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Land-form features in compound meandering channels and classification diagram of flood flows based on sinuosity and relative depth

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ABSTRACT: Using several Japanese rivers, flow characteristics in compound meandering channels were investigated by conducting a series of experiments where sinuosity and relative depth were changed. Laboratory results were then compared with results of flood flow analysis using aerial photographs. Representative parameters governing flow characteristics were studied in order to make sense of the results of experimental channel and river flows. Land-form parameters were considered from field data from 10 Japanese compound meandering rivers. Finally, classification diagram of the occurrence of the flood flows in compound meandering channels was presented 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).

1 INTRODUCTION

In Japan, rivers generally have a compound cross section (main channel and flood plain) at their middle and lower reaches.

According to previous laboratory studies of compound meandering channel flows, flow structure differs from that of simple meandering channels due to flow mixing between the main channel and flood channel, as well as differences in bed variation and sediment transport rate (Fukuoka (2000)). In recent years, experiments with movable beds as well as numerical simulation have been performed, and the resultant flow types were: simple meandering channel flow and compound meandering channel flow (Fukuoka et al. (1999a), Fukuoka (2000)). Also in rivers, bed level changes of sand bars located on the inner bank of main channels were measured during flood in situ by using colored sediment columns. Measurements confirmed the occurrence of different flow types during floods (Okada et al. (2001)).

These results have provided important information for river planning, river improvement and structure design. However, most experimental land-forms used (the main channel alignment follows a sine function curve and the levee is straight levees), have a simplified prospective shape and differ from that of rivers. Therefore, it is necessary to clarify how flood flow and bed variation seen in rivers and in experimental channels are related.

For this reason, a series of experiments where sinuosity and relative depth were altered, have been conducted. To standardize the experimental data and river data, the representative parameters of prospective channel form and hydraulic conditions were examined. Form parameters were considered from 6 experimental channel data and field data from 10 Japanese compound meandering rivers.

Finally, a diagram of flood flow occurrence in compound meandering channels is presented, classifying by flow characteristics based on sinuosity, relative depth, location of the maximum velocity filament and the maximum scouring depth at the meander apex section.

2 FLOW AND BED TOPOGRAPHY IN A COMPOUND MEANDERING CHANNEL

2.1 *Movable bed experiment of compound meandering channel with sine generated curve*

Figure 1 shows the planned structure of the experimental channel. Meandering channel form is generally assumed to follow a sine generated curve which can be expressed by Equation 1.

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

where, $\theta_{\max}$: maximum deflection angle, L_m: meander length.

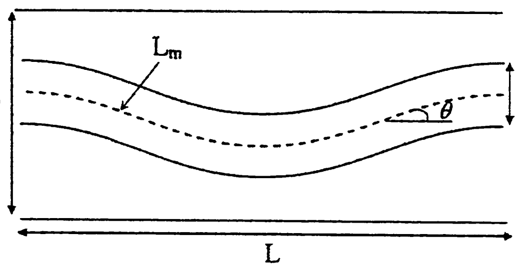

Figure 1. Plan shape of the experimental channel.

Table 1. Experimental channel dimension and condition.

	Channel A	Channel B	Channel C
Sinuosity S (= L_m/L)	1.028	1.04	1.10
θ_{max} (degree)	19.0	22.6	35.0
Meander length L_m(cm)	473	624	750
Wave length L (cm)	460	600	680
Main channel width b_{mc} (cm)	40	80	80
Channel width B (cm)	400	300	400
Relative depth Dr	0, 0.27, 0.40	0.25, 0.40	0, 0.31, 0.44

The experiments were conducted in channels with three types of prospective shapes. Table 1 shows experimental channel dimensions and conditions. Channel sinuosity S were 1.028 for Channel A, 1.04 for Channel B and 1.10 for Channel C (Fukuoka et al. (1999a)).

Floodplains of the channels had artificial grass, whose Manning coefficient of roughness is about 0.018. The main channel was covered with uniform sediment having 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 a 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 from the upstream end of the channels.

2.2 *Effect of sinuosity and relative depth on the flow and bed topography of compound meandering channels*

Figures 2, 3 and 4 indicate bed level contour lines at equilibrium bed conditions for each relative depth at a given sinuosity. Dark and light colors show scouring and deposition measured from the average longitudinal bed slope, respectively. Comparisons of bed shape at each relative depth for *Experiment A*, *Experiment B* and *Experiment C* gives the effect of sinuosity on bed variation.

As for the effect of sinuosity, its incremental increase produces an increase in scouring depths at outer banks when Dr = 0. This result proves the

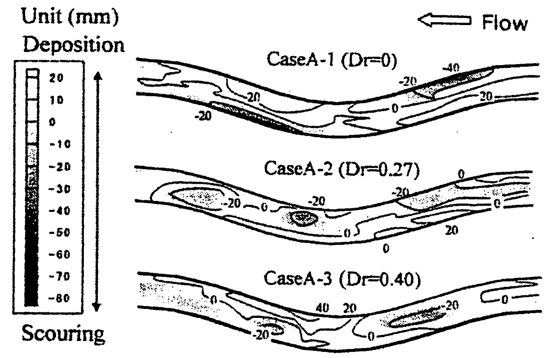

Figure 2. Contour lines of bed level for Experiment A (S = 1.028).

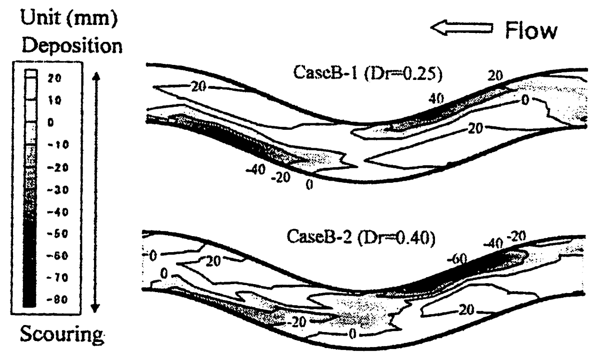

Figure 3. Contour lines of bed level for Experiment B (S = 1.04).

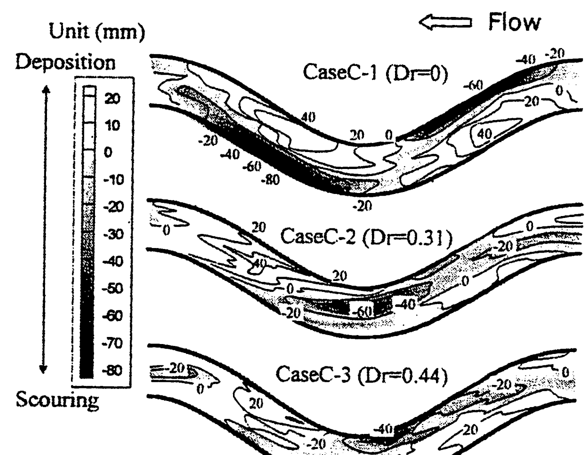

Figure 4. Contour lines of bed level for Experiment C (S = 1.10) (Fukuoka et al. 1999a)).

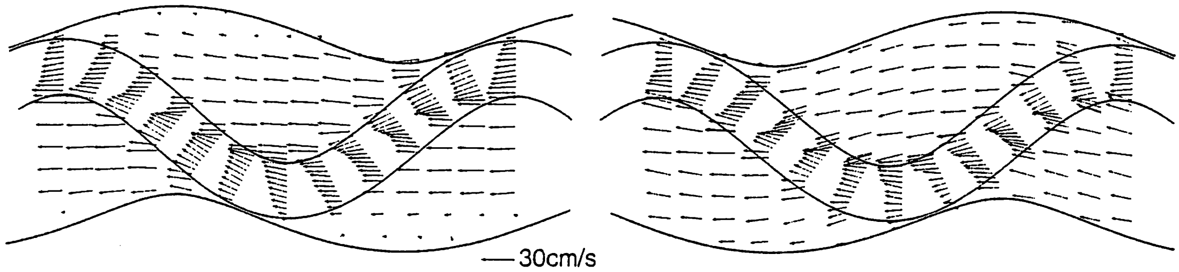

Figure 5. Velocity distributions with phase lug between main channel and levee alignment.

existence of the growth of secondary flow 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 to the main channel. Therefore, relative depth generated maximum scouring to occur near the bankfull case (Dr = 0).

The relative flow depth borderline for the simple meandering channel flow and the compound meandering channel flow is almost 0.3 for Channel C (S = 1.10). But when sinuosity is small, this value can be considered to be smaller due to a decrease in the effect of channel meandering.

These experimental results (flow and bed topography of simple and compound channel flows) for the simplified land-form were confirmed using a 3-D numerical simulation model (Fukuoka et al. (1999b)).

3 PLAN SHAPE FEATURES OF COMPOUND MEANDERING RIVERS

In Section 2, the effect of sinuosity and relative depth on the flow and bed variation of the compound meandering channel was investigated. However, rivers generally have meandering levee and phase differences with respect to main channel alignment. Therefore, to apply this experimental knowledge for the flow and bed variation of rivers, there are some problems to be clarified which require sufficient understanding of both experimental channel and river flow.

As an approach to unify these phenomena, prospective land-form parameters of compound meandering channels and rivers were considered. The most remarkable difference between experimental channels and rivers is the levee alignment. Consequently, the effect of levee alignment on the flow characteristics was studied initially.

Figure 5 shows the velocity distribution with phase lag between the main channel and levee alignment (Fukuoka et al. (1998)).

Comparison 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 channels and flood channels occurred primarily in the meander belt. Therefore, it can be said that main channel alignment is a lager factor affecting flow characteristics than levee alignment. Hence, focus was placed on main channel alignment.

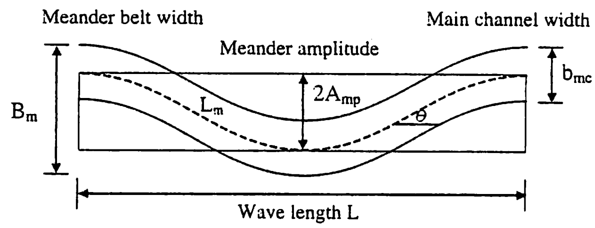

Figure 6. Definition of plan shape parameters of the main channel.

In Section 2, sinuosity was used as a representative parameter that could describe meander channel prospective shape. However, sinuosity (S) shows only the centerline alignment of main channels. Figure 6 indicates these parameters of the main channel being defined using a sine-generated curve. Meander belt width B_m is the sum of twice the main channel amplitude A_{mp} and main channel width b_{mc}.

On the basis of this sine-generated curve channel, one can see that the main components which produce prospective channel 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 Equations 2 and 3.

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

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

As sinuosity (S) is defined by the ratio between meander length L_m and meander wave length L, A_{mp} and L are also functions of sinuosity.

Thus, these three parameters (L, A_{mp} and b_{mc}) describe prospective shape of main channel.

Table 2. Plan shape parameters of rivers.

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
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

Table 3. 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	460	89	40	0.45	0.09
Channel B	600	157	80	0.51	0.13
Channel C (Fukuoka)	680	220	80	0.36	0.12
Channel D (Fukuoka)	1200	425	100	0.24	0.08
Channel E (Ashida)	220	61	20	0.33	0.09
Channel F (Ishigaki)	307	100	30	0.30	0.10

We surveyed land-form features of 10 Japanese rivers and our experimental channels. Table 2 shows prospective shape parameters of compound meandering rivers. Table 3 also shows experimental channel conditions used in the previous study in Japan (where channel sinuosity was less than $S = 1.17$) (Fukuoka et al. (1999a), Ashida et al. (1989) and Ishigaki et al. (1998)).

Non-dimensional parameters of prospective meandering channels b_{mc}/B_m, $2A_{mp}/L$ and b_{mc}/L have the relationship as indicated in Figure 7 (assumed by sine generated curve). This figure shows the relationship between b_{mc}/B_m and $2A_{mp}/L$ for a constant value of b_{mc}/L, changing only wave amplitude. A similar family of curves were obtained for different b_{mc}/L values.

Plotted non-dimensional prospective land-form parameters from Table 2 (for the compound meandering rivers) and Table 3 (for the experimental channels) is shown in Figure 8. Non-dimensional prospective land-form parameters of compound meandering rivers carry vertical axis values ($2A_{mp}/L$) up to 0.4 and horizontal axis values (b_{mc}/B_m) from 0.1 to 0.5. Parameter axis values (b_{mc}/L) range from 0.04 to 0.08.

The vertical axis $2A_{mp}/L$ (ratio of meander amplitude and meander wavelengh) expresses the degree of "channel bending", therefore it bears the same meaning as sinuosity is about 1.00–1.35.

Horizontal axis values b_{mc}/B_m (ratio of main channel width and meander belt width) were plotted to be less than 0.5 due to the following reason: Figure 9 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 and its velocity increased. Due to the existence of this high velocity region, secondary flow cannot develop by the reduction of centrifugal force generated by channel meandering. In fact, preliminary experiments for Channel A ($S = 1.028$) having a main channel width ($b_{mc}/B_m = 0.62$) (Okada et al. (2002)) of 80 cm

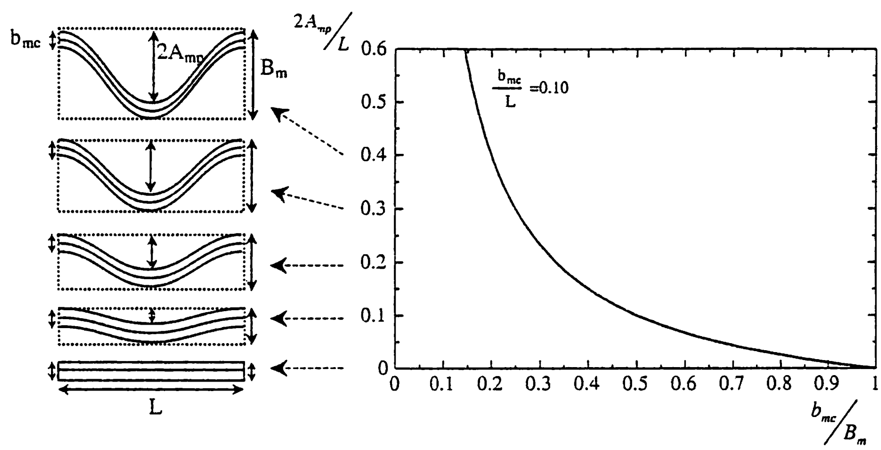

Figure 7. Relationships among non-dimensional plan shape parameters b_{mc}/B_m, $2A_{mp}/L$ and b_{mc}/L (assumed sine generated curve).

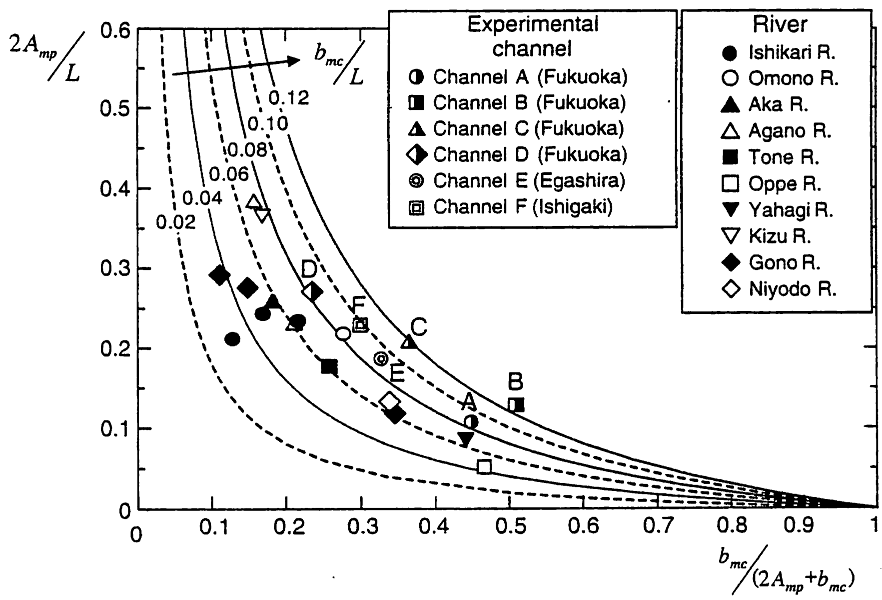

Figure 8. Non dimensional plan shape parameters of rivers and experimental channel.

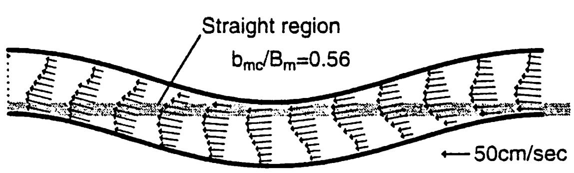

Figure 9. Channel plan shape in the case of $b_{mc}/B_m > 0.50$.

showed that maximum scouring occurred on the inside of the main channel apex section. Flow and bed formation pattern differed from that of Channel A (40 cm main channel width and $b_{mc}/B_m = 0.45$) due to weak secondary flow. Therefore, it was concluded that this type of channel is an exception case and is not generally seen in natural rivers.

Geometoric 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.

Experimental channel data (A–F) were plotted in the same figure. The value of b_{mc}/L is slightly larger than that of rivers, especially Channel B(0.13) and Channel C(0.12), Channel B's b_{mc}/B_m value being almost 0.5.

Although the b_{mc}/L value of Channel C is 0.12, inner bed scouring did not occur as in the preliminary experiment of channel A. It is considered that secondary flow can develop channels with large sinuosity even if the value of b_{mc}/L is larger than the value of $b_{mc}/L = 0.04$–0.08.

Table 4. Definition of compound meandering river classified by occurrence of flow characteristics

	Flow characteristics	Effect of main channel alignment	Effect of main channel alignment
Channel 1	Presence of the simple meandering channel flow and compound meandering channel flow with relative depth variation (compound meandering river from the standpoint of river engineering)	Fulfill the land-form condition of secondary flow development due to centrifugal force $b_{mc}/L = 0.04 - 0.08$ $b_{mc}/B_m < 0.5$	Large
Channel 2	Only simple meandering channel flow		Small
Channel 3	Maximum velocity filament occurs center of main channel at all the time	Secondary flow due to centrifugal force cannot develop	

Therefore, compound meandering rivers were seen as having three pattarns based on the flow characteristics shown in Table 4.

In Channel 1, simple meandering channel flow and compound meandering channel flow exist with relative depth variations. In this paper, we defined compound meandering rivers from the standpoint of river engineering. And in Channel 2, only simple meandering channel flow appears as a result of flood channel inflow. This type of river, can be considered as a simple meandering channel. These two channels also fulfill the land-form conditions of secondary flow development due to centrifugal force as shown in Figure 8.

The above consideration suggests that when we conduct experiments on compound meandering channels, large flood channel width and the main channel parameter (prospective shape) b_{mc}/L should be chosen on the basis of river land-form features as shown in Figure 7.

In other words, if channel shape fulfilled these conditions (i.e. secondary flow can develop due to centrifugal force), flow pattern and bed topography will not change based on main channel width but only if relative flow depth remains the same. This indicates that the sinuosity of the main channel defined by Equation 4 is a representative parameter of the compound meandering channel.

$$\text{Sinuosity } S = \frac{\text{meander length } L_m}{\text{meander wavelength } L} \tag{4}$$

4 CLASSIFICATION DIAGRAM OF FLOOD FLOWS IN COMPOUND MEANDERING CHANNELS

As a summary of the experimental results of flow and bed variation in compound meandering channels, simple and compound meandering channel flows were classified by using the representative parameters of sinuosity and relative depth. Each flow showed that

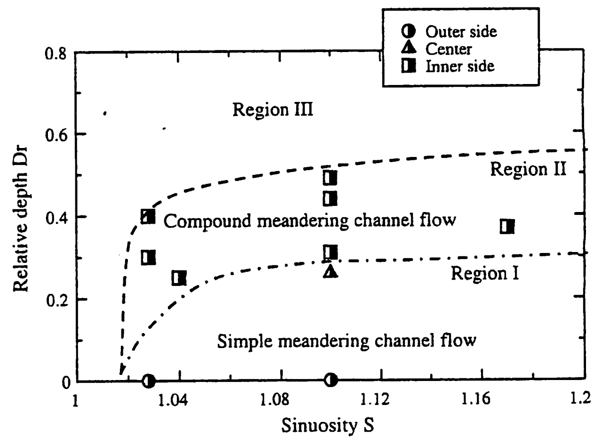

Figure 10. Flow classification diagram based on location of the maximum velocity at meander apex section (Experimental channel).

the maximum velocity and scouring depth were seen at different locations (Fukuoka et al. (1997)). These locations were surveyed for each experiment.

Figures 10 and 11 classify flood flows drawn from locations of maximum velocity filament and the maximum scouring, respectively. Channel sinuosity S is taken as the abscissa and relative depth Dr on the ordinate axis. Surface velocity vectors and distribution were obtained from sequential floating tracer photographs. Experimental results that fulfilled the conditions of the plan shape obtained in Section 3 ($b_{mc}/B_m < 0.5$, $b_{mc}/L = 0.04 - 0.08$) were used to make the diagram.

In Figure 11, 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 by due to centrifugal force. This is simple meandering channel flow. Region II has a considerable relative depth and maximum velocity tends to occur between the center and the inner side of the main channel due to flow mixing between the main channel and the flood

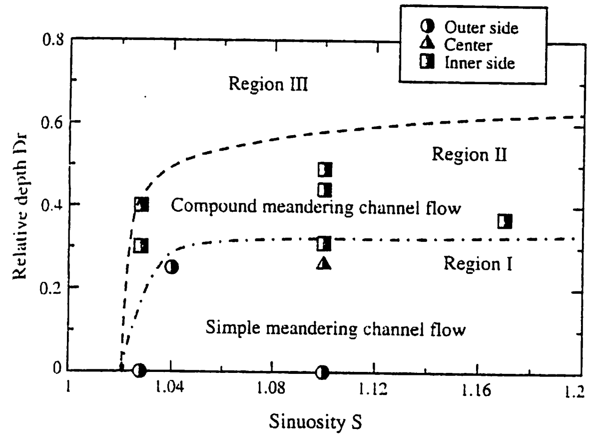

Figure 11. Flow classification diagram based on the location of maximum scouring at meander apex section (Experimental channel).

channel. 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 the 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 of large rivers in Japan is generally smaller than 0.5. Location of maximum scouring cannot be seen during floods, but maximum velocity is measured by taking aerial photographs. This is why Figure 11 is important to understand flood flow characteristics. To this end, we also made a flow diagram based on maximum scouring occurring at the apex section (Figures 2–4) as shown in Figure 12. This figure is similar to Figure 10. The same method of flow classification was applied for five rivers in Japan (Fukuoka et al. (1998)). Figure 12 shows surface velocity distribution and maximum velocity filament for the Gono River flood in July 1983 ($Dr = 0$). Analysis was done using aerial photographs. Figure 13 shows classific of flood flow estimated from surface velocity distributions in compound meandering rivers. The channel alignment of the five rivers was not uniform and the flow data might contain the effect of upstream channel alignment. However, the division lines are similar to those in Figure 10 which was obtained from experimental results. Therefore, by using sinuosity and relative depth as representative parameters, flood flow characteristics of compound meandering rivers can be estimated.

5 CONCLUSION

1. Effects of sinuosity and relative depth on the flow and bed variation were investigated from a

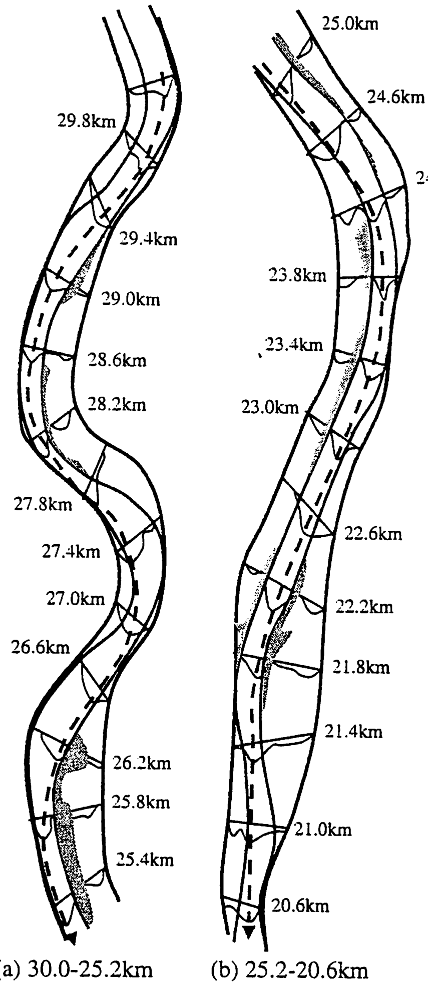

Figure 12. Surface velocity distribution and maximum velocity filament at Gono River in July 1983 flood (analyzed by using aero photograph).

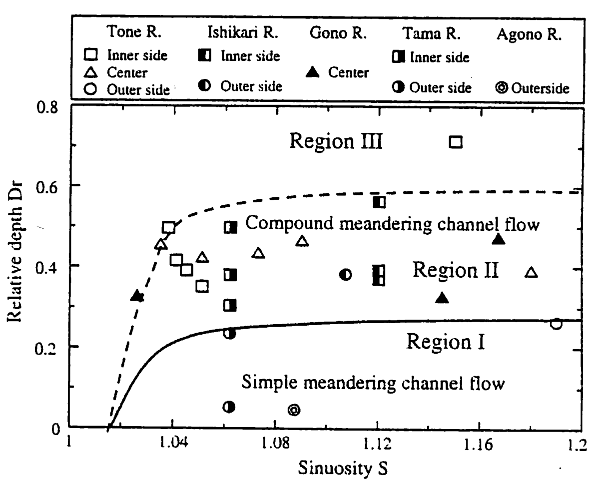

Figure 13. Flow classification diagram based on the location of maximum velocity at meander apex section (River data).

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 the bankfull discharge. The change from simple meandering channel flow to compound meandering channel flow occurs at a relative depth that nears 0.3. However, for minimal sinuosity, this value can be considered smaller due to a decrease of centrifugal force.

2. The prospective land-form features of meandering rivers were wave length L, meander belt width B_m and main channel width b_{mc}. $b_{mc}/B_m < 0.5$, with typical b_{mc}/L values falling between 0.04 and 0.08. It was showed that sinuosity could become a representative parameter when secondary flow develops during simple meandering channel flow as in natural rivers.
3. 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 the river showed a similarity the flow diagram.

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