PLAN SHAPE FEATURES IN COMPOUND MEANDERING CHANNELS AND CLASSSIFICATION DIAGRAM OF FLOOD FLOWS BASED ON SINUOSITY AND RELATIVE DEPTH

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SYNOPSIS

The objective of this study is to clarify the representative parameters governing flow characteristics in compound meandering channels in order to make sense of the results of experimental channel and river flows. Plan shape parameters were considered from field data from eleven compound meandering rivers in Japan. Hydraulic parameters were also studied by conducting a series of experiments with various sinuosity and relative depths. Laboratory results were then compared with results of flood flow analysis using aerial photographs. Finally, a classification diagram of the occurrence of the flood flows in compound meandering rivers was devised on the basis of these representative parameters such as sinuosity, relative depth, location of the maximum velocity filament and the maximum scouring depth at the meander apex section.

INTRODUCTION

In Japan, rivers generally have a compound cross section (main channel and flood plain) at their middle and lower reaches. Therefore, establishing a hydraulic design method of compound meandering rivers has been important.

According to previous studies of compound meandering channel flows, flow structure differs greatly from those of bankfull flows due to flow mixing between main and flood channels, Ashida et al. (1), (2), Kinoshita (3), Mori et al. (4), Willet et al. (5),(6) and Sellin et al. (7).

Incremental horizontal shear stress near the boundary due to flow interaction between main channel and flood channel creates an opposite secondary flow in the main channel and shift of maximum velocity filament to the center (Muto et al., (8); Fukuoka et al., (9)). These flow structural changes also yield a reduction of sediment discharge and a scouring near the inner bank bed. From these results possibility of occurrence of sediment deposition and inner bed scouring during flood were pointed as the flood control problems. And these flows were defined as simple meandering channel flows and compound meandering channel flows (Fukuoka et al. (9)). In recent years, numerical simulation of compound channel flows as well as movable bed experiments have been performed by Fukuoka, et al. (10), (11). In rivers, bed level changes of main channel inner bank during flood were measured in situ by using colored sediment columns. From these measurements the occurrence of different flow during floods (simple meandering channel flows and compound meandering channel flows) were confirmed (Okada, et al. (12)). All these results have provided important information about river planning, river improvement and structure design. However, the plan shapes used in most experiments (main channel alignment follows a sine function curve with straight levees) have a simplified shape and differ from that of

rivers. Therefore, it is necessary to clarify how flood flow and bed variation in rivers is related to that in experimental channels.

The objective of this study is to clarify the representative parameters governing flow characteristics in compound meandering channels in order to standardize the flood flow phenomenon in experimental channels and rivers.

The plan shape data were obtained from eleven Japanese compound meandering rivers. The effects of sinuosity and relative depth on the flow and bed formation in compound meandering channels were investigated from a series of experiments with various sinuosities and relative depths.

Finally, diagrams of flood flow occurrence in compound meandering channels and rivers are illustrated. The classification of flow characteristics is based on sinuosity, relative depth, location of the maximum velocity filament and the maximum scouring depth at the meander apex section.

PLAN SHAPE FEATURES OF COMPOUND MEANDERING RIVERS

Hydraulic model experiments can replicate the flow phenomenon in rivers with some simplification and without losing generality. Hitherto many kinds of experimental channels for flow and bed formation in compound meandering channel have been used. However, no information in regard to the importance of channel shapes exists.

In order to deal with this issue, plan shape parameters of compound meandering rivers were examined from eleven Japanese rivers. Rivers generally have different sinuosity and phase lag between main channels and levee alignments. Consequently, the effect of levee alignment on the flow characteristics was studied initially. Figure 1 shows the velocity distribution when a phase lag exists between the main channel and levee alignment (Fukuoka, et al. (13)).
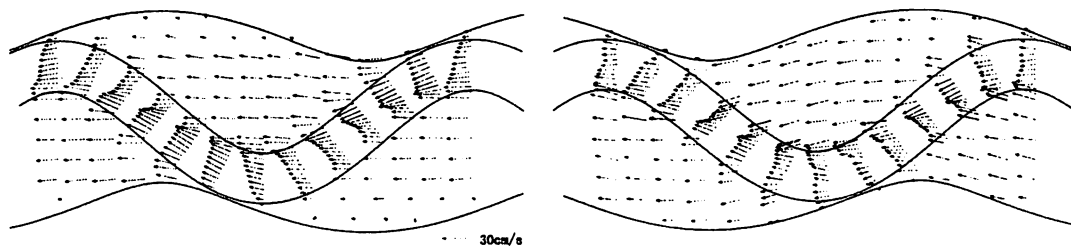

Figure 1 Velocity distributions with phase lug between main channel
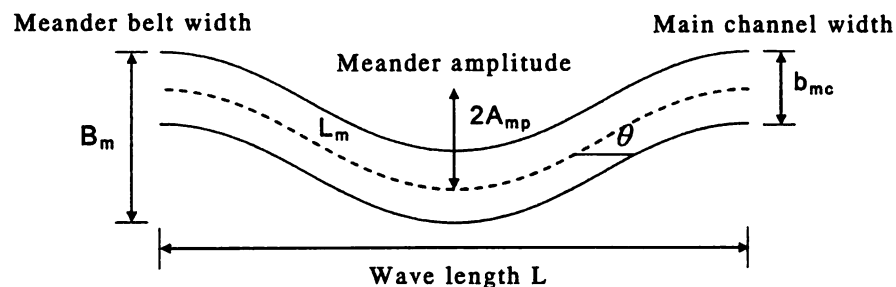and levee alignment

Figure 2 Definition of plan shape parameters of the main channel

A comparison made between these figures indicates that the effect of levee alignment on flow characteristics (position of maximum velocity filament and velocity distribution in the main channel) was small compared to other factors. In other words, flow mixing between main and flood channels occurred primarily in the meander belt. Therefore, it can be said that main channel alignment plays a larger role in affecting flow characteristics than the levee alignment alone. Hence, we focused on the main channel alignment.

Centerline alignment of the main channel was generally described by *sine-generated* curve as shown in Eq.(1) .

$$\theta = \theta_{max} \sin\frac{2\pi s}{L_m}$$
(1)

Where, θ_{max} : maximum deflection angle, L_m: meander length, s : distance for axial direction $(0 \leqq s \leqq L_m)$

Figure 2 indicates these parameters of the main channel being defined using a *sine-generated* curve. The meander belt width B_m is the sum of twice the main channel amplitude A_{mp} and the main channel width b_{mc}.

On the basis of this *sine-generated* curve channel, one can see that the main components which characterize the channel plan shape are L_m, θ_{max} and b_{mc}.

Integrating along the centerline axis, L_m and θ_{max} were transformed to meandering wave length L and meandering amplitude A_{mp}, as shown in Eq(2) and (3).

$$L = \int_0^{L_m} \cos\theta ds = \int_0^{L_m} \cos\left(\theta_{max} \sin\frac{2\pi s}{L_m}\right) ds$$
(2)

$$2A_{mp} = \int_0^{L_m} \sin\theta ds = \int_0^{L_m} \sin\left(\theta_{max} \sin\frac{2\pi s}{L_m}\right) ds$$
(3)

$$\text{Sinuosity } S = \frac{\text{Meander length } L_m}{\text{Meander wavelength } L}$$
(4)

As sinuosity S is defined by the ratio between meander length L_m and meander wave length L, as shown in Eq.(4). A_{mp} and L are also functions of sinuosity. Thus, these three parameters (L, A_{mp} and b_{mc}) describe the plan shape of the main channel.

We surveyed plan shape features of eleven Japanese rivers and compared them with our experimental channels. Table 1 shows the plan shape parameters of compound meandering rivers.

Table 1   Plan shape parameters of rivers in Japan

| River	Wave length $L(m)$	Meander belt width $B_m(m)$	Main channel width $b_{mc}(m)$	b_{mc}/B_m	b_{mc}/L
Ishikari	4000	1175	200	0.17	0.05
	6400	1550	200	0.13	0.03
	3850	1150	250	0.22	0.06
	2450	850	200	0.24	0.08
Uryu	900	165	50	0.30	0.06
Omono	2750	830	230	0.28	0.08
Aka	1750	550	100	0.18	0.06
Agano	4420	1270	270	0.21	0.06
	3770	1710	270	0.16	0.07
Tone	5370	1280	330	0.26	0.06
Oppe	790	75	35	0.47	0.04
Yahagi	2160	340	150	0.44	0.07
Kidu	2660	1180	200	0.17	0.08
Gono	3060	550	190	0.35	0.06
	3840	1260	140	0.11	0.04
	2900	940	140	0.15	0.05
Niyodo	3840	770	260	0.34	0.07
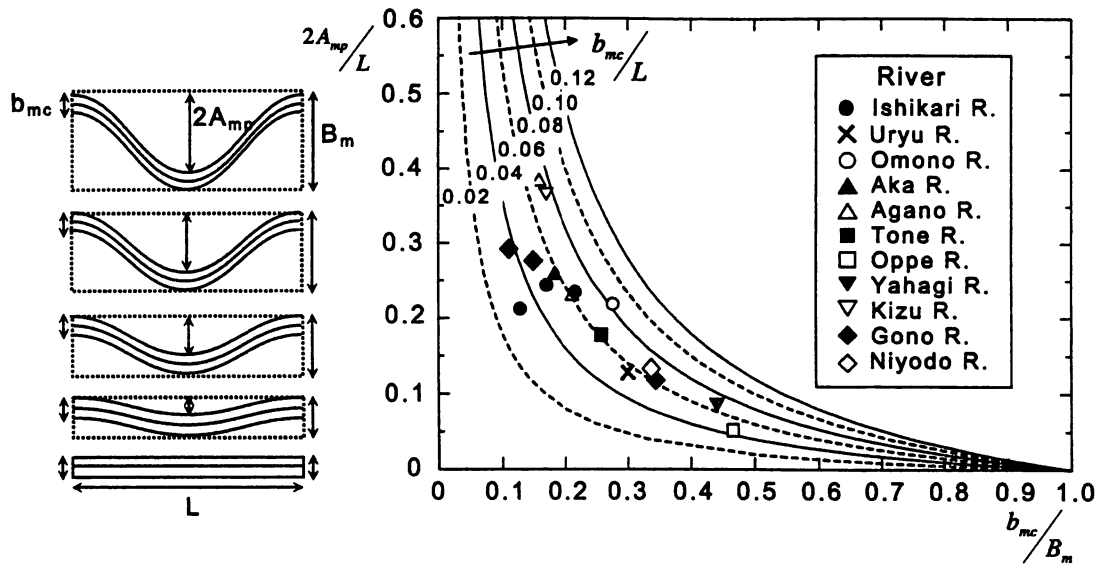
Figure 3 Non-dimensional plan shape parameters (b_{mc}/B_m, $2A_{mp}/L$ and b_{mc}/L *assuming a sine-generated curve*) of rivers in Japan
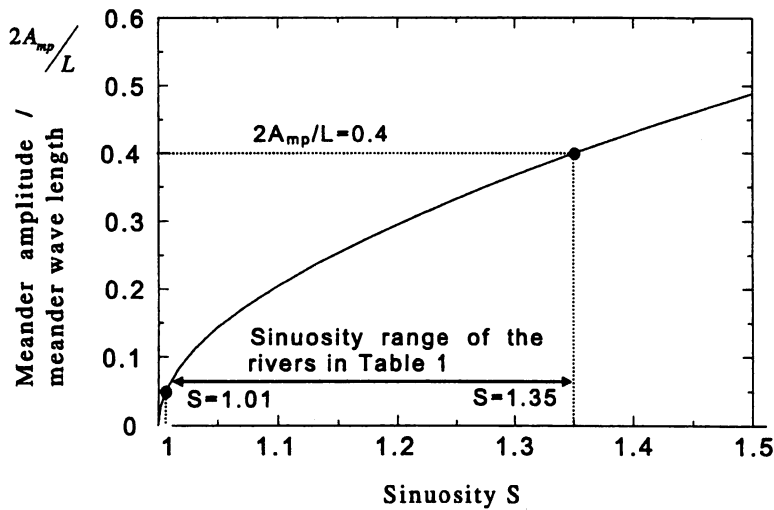

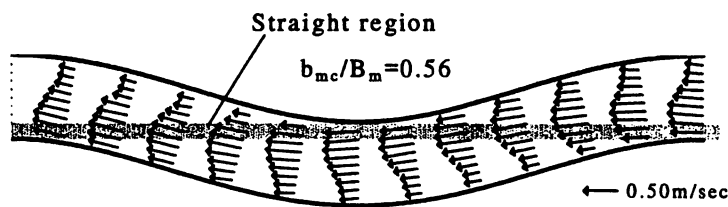Figure 4 Relation between Sinuosity S and $2A_{mp}/L$ (assuming a *sine-generated curve*)

Figure 5 Channel plan shape in the case of $b_{mc}/B_m > 0.50$

Non-dimensional plan shape parameters of meandering channels b_{mc}/B_m, $2A_{mp}/L$ and b_{mc}/L have a relationship which is shown in Figure 3 (assuming a *sine-generated curve*). It shows the relationship between b_{mc}/B_m and $2A_{mp}/L$ for a constant value of b_{mc}/L, changing only the wave amplitude. A similar family of curves was obtained for different b_{mc}/L values. Furthermore non-dimensional plan shape parameters from Table 1 (for the compound meandering rivers) are plotted in the same figure.

From this figure, it can be seen that the sinuosity-related Non-dimensional parameter $2A_{mp}/L$ varies up to 0.4; the width ratio b_{mc}/B_m ranges from 0.1 to 0.5, and values b_{mc}/L range from 0.04 to 0.08.

Figure 4 shows the relationship between Sinuosity and $2A_{mp}/L$ (assuming a *sine-generated curve*).

The values $2A_{mp}/L$ (ratio of meander amplitude and meander wavelengh) express the degree of "channel bending"; therefore indicating a similar import to sinuosity when it is about 1.00-1.35.

Horizontal axis values b_{mc}/B_m (ratio of main channel width to meander belt width) were plotted to be less than 0.5 due to the following reason: Figure 5 shows the depth-average velocity distribution in the case of $b_{mc}/B_m=0.56$. When b_{mc}/B_m exceeded 0.5, a continuous straight region (shaded part) flowing streamwise appeared in the main channel with increased velocities. Due to the existence of this high velocity region, the effect of centrifigal force on the generation of secondary flow is significantly reduced, in spite of the channel meandering. Therefore, it was concluded that this type of channel is an exception case and it is not generally observed in natural rivers.

Geometric data include both rivers and channels. The fact that b_{mc}/L values (ratio of main channel width and meander wave length) are concentrated between 0.04 and 0.08 is important.

The above finding suggests that when we conduct experiments on compound meandering channels, the plan shape parameter b_{mc}/L should be chosen between the ranges mentioned here, that is, following a relationship like the one shown in Figure 3.

PLAN SHAPE FEATURES OF COMPOUND MEANDERING CHANNELS USED IN PREVIOUS STUDIES

Plan shape parameters of experimental channels used in previous studies were compared to river features investigated in Chapter 2. Table 2 shows experimental channel conditions used in previous studies in Japan (where channel sinuosity was less than S=1.17) (Fukuoka, et al. (9), Ashida, et al. (1) and Ishigaki, et al. (15)). Meandering channel form is generally assumed to follow a *sine-generated curve*, which can be expressed by Eq.(1).

Table 2 Plan shape parameters of experimental channels

	Wave length L(m)	Meander belt width $B_m(m)$	Main channel width $b_{mc}(m)$	b_{mc}/B_m	b_{mc}/L
Channel A	4.60	0.89	0.40	0.45	0.09
Channel A'	4.60	1.29	0.80	0.62	0.17
Channel B	6.80	2.20	0.80	0.36	0.12
Channel C (Fukuoka)	6.00	1.57	0.80	0.51	0.13
Channel D (Fukuoka)	12.00	4.25	1.00	0.24	0.08
Channel E (Ashida)	2.20	0.61	0.20	0.33	0.09
Channel F (Ishigaki)	3.07	1.00	0.30	0.30	0.10

Experimental channel data (A-F) in Table 2 were plotted in Figure 6 as in the Figure 3. Channel A' has twice the main channel width of Channel A. The value of b_{mc}/B_m exceeds 0.5. In fact, experimental results for Channel A' ($b_{mc}=0.80$m, $b_{mc}/B_m=0.62$) showed that maximum scouring occurred at the inside of the main channel apex section. Flow and bed patterns differed significantly from that of Channel A ($b_{mc}=0.40$m, $b_{mc}/B_m=0.45$) due to weak secondary flow. For this reason, results of Channel A' were removed from the analysis in this paper.
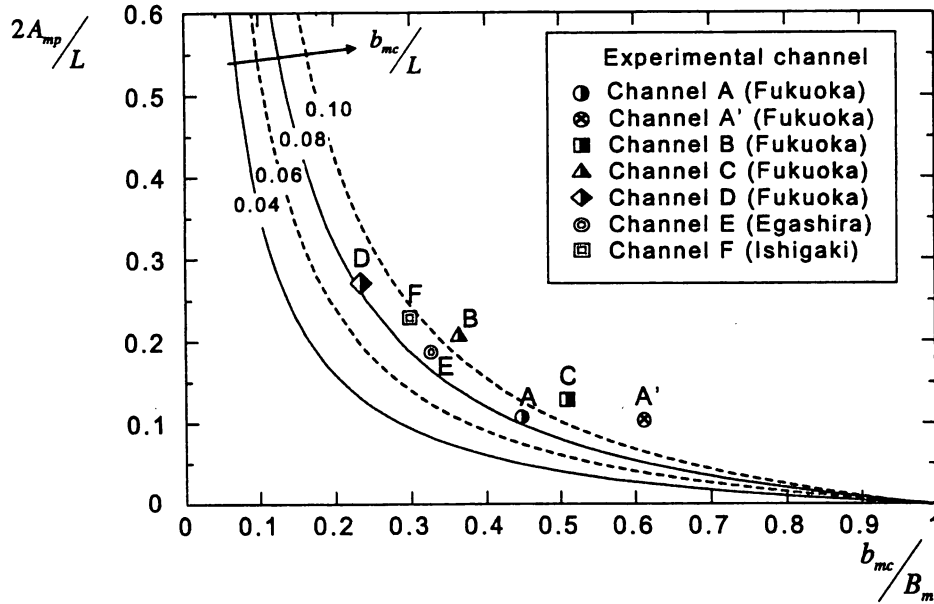
Figure 6 Non-dimensional plan shape parameters of experimental channels

For other channel cases, the value of b_{mc}/L is slightly larger than those of rivers, especially Channel B(0.12) and Channel C(0.13) due to restrictions of the inside experimental facilities.

Although the b_{mc}/L value of Channel B is 0.12, inner bed scouring did not occur as in the preliminary experiment of Channel A'. It is thought that secondary flow may develop in channels with large sinuosity even if the value of b_{mc}/L is above the range 0.04-0.08.

In this chapter, the effects of plan shape and relative depth on the flow and bed topography was investigated by comparing the experimental results of Channel A and Channel B.

Effect of Plan Shape and Relative Depth on the Flow and Bed Topography of Compound Meandering Channels

Table 3 Experimental channel conditions

	Sinuosity S ($=L_m/L$)	θ_{max} (degree)	Meander length L $_m$(m)	Main channel width b_{mc} (m)	Channel width B (m)	Bed slope I	Relative depth Dr
Channel A	1.028	19.0	4.73	0.40	4.00	1/600	0, 0.27, 0.40
Channel B	1.10	35.0	7.50	0.80			0, 0.26, 0.31, 0.44

Table 3 shows the experimental conditions. Sinuosity of each channel is 1.028 (Channel A) and 1.10 (Channel B). Floodplains had artificial grass, whose Manning coefficient of roughness is about 0.018. The main channel was covered with uniform sediment and has a mean diameter of 0.8 mm.

Three different values of relative depth Dr (flood channel depth / main channel depth) were used: simple meandering channel flow (Dr=0), compound meandering channel flow (Dr=0.44) and transition flow (Dr=0.30).

Each experiment was started from an initial flat bed with a slope of 1/600 or 1/1000. Equilibrium bed conditions were obtained after 9-20 hours. Measurement sections were chosen to be midway of the second and third wavelength counted from the upstream end.
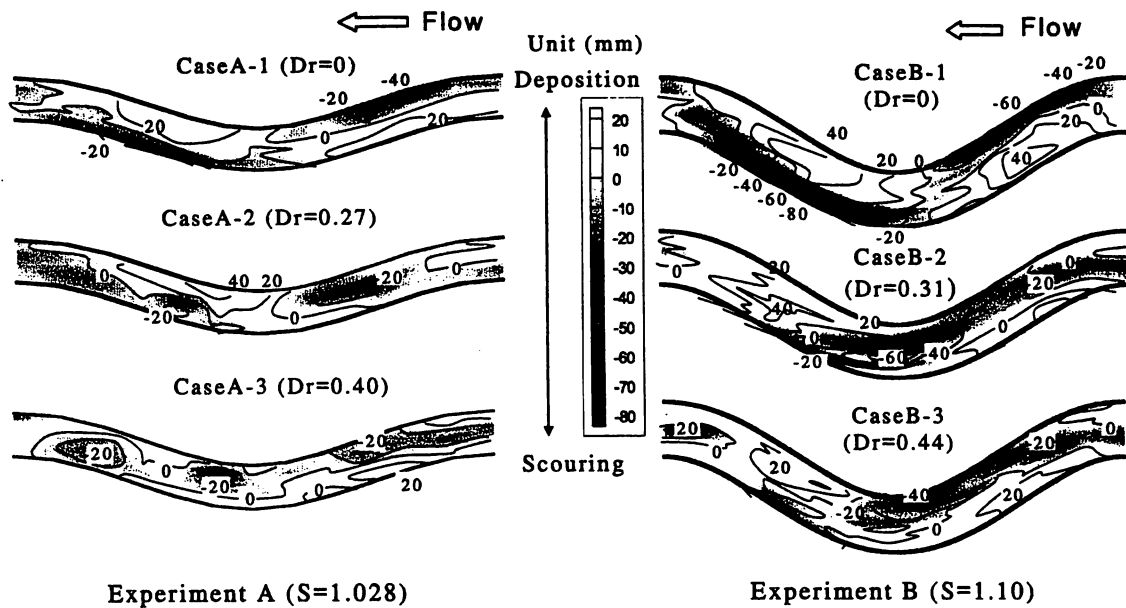
Figure 7 Contour lines of bed level for equilibrium condition of Experiment A and B

Figure 7 shows the bed level contour lines at equilibrium conditions for each relative depth. Black and white colors indicate scouring and deposition, respectively. They are referenced to the cross-sectional averaged bed elevation. Comparisons of bed shape for each relative depth in *experiments A* and *B,* shows the effect of sinuosity on bed variation.

As for the effect of sinuosity, an increment will be reflected in an increase of scouring depths at outer banks when Dr=0. This result proves the existence of the secondary flow growth due to centrifugal force caused by main channel alignment.

For the compound meandering channel flow in each case, lateral bed level change and maximum scouring depth dropped to a marginal level because of flow mixing from the flood channel toward the main channel. Therefore, near bankfull condition flow, generates the maximum scour at the outer bank. The delimiting relative flow depth between a simple and a compound meandering channel flow is almost 0.3 for Channel B (S=1.10). As for a small sinuosity case such as Channel A (S=1.028), this value is thought to be smaller due to a decrease in the effect of channel meandering.

Another important finding concerning representative parameter of plan shape in compound meandering channels was clarified.

If the same relative depth and channel shape fulfill these conditions, (i.e. secondary flow can develop due to centrifigal force), flow pattern and bed topography will not change based on main channel width. This indicates that the main channel sinuosity defined by Eq.(4) is a representative parameter of compound meandering channels.

FLOW CHARACTERS IN COMPOUND MEANDERING CHANNELS DURING FLOOD
- SIMPLE AND COMPOUND MEANDERING CHANNEL FLOW -

As a summary of the experimental and field observations of flow and bed variation in compound meandering channels, simple and compound meandering channel flows were classified based on the representative parameters.

Each flow showed that the maximum velocity filament and scouring are at different locations especially meander apex section (Fukuoka et al. (16)). These locations were determined for each experiment and for real floods by means of aerial survey photographs.

Figure 8 and Figure 9 classify flood flows depending on the locations of maximum velocity filament and the maximum scouring, respectively.
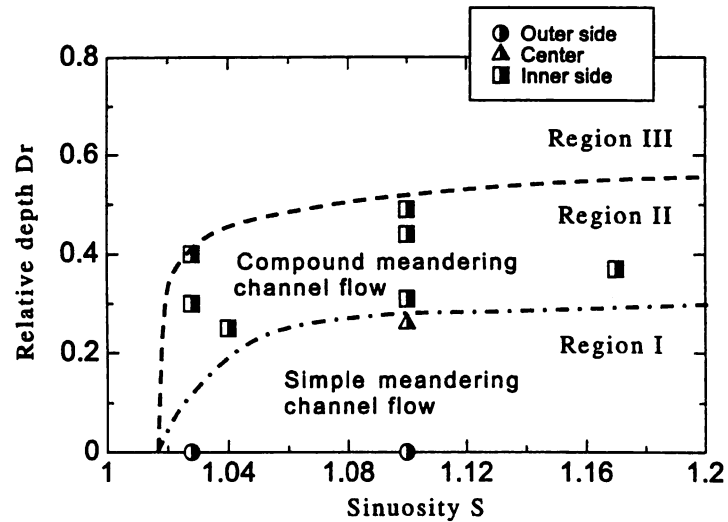
Figure 8 Flow classification diagram based on location of
the maximum velocity at meander apex section
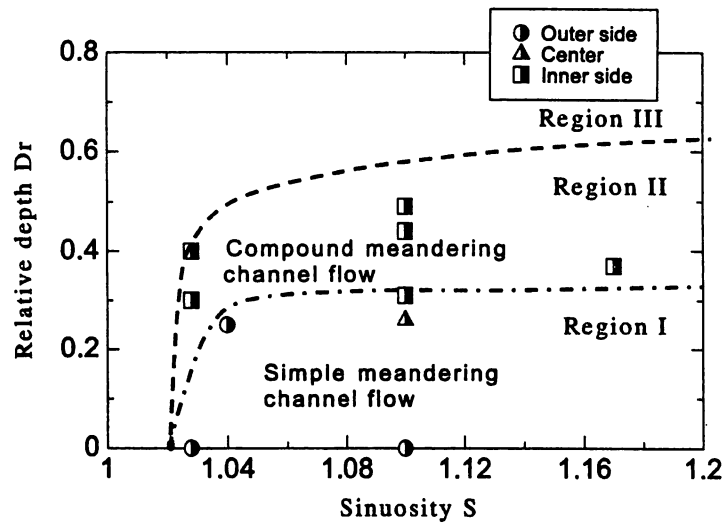(Experimental channel)

Figure 9 Flow classification diagram based on the location
of the maximum scouring at meander apex section
(Experimental channel)

Relative depth Dr is used as a representative parameter of hydraulic condition on the ordinate axis, and channel sinuosity S is represents a plan shape parameter on the abscissa axis.

Surface velocity vectors and distribution were obtained from floating tracer sequenced photographs. Experimental results that fulfilled the conditions of plan shape obtained in Chapter 3 ($b_{mc}/B_m < 0.5$, $b_{mc}/L = 0.04$-0.08) were used to make the diagram.

In Figure 8, we can demarcate three regions based on the location of maximum velocity filament. Region I has minimal relative depth and maximum velocity occurs on the outer side of the main channel due to centrifugal force. This is a simple meandering channel flow. Region II has a considerable relative depth, and maximum velocity tends to occur between the center and inner side of the main channel due to flow mixing between the main and flood channels. This is compound meandering channel flow. Relative depth dividing these two types of flow is about 0.3.

Lastly, Region III has a relative depth above 0.5 and also contains compound meandering channel flow. However maximum velocity occurs almost at the center of the main channel because larger relative depth decreases the main channel meandering effect. The maximum relative depth in Japanese large rivers is generally smaller than 0.5.
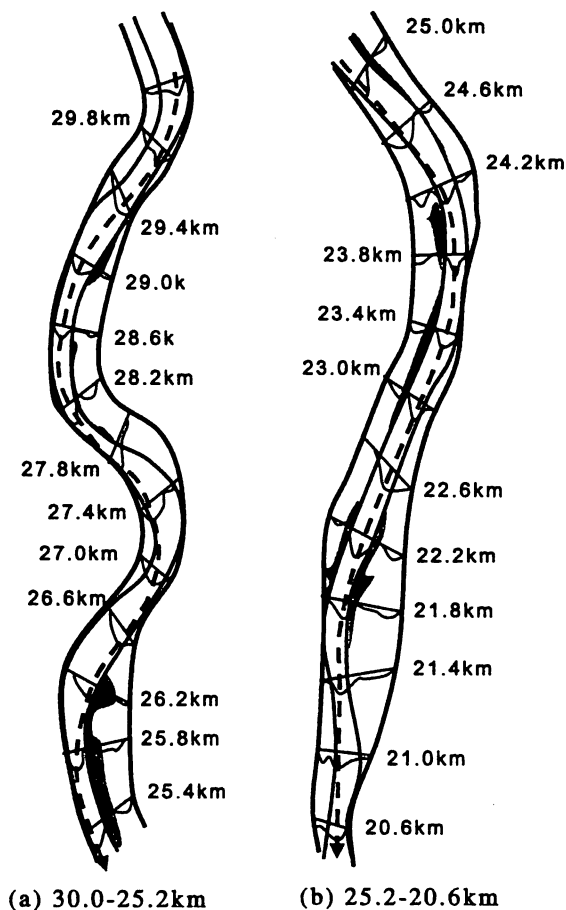
(a) 30.0-25.2km   (b) 25.2-20.6km

Figure 10 Surface velocity distribution and maximum velocity filament at Gono River in July 1983 flood (analyzed by using aero photograph)
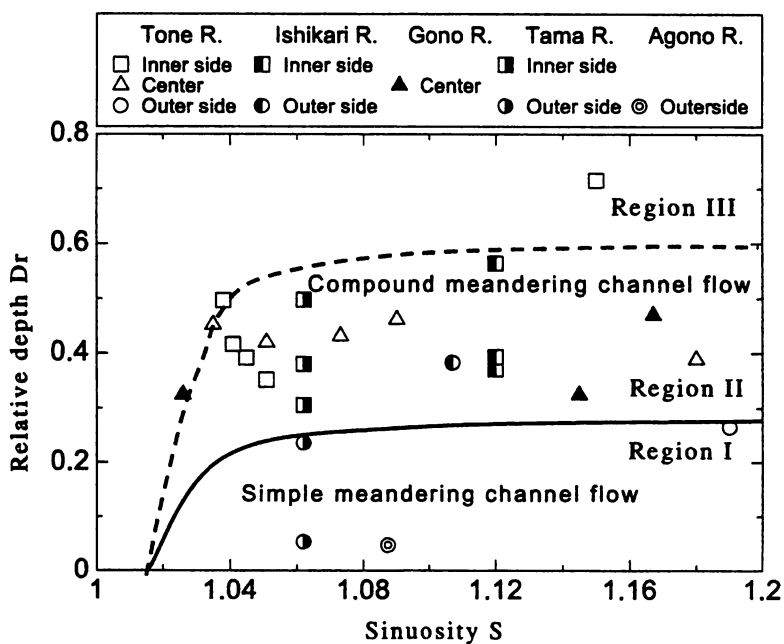

Figure 11 Flow classification diagram based on the location of maximum velocity at meander apex section (River data)

We also made a flow diagram based on maximum scouring occurring at the apex section as shown in Figure 9. This figure is similar to Figure 8. Location of maximum scouring cannot be seen during floods, but maximum velocity is measured by taking aerial photographs. For this reason Figure 8 is helpful in understanding flood flow characteristics.

The same method of flow classification was applied for five rivers in Japan. Figure 10 shows surface velocity distribution and maximum velocity filament for the Gono River flood in July 1983 (Dr=0). Analysis was performed by using aerial photographs. Figure 11 illustrates the classification of flood flow estimated from surface velocity distributions in compound meandering rivers. Here, sinuosity S was calculated by focusing on the main channel alignment as Equation 4. The channel alignment of the five rivers was not uniform, and the flow data might contain some effect of upstream channel alignment. However, the dividing lines are similar to those in Figure 8, which was obtained from experimental results.

These findings shows that flood flow characteristics of compound meandering rivers can be estimated by using sinuosity and relative depth as representative parameters.

CONCLUSION

1) The plan shape features of meandering rivers reveal wave length L, meander belt width B_m and main channel width b_{mc}. The relationship between these parameters was clarified by data taken from eleven rivers. Those are b_{mc}/B_m less than 0.5, with typical b_{mc}/L values falling between 0.04 and 0.08. If the channel shape fulfills these conditions, the main channel sinuosity represents the plan shape of compound meandering channels.

2) Effects of sinuosity and relative depth on the flow and bed variation were investigated from a series of compound meandering channel experiments. Scouring depth becomes larger as sinuosity increases, and maximum bed scouring occurs when the relative depth is just above bankfull discharge. The change from simple to compound meandering channel flow occurs at a relative depth of nearly 0.3. However, for minimal sinuosity, this value becomes smaller due to a decrease of centrifugal force.

3) By using these representative parameters, (sinuosity and relative depth) flood flows were classified according to location of maximum velocity filament and the maximum scouring at the main channel apex section. Classification of the flood flow in rivers showed a similarity to the flow diagram derived from experiments.

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