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Experimental Study on Flow and Bank Erosion in Steep and Curved Trapezoidal Channels

EXPERIMENTAL STUDY ON FLOW AND BANK EROSION IN STEEP AND CURVED TRAPEZOIDAL CHANNELS

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ABSTRACT

It is very difficult to evaluate the quantity of sediment transport in steep rivers and there are many unknowns concerning the relations between flow characteristics and bank erosion. This paper aims at investigating the characteristics of sediment transport as well as bank erosion process in curved steep slope rivers through hydraulic experiments. The experiments were conducted by varying the width and the curvature of the trapezoidal channel for different discharge. Riverbed elevation was measured at start and end of each test. During the tests, flow pattern and the shape of river channel were recorded by video cameras and Particle Image Velocimetry (PIV) method was used for both measuring velocities and analyzing sediment transport characteristics. By using two kinds of tracers, not only surface flow pattern but also depth-averaged velocity distribution could be measured, from which the difference between each flow pattern was made clear. Flow pattern near the bed was also estimated by analyzing transport of the colored sand. It was also made clear that bank erosion process and characteristics of sediment transport were influenced by the complicated secondary flow generated due to the strong curvature of the channel.

Keywords: steep river, bed form, bank erosion, secondary flow and sediment transport

1. INTRODUCTION

In Japan, the landslides caused by intense rainfall and snow melts take place at a remarkable rate and a great quantity of sediment is discharged at the upper reaches. From the view point of the comprehensive sediment management, it is necessary to convey the sediment flow downstream in a natural way. Therefore, sediment flushing operations and grid dams are often adopted at the upper reaches. However, it is very difficult to evaluate the quantity of sediment transport in steep rivers and there are many unknown factors concerning the relations between flow characteristics and bank erosion. Because the curved reaches in rivers are considered to be structural weak points, many experimental researches have been carried on (e.g., Muramoto et al., 1968; Hasegawa, 1983). However, most of the objects of such researches were alluvial channels and few experiments have treated steep slope rivers.

This paper aims at investigating the characteristics of sediment transport as well as bank erosion process in curved steep slope rivers by conducting hydraulic experiments. Hydraulic experiments with fixed bed were conducted for describing flow patterns in the curved steep river. By using two kinds of tracers, not only surface flow pattern but also depth-averaged velocity distribution was measured. Moreover, experiments with movable bed were carried out for investigating bed form and sediment transport.

2. EXPERIMENTS

The experiments were conducted in a curved flume with a length of 12m and a width of 2.0m. Flood plain was set as shown in Figure 1. The trapezoidal lower channel located along the center of the flume was composed with straight and arc channels. Water was circulated by a pump, and the discharge was measured with a magnetic flowmeter. An adjustable tailgate controlled the flow depth at the downstream end.

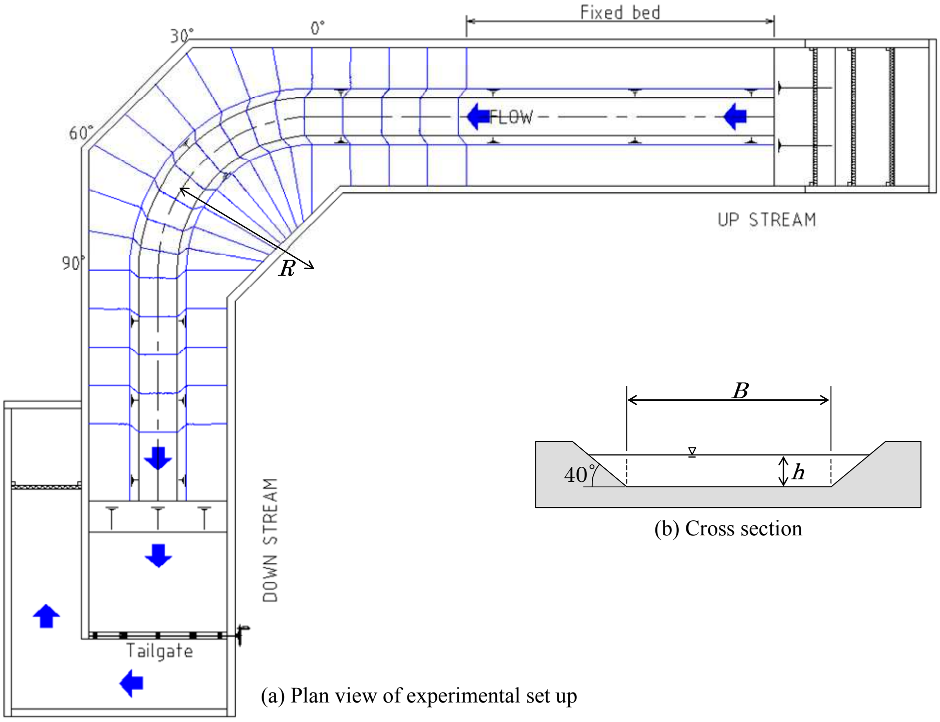


Figure 1 Experimental set up

Ten kinds of experiments as indicated in Table 1 were conducted in which the river bed condition, the width and curvature of the trapezoidal channel and discharge were changed. The bed with a slope of 1/80 was formed in the all experiments. The flume was spread with mortar for the experiments with the fixed bed and filled with 1.86mm silica sand for the experiments with the movable bed. The molded flume was filled with still water before the start of experiments. Then the tailgate was opened and the water was recirculated.

The elevation of free surface was measured by an ultrasonic sensor. The riverbed elevation was measured by a CCD laser displacement sensor at start and end of each test. During the tests, the flow pattern and the shape of river channel were recorded by digital video cameras and the Particle Image Velocimetry (PIV) method was used for both measuring velocities and analyzing sediment transport characteristics. Two digital cameras have been mounted on a crane and set above the curve. We set the camera about 4.5m above the free surface plain. Surface flow was measured by using vinyl chloride (d=0.1mm) as tracer particles and dye-injection method (Moriyama, et al., 2008) was used for measuring depth-averaged velocities. In Run M7, colored sand was also used as tracer that describes flow near the bottom and sediment transport.

Table 1 Experimental Conditions

Run number	Width B(m)	Radius R(m)	R/B	Discharge Q(m^3/s)	Initial depth h(cm)	Mean velocity V(m/s)	Riverbed conditions	Froude Number Fr	Total run time (min)
F1	0.5	2.0	4.0	0.0085	2.4	0.68	Fixed	1.40	
F2				0.0170	3.6	0.87		1.48	
M1				0.0085	2.4	0.68	Movable	1.40	57
M2				0.0170	3.6	0.87		1.48	12
M3		3.0	6.0	0.0085	2.4	0.68		1.40	57
M4				0.0170	3.6	0.87		1.46	21
M5	1.0	2.0	2.0	0.0085	1.6	0.54		1.35	55
M6				0.0170	2.4	0.70		1.43	15.5
M7		3.0	3.0	0.0085	1.6	0.54		1.35	58
M8				0.0170	2.4	0.70		1.43	31

Bed slope : I=1/80, Lateral slope : I_L=1/1.192, Height of channel : $h_{channel}$=10cm

3. VISUALIZATION

Because the object of this study is a steep slope river, supercritical flow occurs and flow depth is very small in the laboratory flume. Such a shallow water flow cannot be measured with LDA because the laser beams are interrupted by the riverbed and free surface. On the other hand, PIV, which are recently introduced to flow analysis in hydraulic engineering, is very useful to measure flow field in shallow water flow. In this study, flow pattern was visualized by using two kinds of tracers and two-dimensional velocity distribution was measured by making use of PIV.

Table 2 Analysis parameters for PIV

Physical length of pixel (m/pixel)	0.0025
Template size (pixel)	30*30
Number of template	About 1500
Frame rate (fps)	30
Number of image	About 750

Analysis parameters for PIV are shown in Table 2. Generally, vectors for which their templates satisfy the condition that the cross-correlation coefficient R (eq.1) is greater than a threshold level are picked up in order to eliminate abnormal vectors,

$$R = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left\{\left(I_{i,j}-\overline{I_{i,j}}\right)\left(I'_{i+x,i+y}-\overline{I'_{x,y}}\right)\right\}}{\sqrt{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I_{i,j}-\overline{I_{i,j}}\right)^2\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I'_{i+x,j+y}-\overline{I'_{x,y}}\right)^2}} \tag{1}$$

where $I_{i,j}$=distribution of intensities in a template, M=width of the template, and N=height of the template. In the case of dye-injection method, pattern of image intensity is vaguer than vinyl chloride. Therefore threshold levels are provided for variance I_{var} (eq.2) and maximum difference I_{dif} (eq.3) of image intensity to eliminate abnormal vectors rigidly.

$$I_{\mathrm{var}} = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I_{i,j} - \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}I_{i,j}\right)^2 \tag{2}$$

$$I_{dif} = MAX\left(I_{i,j}\right)_{i=1\sim M,j=1\sim N} - MIN\left(I_{i,j}\right)_{i=1\sim M,j=1\sim N} \tag{3}$$

4. RESULTS

4.1 Velocity Distribution on fixed bed

Figure 2 compares the mean velocity distributions measured by using vinyl chloride and dye-injection method in Run F2. By using two kinds of tracers, not only surface flow patterns but also depth-averaged velocity distributions were measured successfully (Moriyama, et al., 2008), from which the difference between each flow pattern was made clear. Surface flow measured by vinyl chloride converged along the outer side of channel, on the other hand, dye distributed widely throughout the cross section. Difference between direction of surface flow and depth-averaged flow became great at the latter section of the curve. The reason for such a difference of flow pattern can be the generation of strong secondary flow at the curve section.

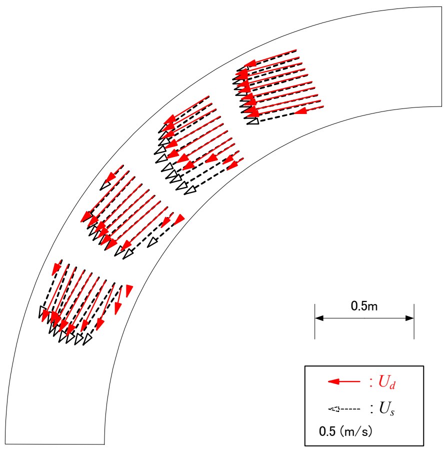
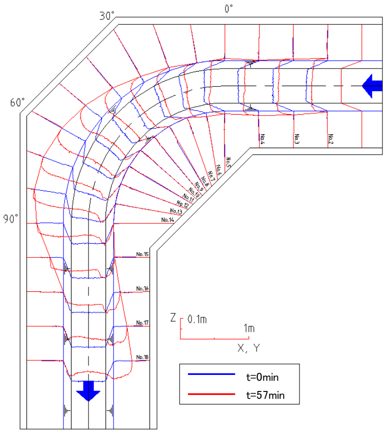


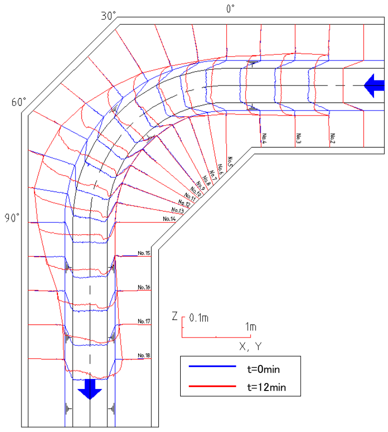
Figure 2 Surface velocity and depth-averaged velocity

4.2 Bed form change

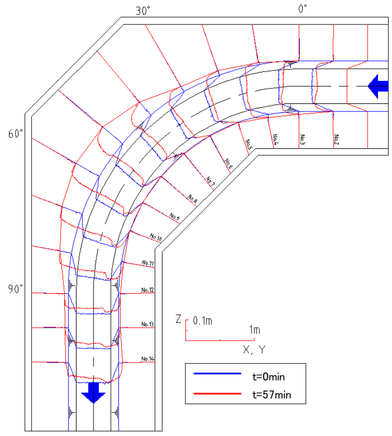
In the case of movable bed experiments, each experiment was continued for a total run time shown in Table 1 until eroded bank attained the wall of the flume or video tape became full. Therefore, each Run has not reached a stable state. The comparison of the lateral bed profiles at each section between the start and the end of the experiments are shown in Figure 3. Deposition occurred in the central bed region and erosion occurred out side of bank. The longitudinal section where remarkable bank erosion occurs is different each case.



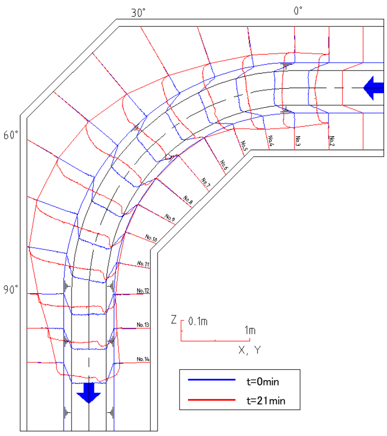
(1) Run M1
B=0.5m, R=2.0m,
Q=0.0085m^3/s



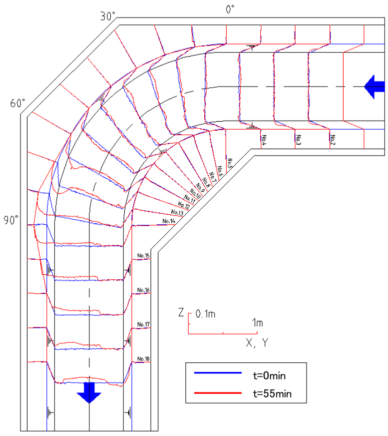
(2) Run M2
B=0.5m, R=2.0m,
Q=0.0170m^3/s



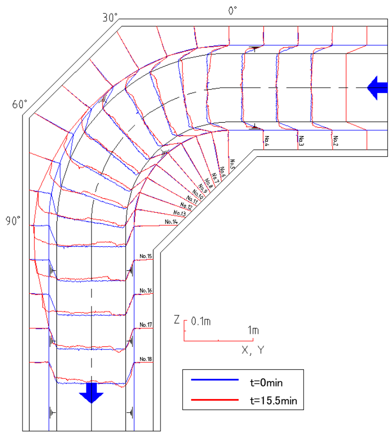
(3) Run M3
B=0.5m, R=3.0m,
Q=0.0085m^3/s



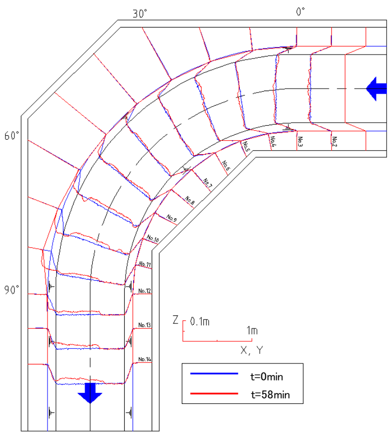
(4) Run M4
B=0.5m, R=3.0m,
Q=0.0170m^3/s



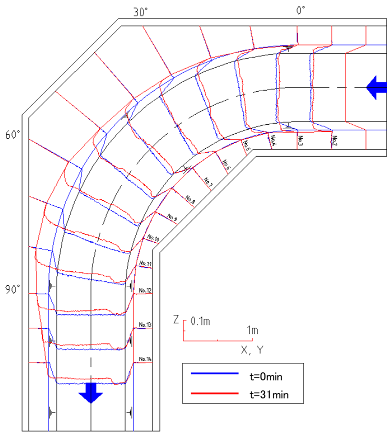
(5) Run M5
B=1.0m, R=2.0m,
Q=0.0085m^3/s



(6) Run M6
B=1.0m, R=2.0m,
Q=0.0170m^3/s



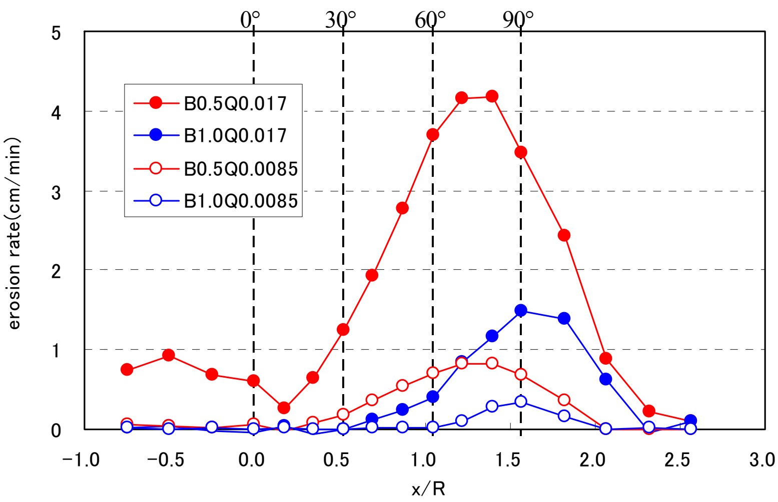
(7) Run M7
B=1.0m, R=3.0m,
Q=0.0085m^3/s



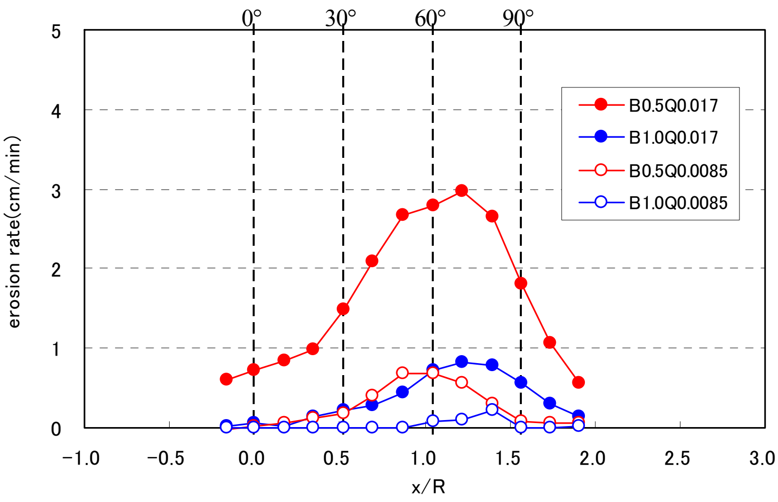
(8) Run M8
B=1.0m, R=3.0m,
Q=0.0170m^3/s

Figure 3 comparison of the lateral bed profiles at each section

Figure 4 shows longitudinal distributions of erosion rate of the outer bank. Because bed form was measured at the start and the end of each experiment, vertical axis shows averaged erosion rate during total run time. In the case where erosion occurs, bank shoulder retreats toward outside and the distance between initial points and bank shoulder increases (positive value). Remarkable erosion occurred in the latter section of the curve. Both the region where the maximum erosion occurs and the erosion rate are influenced by the hydraulic conditions.



(a) R=2m



(b) R=3m

Figure 4 Longitudinal distributions of erosion rate of the outer bank

Figure 5 shows relationship between the section where maximum erosion rate occurred and the ratio of the radius to the channel width (R/B). The region where remarkable erosion occurred correlates with R/B. In the case of sharp curve (R/B is small), the erosion occurred at the latter section at a great rate. It is because current from upstream channel flows straight and attacks the outer bank where the upstream channel faces and the upstream channel faces relatively the latter section of the sharp curve. On the other hand, interrelation between the discharge and erosion region is not clearly observed in the present experiment.

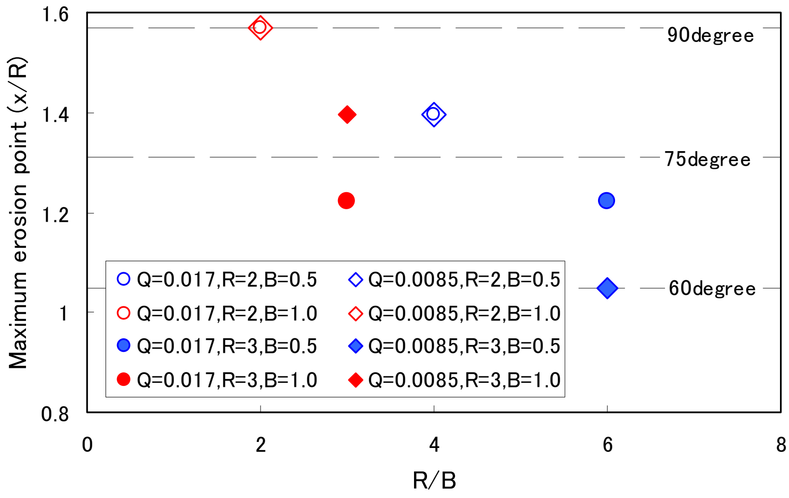


Figure 5 Relationship between Maximum erosion point and *R*/*B*

Figure 6 shows relationship between the maximum erosion rate and the mean velocity. Mean velocity is calculated by using discharge and cross section area. The maximum erosion rate is influenced by mean velocity. Erosion proceeds at a great rate with large mean velocity. Under the condition of the same mean velocity, erosion rate becomes large value under the sharp curve (*R*=2m). It can be due to the generation of stronger secondary flow at the sharp bend. It is found that erosion rate is influence with not only mean velocity but also local flow velocity.

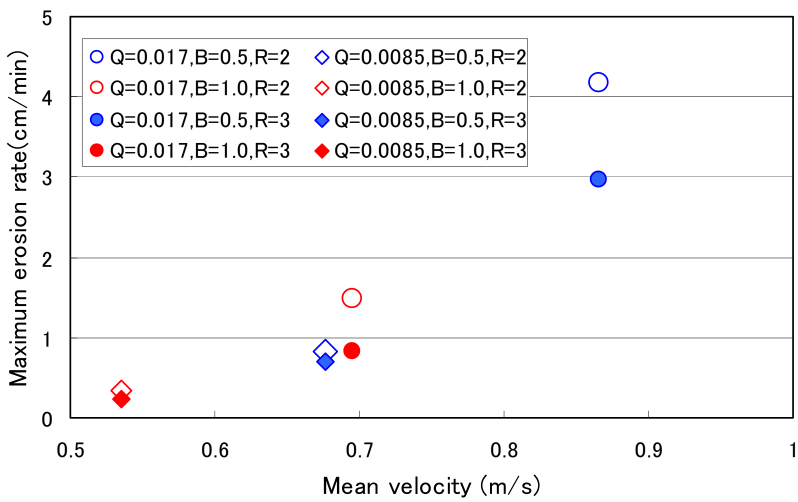
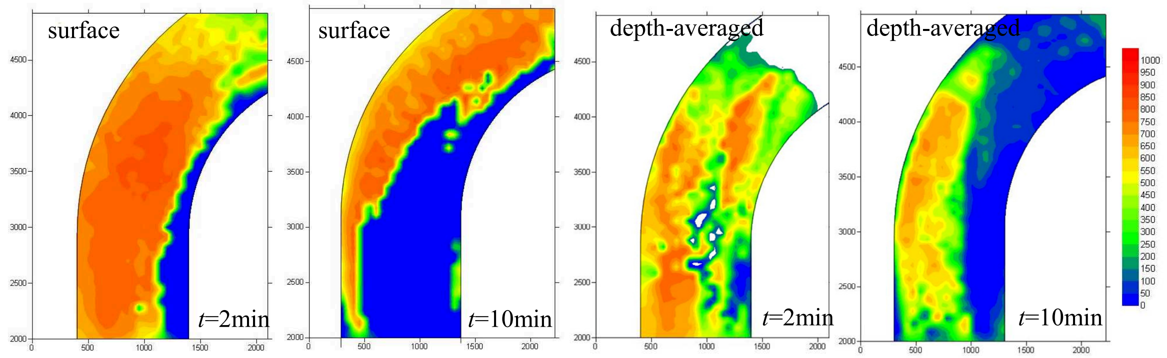


Figure 6 Relationship between maximum erosion rate and mean velocity

4.3 Relationship between flow pattern and sediment transport

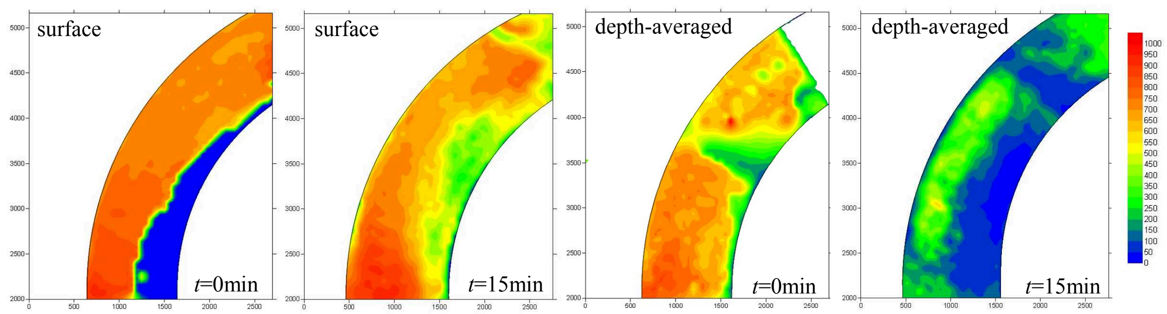
Figure 7 shows contours of surface flow velocity and depth-averaged velocity in the cases of Run M6 (*B*=1.0m, *R*=2.0m, *Q*=0.017m^3/s) and M8 (*B*=1.0m, *R*=3.0m, *Q*=0.017m^3/s).

Surface flow velocity measured by vinyl chloride is faster than depth-averaged velocity measured by dye injection method. And, at the surface, the width of region where great velocity is generated is narrower than the depth-averaged velocity. Although an even flow is observed at the former sections, flow converges along outer bank at the latter sections. In the case of sharp curve (M6; R=2.0m), the particularly remarkable flow convergence occurs along outer bank. This is the reason why the maximum erosion rate under the condition of sharp curve is larger. The region where the great depth-averaged velocity occurs is spread parallel to the downstream straight channel from exit of the curve.



(a) surface flow velocity (b) depth-averaged velocity

(1) Run M6 (B=1.0m, R=2.0m, Q=0.017m^3/s)



(a) surface flow velocity (b) depth-averaged velocity

(2) Run M8 (B=1.0m, R=3.0m, Q=0.017m^3/s).

Figure 7 Contours of surface flow velocity and depth-averaged velocity

Figure 8 shows the distribution of colored sand that composed the outer bank and surface velocity vectors in the case of M7(B=1.0m, R=3.0m, Q=0.0085m^3/s) at t=20min. Bank erosion occurred and eroded sediment moved toward the central bed region. The eroded sediment didn't attain the inner bank and moved downstream. Bank erosion is the cause of deposition in the central bed region shown in Figure 3. Flow diverges to the both inner and outer side bank because of deposition at the center of the channel.

Flow pattern near the bed was estimated by analyzing transport of the colored sand. Although surface flow converges along outer bank under the influence of the centrifugal force, flow near the bottom directs toward the center part of the cannel. It is indicated that flow directions at surface and bottom are different with each other. It was also found that bank erosion process and characteristics of sediment transport were influenced by the complicated secondary flow generated due to the strong curvature of the channel.

Figure 8 Distribution of colored sand and surface velocity vectors

5. CONCLUSIONS

The characteristics of sediment transport as well as bank erosion process in a curved steep slope river were investigated by conducting hydraulic experiments. The region where bank erosion occurs and its rate were influenced by radius and the mean velocity, respectively. It was also found that bank erosion process and characteristics of sediment transport were influenced by the complicated secondary flow generated due to the strong curvature of the channel.

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