STUDY OF FLOW CHARACTERISTICS OF JUNCTION FLOW WITH FREE FLOW CONDITION AT BRANCH CHANNEL

Sunil Kumar LAMA[1], Keita KUDOH[2], Mikio KUROKI[3]

[1]Student Member of JSCE, Postgraduate student, Dept. of Civil Engineering, Faculty of Engineering, Hokkaido University (North 13, West 8,Kitaku, Sapporo, 060, Japan)

[2]Student Member of JSCE, Graduate student, Dept. of Civil Engineering, Faculty of Engineering, Hokkaido University (North 13, West 8,Kitaku, Sapporo, 060, Japan)

[3]Member of JSCE, Dr. of Eng., Assoc. Professor, Department of Civil Engineering, Faculty of Engineering, Hokkaido University (North 13, West 8,Kitaku, Sapporo, 060,Japan)

Diversion of flow at junction with free flow condition (no flow control) at branch channel showed the simple pattern of flow characteristics and found to be primarily depending upon the incoming Froude Number (F_1). Various types of separation zones were observed at the branch channel, depending upon the F_1 and aspect ratio d_1/b_3 (defined as ratio of depth of incoming flow to the branch channel width). Difference of depths ratio at the branch to the main channel (d_3/d_1) was also found to be depending upon F_1 and aspect ratio. Water surface profiles and flow characteristics for the junction flow with width ratio greater than 1:4 and free flow condition at the branch channel were found to be similar to each other, allowing generalization of such junction flow study.

Key words: *flow diversion, discharge division, separation zone, dividing streamlines flow contraction, water surface profile, surface of discontinuity*

1. INTRODUCTION

Reservoir sedimentation is one of the problems in the water resource utilization, causing the early end of the life of the reservoir. Among the various direct or indirect techniques of the sediment management of the watershed system, sediment diversion is one of the remedial methods regarding. Generally, the intake at the river system is designed to divert the flow with the minimum of the sediment, but in the case of sediment diversion intake, maximum of the sediment is intended to be diverted. Purpose of the present research is to understand the flow characteristics at the junction, which could be applied further for the study of sediment diversion. In past, numbers of researches (Taylor[1], Dancy[2], Ramamurthy[3], Neary[4]) have been conducted on the junction flow diversion and much has been understood on its flow characteristics. As the flow at the junction could be of non-submerged (when change in flow condition at branch channel will not affect flow condition at main channel) and submerged condition, highly three dimensional with occurrence of the flow separation zones, it was realized that it is difficult to get the general analytic solution. However Law and Reynolds[5], who have conducted the extensive research on the junction flow, had prevailed that the flow characteristics followed the simple pattern when the flow at the branch channel was of free flow type (no flow control at branch flow), indicating the possibility of generalization of the results. Bulle[6] in his experiments with the junction flow of various off taking angles (30°, 60°, 90° and 120°) had concluded that maximum of sediment was diverted when the off taking angle was 30° with the equal division of flow at the channels. In past, most of the junction flows have been researched with the small width ratio of the branch to the main channel (1:1 or 1:2) (Lakshmana[7] up to 1:4) with flow condition having large incoming Froude Number F_1. In the case of the low F_1 with free flow condition at the branch channel, maximum portion of the flow will be diverted in to it. As for example, in the case of 30° junction with the 1:4 ratio for F_1= 0.15, almost 75% of incoming water will be diverted.

One of the most important characteristics of the junction flow for the study of sediment diversion is the location of bottom dividing streamline(**Fig.1**), which varies with the flow condition. Width of the bottom dividing streamline was found to be wider at the flow condition having low F_1 and goes on decreasing with the increase of F_1.

Junction flow with off taking angle 30° and width ratios 1:10, 1:7 and 1:4 were experimented with various aspect ratios d_1/b_3 with free flow condition at the branch channel. Theoretical relationship for the discharge division for junction flow of 30° intersection (Lama[8]) with the width ratio 1:17 and branch channel width 4.5 cm, which were developed through the mass and momentum equation for free flow condition at the branch channel and the flow condition with F_1 varying up to 0.3, was tested for higher F_1 too for above mentioned junction ratios, in order to know the limit of its validity.

2. EXPERIMENTAL SETUP

Experiments (setup 1, $d_1/b_3 \geq 1$) were carried out at the 30° junction with the main channel of different widths 45, 31 and 18 cm and the branch channel was of 4.5 cm, so the junction ratio was of 1:10, 1:7 and 1:4. Main and branch channel were of rectangular shape and the walls of the junction were of sharp edge. Main channel bed was made rough by sticking sand, passing through the sieve size of 0.9 mm mesh and roughness coefficient was found to be 0.012, whereas branch channel was made of smooth bed. The slope of the main channel was 1:500 and branch channel was of horizontal slope. Main channel was of 8 meters in length with off taking branch channel at 3 meters from the start of the main channel, where flow was considered to be fully developed. Depths were measured with the point gauges up to 0.10 mm accuracy. Incoming discharge was measured through the calibrated V-notch provided at the overhead tank and branch discharge with the bucket and the stopwatch. Flow conditions were changed either by varying the incoming discharge (Q_1) or by manipulating the gate provided at the end of the main channel. When the flow depth at the main channel was high, backwater effect due to the gate provided at the end of the main channel reached up to the junction area, but non-uniformity of flow at the main channel upstream of the junction was found to be minimum when checked by the measurements, so the flow was considered almost uniform at that reach. In order to find out the effect of the aspect ratio (d_1/b_3) in the junction flow characteristics, width of the branch channel was changed to 10 cm (setup 2, $d_1/b_3 < 1.0$) with the main channel width 40 cm and keeping entire flume condition same to the setup 1. Incoming water depths were kept of the same depths as of previous experiments, so the similar flow condition could be analyzed as of setup 1 with varying aspect ratio. For both the experimental setups, the bottom dividing streamline (**Fig.1**) was tracked with the 6 mm diameter round plastic beads of specific gravity 1.06, which was slightly greater than the water.

Table 1

Setup 1(with 4.5 cm branch channel)

Run No.	F_1	d_1 cm	d_3 cm	d_3/d_1	Q_1, lt/s	Q_3, lt/s	Q_3/Q_1 %
1:10							
1	0.10	5.69	2.89	0.51	1.98	0.81	40.81
2	0.17	6.53	3.23	0.49	4.09	1.02	24.94
3	0.19	6.30	3.17	0.50	4.29	1.00	23.38
4	0.43	4.58	3.01	0.66	5.99	0.67	11.16
1:7							
5	0.10	4.80	2.58	0.54	1.09	0.66	60.00
6	0.22	6.38	3.43	0.54	3.49	1.04	27.72
7	0.27	6.79	3.70	0.54	4.59	1.14	24.80
8	0.40	7.20	4.32	0.60	7.62	1.30	17.10
1:4							
9	0.15	8.48	4.32	0.51	2.08	1.62	77.61
10	0.21	8.43	4.67	0.55	2.97	1.53	50.00
11	0.25	8.22	4.60	0.56	3.41	1.57	46.00
12	0.32	6.42	3.92	0.61	2.97	1.08	36.36
13	0.38	5.81	3.61	0.62	2.97	0.98	33.00
14	0.48	4.50	3.00	0.67	2.55	0.64	25.04

Setup 2(with 10 cm branch channel)

1:4							
15	0.17	8.20	6.23	0.76	5.04	2.94	58.33
16	0.19	7.39	5.72	0.77	4.96	2.62	52.76
17	0.23	6.39	5.47	0.86	4.65	2.04	43.85
18	0.37	7.89	6.73	0.85	10.26	3.10	27.35
19	0.53	6.84	6.08	0.89	12.05	2.58	21.04

3.FLOW CHARACTERISTICS

For the experiments with the setup 1 for 1:4 width ratio, F_1 was varied from 0.1 to 0.5 and flow

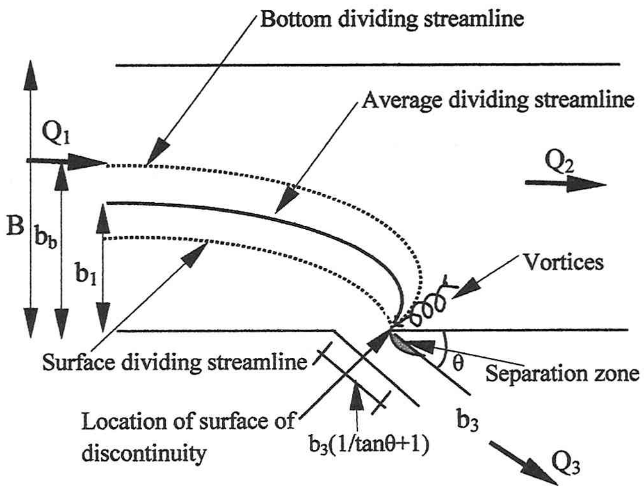
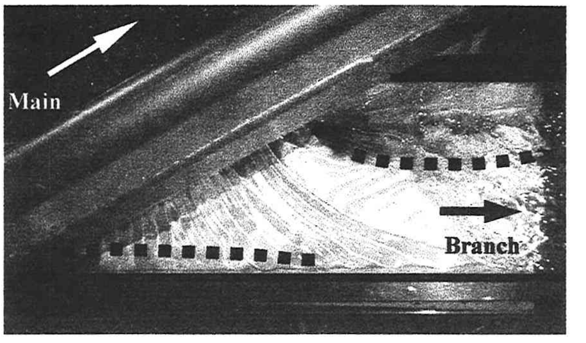


Fig 1. Schematic diagram of junction flow



Pic. 1 Flow showing the separation zone (marked by the dotted line) formed along both the walls of the branch channel **(type B)**

characteristics were analyzed accordingly. The water depth at the branch channel (d_3) was measured at the minimum water level at the branch channel, which was approximately located at $b_3(1/\tan\theta+1)$ distance from the entrance of the upstream edge of the branch channel, where the flow contraction was found to be almost vanished. As the flow enters the branch channel, surface of discontinuity (**Fig.1**) was formed just at the entrance of the downstream wall of the branch channel for every case of junction width ratios. This was because the flow took the sharp turn at the edge of the downstream entrance wall while entering into the branch channel, after which flow separation took place. The water depth at the surface of discontinuity decreased from the upstream main channel depth (d_1) to the branch channel minimum water level (d_3).

For the junction with the width ratios greater than 1:10, bottom dividing streamline was found to be not extending to the left wall of the main channel even in the low F_1 and water surface profiles were found to be same as that of the 1:17 model for the given range of the flow condition. For the junction with the width ratio 1:7, at low F_1 the bottom dividing streamline was found to be extended up to the left wall of the main channel causing the contraction of the bottom dividing streamline.

The bottom dividing streamline had curvature shape near the entrance wall of the branch channel (**Fig.1**) and this curvature decreased as the F_1 was increased. Because of the curvature of the dividing streamline, vortices (**Fig.1**) was found to be forming at the bottom along the right wall of the main channel extension near to the junction entrance and was directed towards the branch channel with counterclockwise revolving.The dividing streamline approaching to the branch entrance stroked to the surface of the vortices and followed the path along its surface while entering into the branch channel.

The strength of the vortices was found to be more in the case of flow with the low F_1. As F_1 was increased, size of the surface of discontinuity was decreased and when F_1 reached up to around 0.40, surface of discontinuity had started vanishing and water wave was started to be forming at that location. Beyond that limit of F_1, surface of discontinuity started to form at the entrance of the upstream wall of the branch channel with the oblique wave along the main channel.

For the setup 2 experiments, surface of discontinuity was still found to be forming, but its size was found to be less than that of setup 1 when comparing with the same F_1. So it was understood that the size of the surface of discontinuity decreased with the decrease of the flow aspect ratio even in the same condition of flow at upstream of main channel.

4.SEPARATION ZONE AT BRANCH CHANNEL

Various types of separation zones were formed at the branch channel depending upon the flow condition at the junction. The observation of separation zone was conducted with dye (potassium permanganate). For setup 1 experiments, it was found to be forming only along the downstream wall of the branch channel (**Fig.2, type A**) with the flow condition F_1 up to 0.3. The separation zone was found to be wider at the bottom and goes on decreasing up to the surface. The vortices at this zone were found to be revolving along the Z-axis directing upwards with the counterclockwise direction.

When the flow entered in to the branch channel, curve surface was formed (**Pic.1**) and it was extended up to the upstream wall of the branch channel. This curve surface had suppressed the possible formation of the separation zone at the upstream wall of the branch channel, so there was

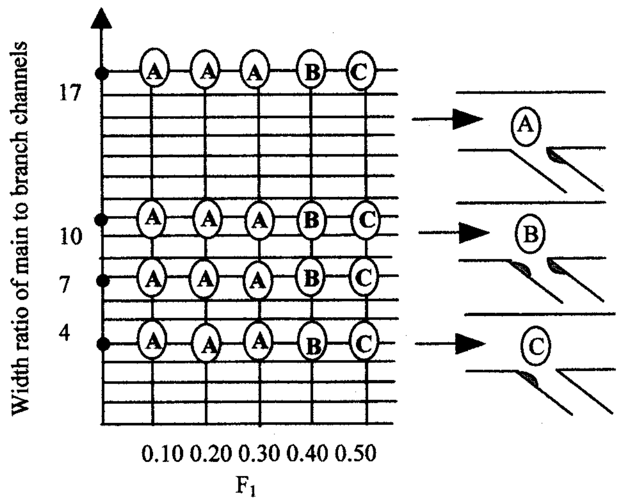


Fig. 2 Formation pattern of the separation zones at the branch channel (setup 1) for 30° junction with the change of upstream Froude Number F_1

separation zone only along the downstream wall for flow condition F_1 up to 0.3. When F_1 reached beyond the value 0.3 the incoming flow had the sufficient momentum, which caused the flow starting to be separating along the upstream wall too (**Type B**).The separation zone along the upstream wall of the branch channel was found to be wider at the surface and goes on decreasing towards the bottom. As F_1 was further increased, the size of the separation zone along the upstream wall was increased, whereas of the downstream wall decreased and ultimately with the increase of F_1 beyond the value 0.40, flow condition at branch was becoming near to the **Type C** of separation. Also in the case of the submerged flow at the junction, separation zone was found to be of **Type C**.

In the case of the setup 2 experiments, flow entered in to the branch channel with the curve surface as similar to the setup 1, but found to be not much extended up to the upstream wall of the branch channel. As the d_3/d_1 ratio was found to be smaller than that of the flow with the setup 1, even in the same $F_1$and d_1, the entrance velocity was found to be less in the case of setup 2 experiments. The suppress effect of the curve surface was found to be small, so the separation zone was observed along the upstream wall of the branch channel even in the low upstream F_1 (**Type B**) and F_1 beyond 0.4 **Type C** separation started to be forming. Surface disturbances are found to be forming beyond the curve water surface at the branch channel and separation zone was found to be vanishing reaching to the minimum section of water level at the branch channel.

5.THEORETICAL ANALYSIS

The theoretical analysis of the 30° junction with width ratio 1:17 and free flow condition at the branch was analyzed (Lama[8]) through mass and the momentum equation with accounting contraction coefficient (C_c) at the branch channel and various pressure forces by measuring the water surface profiles along the surface of control volume. The contraction coefficient at the location of the d_3 measurement was found to be almost constant C_c=0.95. Through the analysis, simple expression (Eq.1) was developed for the calculation of the Froude Number at the branch channel (F_3) depending only to the depth ratio of the main and the branch channel d_3/d_1.

$$F_3 = \sqrt{\frac{0.40 + 0.40\frac{d_3}{d_1} - 0.72\left(\frac{d_3}{d_1}\right)^2}{C_c\left(\frac{d_3}{d_1}\right)^2}} \tag{1}$$

The discharge distribution at main (Q_1) and the branch (Q_3) channel could be written,

$$\frac{Q_3}{Q_1} = \frac{b_3}{B}\frac{F_3}{F_1}\left(\frac{d_3}{d_1}\right)^{\frac{3}{2}} \tag{2'}$$

$$\approx \frac{b_3}{B}\frac{CONSTANT}{F_1} \tag{2''}$$

As the junction flow characteristics of 1:17 model was found to be almost the same to the junction having width ratio 1:10, Eq. (2') represents the relationship of the discharge division greater than that width limit with sufficient accuracy. For the flow condition with F_1 up to the 0.5, it was assumed that the radial acceleration of the fluid particles along the separation surface formed at the upstream wall of the branch channel was small, where intensity of recirculation was found to be not intense when observed with dye. So, pressure was assumed hydrostatic along that surface for the analysis of flow with the momentum consideration.

Fig.3 shows the plot of the Eq. (2') and measured value of the experiments of setup 1 and 2 with the junction width ratio 1:4. Measured data with the legend "Δ" were of branch channel with width of 4.5 cm and data that with the "O" legend were of the branch channel with the 10 cm width.

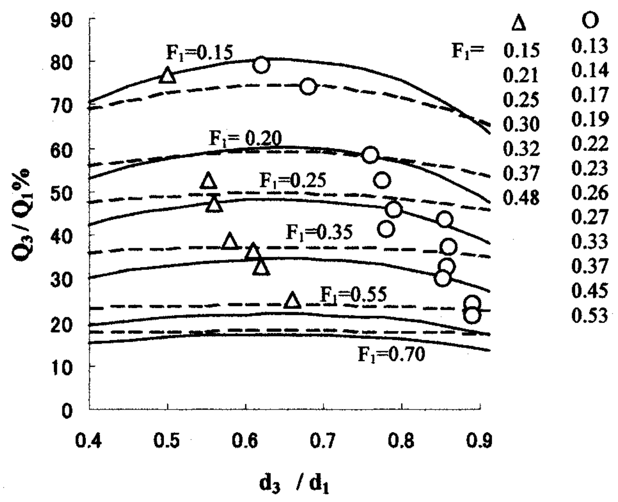


Fig.3 Theoretical relationship of discharge division (Q_3/Q_1) and d_3/d_1 ratio taking F_1 as parameter for 30° junction with 1:4 width ratio, symbol Δ and O shows the measured data plotted from above to down, dotted line shows the empirical relationship of Lakshmana et al.

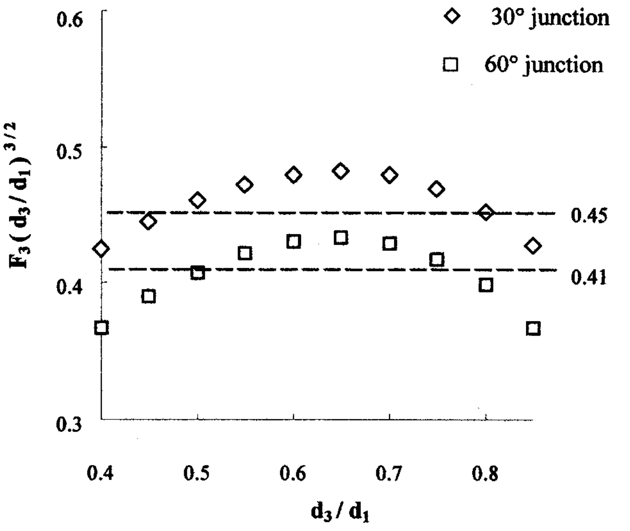


Fig. 4 Variation of $F_3(d_3/d_1)^{3/2}$ with d_3/d_1

Even for the flow with low F_1, in which the bottom dividing streamline has extended up to the left wall of the main channel, Eq. (2') has not much difference with the measured value, so the Eq.(2') could be used with the sufficient accuracy for the discharge division calculation for 30° junction of free flow condition at the branch channel with the junction width ratios greater than 1:4 and the flow condition F_1 varying up to 0.5.

Lakshmana et al[7] proposed the empirical relation for junction flow division with the free flow condition at the branch channel. They obtained the empirical relationship with the regression analysis of the experimental data in the form of equation (3) with the Froude Number of the main channel at downstream of the junction (F_2) as parameter and provided the value of the empirical coefficients K and x (function of junction angles and the width ratios) in tabulated form for the various junction width ratios (from 1:1 to 1:4) and the junction angles (30°, 45°, 60°, 75° and 90°).

$$\log\left(\frac{Q_3}{Q_1}\right) + KF_2^{\ x} = 0 \qquad (3)$$

For calculation of F_2 from the Equation (2'), in order to compare with the Lakshmana's empirical Eq. (3), it was assumed that the head loss between the sections at the main channel, ahead and after the flow diversion is negligible. The dotted line in the **Fig. 3** shows the plot of the Lakshmana's empirical relation for 30° junction with width ratio 1:4 and according to that, Eq. (2') could be extended for the flow condition with F_1 up to 0.7. In the present study the data up to that range was not able to get due to the limitation of experimental setup.

As it was found that product of the $F_3(d_3/d_1)^{3/2}$ of equation (2') **(Fig 4.)** did not vary much with the range of d_3/d_1 , average constant value could be taken for the approximate calculation of the discharge division. Value of constant could be taken equal to 0.45 for the 30° junction.

Similarly, simple expression for the prediction of F_3 (Eq.4), developed through theoretical analysis with the mass and the momentum equation for 60° junction (Lama[9]) with free flow condition at the branch channel was also compared with the empirical data of Lakshmana for junction flow of 1:4 width ratio.

$$F_3 = \sqrt{\frac{\left[0.28 + 1.47\left(\frac{d_3}{d_1}\right) - 1.73\left(\frac{d_3}{d_1}\right)^2\right]^2}{1.73\left(\frac{d_3}{d_1}\right)^2}} \qquad (4)$$

Fig.5 shows the plot of Eq. (2') with combination with Eq. (4) for the junction width ratio 1:4 for the 60° junction. The dotted line in the **Fig.5** shows the empirical relation of the Lakshmana, and it could be seen that Eq. (2') could be extended for the flow condition with F_1 up to 0.7. For the approximate calculation of the discharge division for the 60° junction, value of constant could be taken equal to 0.41.

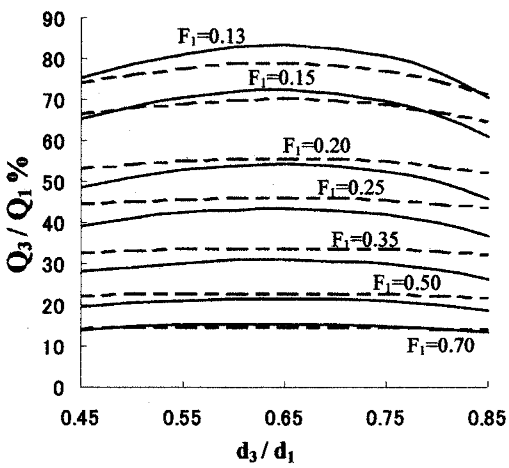


Fig.5 Theoretical relationship of discharge division (Q_3/Q_1) with d_3/d_1 ratio, taking F_1 as parameter for 60° junction with 1:4 width ratio, dotted line shows the empirical relationship of Lakshmana et al.

When compared the measured data of the 30° and 60° junctions with free flow condition at the branch channel having junction ratio 1:17 (Lama[9]), discharge distribution was found to be not much differing with each other, with slightly less in 60° junction when F_1 is low. The same was observed also for the 1:4 junction, when comparing the **Fig. 3** and **Fig. 5**. Comparing the width of the bottom dividing streamline of both of the junction angles for the same flow condition for 1:17 junction, wider was found for the 30° junction (Kudoh[10]), which also confirmed the results of Bulle[7].

6.CONCLUSION

For 30° junctions, various pattern of the separation zones were found to be forming at the branch channel depending upon the incoming Froude Number F_1 and the flow aspect ratio (d_1/b_3). Vortices was formed at the bottom near the entrance of branch channel, which had modified the path of dividing streamline entering in to the branch channel, compelling to follow the track along its surface. Flow division in to the channel junction with the free flow condition at the branch could be expressed with the simple expression and found to be primarily depending upon the incoming Froude Number F_1 and less with the d_3/d_1 ratio. So the generalization of the branch flow with free flow condition at the branch with F_1 up to 0.5 and flow aspect ratio (d_1/b_3) above the value 0.5 was achieved. Similarly, model developed for the 60° junction could also be used for the discharge division calculation with sufficient accuracy. When comparing the width of the bottom dividing streamline for 30° and 60° junction with the similar flow condition, wider was found to be for 30° junction. For the 30° junction with free flow condition at the branch channel and having width ratio less that 1:10 and $d_1/b_3 \geq 1$, bottom dividing streamline extended up to the left wall of the main channel in low F_1, providing possibility of diverting much of the incoming sediment in to the branch channel.

REFERENCES

1) Taylor, E.H. "Flow characteristics at Rectangular Open Channel Junction,"Transcation, ASCE, Vol.109, 1944.
2) Albert Guy Dancy "Thesis submitted to the Graduate Faculty for the Degree of Master of Science"1947,Iowa State College
3) Amruthur S. Ramamurthy, Duc Minh Tran, Luis B. Carballada "Dividing Flow in Open Channels" Journal of Hydraulic Engineers ,ASCE, 1990,116(3)
4) Vincent S. Neary, A. Jacob Odgaard "Three Dimension Flow structures at Open Channel Junction" Journal of Hydraulic Engineers, ASCE, 1993,119(11)
5) Shiu Wai Law, Alan J. Reynolds" Dividing Flow in Open Channel" Proceedings ASCE, 1966
Discussion by N.S Lakshmana Rao and K. Sridharan.
6) Hermann Bulle" Untersuchungen Uber Die Geschiebeableitung Bei Der Spaltung Von Wasserlaufen " 1926,Berlin
7) Lakshmana R.N.S, Sridharan K." Division of Flow in open Channels" Journal of the Central Board of the Irrigation and Power, Vol. 24,No. 4,1967
8) Sunil Kumar Lama, Mikio Kuroki, Kazuyoshi Hasegawa" Study of flow bifurcation at the 30° open channel junction when the width ratio of the branch channel to main channel is large" Annual Journal of Hydraulic Engineering, JSCE, Vol.46, 2002, February.
9) Sunil Kumar Lama, Keita Kudoh,Mikio Kuroki" Study of flow bifurcation at the open channel junction with the large width ratio of branch and main channel" Proceedings of Hokkaido Chapter of JSCE ,No 58,2002
10) Keita Kudoh, Sunil Kumar Lama, Mikio Kuroki" Study of flow characteristics of junction with the large width ratio of main to branch channel" Proceedings of Hokkaido Chapter of JSCE ,No 58,2002(in Japanese)
11) John L Grace, Jr.and Melville S. Priest." Division of flow in open channel junction" Alabama Polytechnic Institute, Bulletin No.31, 1958 June.
12) Lakshmana R.N.S., Sridharan K., Baig M.Y.A.(1968) " Experimental study of the division of flow in an open channel" Australian Conf. on Hydraulic and Fluid Mechanics, Sydney, Australia,139-142
13) Amruthur S.Ramamurthy, Mysore G.Satish" Division of Flow in Short Open Channel Branches." Journal of Hydraulic Engineers, ASCE, 1987,114(4)
14) Ashok S. Shettar " A numerical study of division of flow in open channels" Journal of Hydraulic Research, 1996

(Received September 30, 2002)