occurred and it affected the flow structures in the main channel. In the case of short groyne, the flow in the outer flood plain is accelerated considerably and influences the bed deformation on the flood plain. When groynes are emerged, main flows are deflected toward the main channels that affect the main channel flow. The deflected flows interact with the flow of the compound channel and generate the longitudinal vortex in the main channel. This longitudinal vortex must cause large bed deformation and sediment deposition on the flood plain. The effect of these 3-D flow structures on the sediment transport should be investigated.

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