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HYDRAULIC MODEL EXPERIMENTS WITH MOVABLE BED IN MEANDERING WATER CHANNEL

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ABSTRACT

Recently rivers play an important role in various forms. Increased conscious on environmental impact necessitates proper planning and construction of river structures. There is a need for river planning and design of establishments that can cope with different characteristics of the river banks caused by river channel shapes. This study, using data obtained from hydraulic model experiments, describes characteristics of bed topography and suggests plannning measures for river-planning and design of river establishments.

INTRODUCTION

River bed forms depend mainly on the shape of river channels and medium-sized sand bars in the river beds. Recent theoretical studies1)2) and investigations3) using numerical simulation have established a resonance phenomenon between the shape of river channels and the medium-sized sand bars, but model experiments have not investigated resonance phenomena systematically, and much is yet to be learned. The main influence on scours in river beds may be more related to resonance phenomena than is generally considered. An understanding of the conditions causing resonance phenomena in rivers is very important for flood control and when considering of scour depths of river structures. This study was carried out to investigate resonance phenomena of river shapes and sand bars in river beds using hydraulic experiments with a movable bed. The results of the experiments enable a description of resonance phenomena under specific hydraulic conditions and verify existing theoretical research results. The data is organized in diagrams for the design of revetments and base protection.

OUTLINE OF EXPERIMENTS

Objectives of Experiments

River bed forms mainly depend on curves in river channels and sand bar formation. There have been a number of studies on the formation of sand bars and domain diagrams (signal row, double row). The proposed results, like those by Kuroki, Kishi et al.,4) have been supported by much experimental and observational data. Kinoshita and Miwa5) reported that sand bar movement was dominated by the angle of meander, that it stopped at a limiting angle. However much is left for further investigation. Except for the relations between movement limitations on sand bars and the angle of meander, other parameters as the wavelength of meander, the ratio of river-width to water depth, and the ratio of river-width to radius of curvature are still unknown. There has been no systematic investigation of quantitative forms and movement characteristic of sand bars in meandering flumes.

A final objective of this study is to quantitatively establish the formation and movement of sand bars under various conditions in straight and meandering river channels, and to investigate the interaction among the various conditions mentioned above, by conducting a series of experiments.

Setting the Experimental Conditions

The conditions investigated in this study are the river channel shape and the formation of sand bars.

The shape of the experimental flume uses the Sine-generated Curve Equation (1) which Langbein-Leopold[6] proposed to generally represent rivers here θ is the meander angle of the

$$\theta = \theta_0 \sin\left(\frac{2\pi}{\tilde{L}}\tilde{S}\right) \tag{1}$$

flume; θ_0 the maximum angle of meander of the flume; $\tilde{L}$ the wavelength of meander of the flume; and $\tilde{S}$ the length along the center line of the flume.

Arranging (1) with the relational equation $d\tilde{S} = \tilde{r} d\theta$ gives $(1/\tilde{r}) = (d\theta/d\tilde{s})$, and the right side represents the differential of (1); $\tilde{r}$ is the radius of curvature of the flume.

$$\frac{1}{\tilde{r}} = \frac{2\pi}{\tilde{L}}\theta_0 cos\left(\frac{2\pi}{\tilde{L}}\tilde{S}\right) \tag{2}$$

Solving (2) for θ_0 with the minimum radius of curvature $\tilde{r}_0$ gives $\theta_0 = (\tilde{L}/2\pi)(1/\tilde{r}_0)$, and multiplying the denominator and numerator by 1/2 of the flume width $\tilde{B}$ gives the relational equation $\theta_0 = (\tilde{B}/\tilde{r}_0)(\tilde{L}/\tilde{B})(1/2\pi)$. In the right side, $(\tilde{B}/\tilde{r}_0)$ and $(\tilde{L}/\tilde{B})(1/2\pi)$ are defined as υ and $1/\lambda$. So $\tilde{L}$ and θ_0, representing the shape of the river channel, can be represented by the dimensionless parameter λ and ν; λ and ν are the dimensionless wavenumber of meander and the ratio of river-width to radius of curvature.

Conventionally, theoretical studies propose the ratio of river-width to water depth $\beta = (\tilde{B}/\widetilde{D_0})$ as the dominating parameter in the formation of sand bars, where $\widetilde{D_0}$ is the average water depth.

This study focuses on three parameters λ, ν, and β. To obtain typical alternating sand bars, the three parameters are determined by setting hydraulic conditions with domain diagram like Kuroki and Kishi[4] and Kinoshita and Miwa[5]. Figures-1 and 2 plot the experimental conditions in each domain diagram in the experiments here. Cases*2,3,4 are assumed to form sand bars, but case*-1 not. Flume shapes in cases 1-* and 11-* are assumed to move sand bars, but in cases 5-*, 7-*, and 9-* they are not.

As the water depth of the experimental flume is small compared with the particle size of river bed materials, it is not possible to develop both medium and small sand bars. The experiments here are conducted under conditions where small sand bars form with difficulty. Domain diagram of small sand bars conventionally proposed are based on measured values.

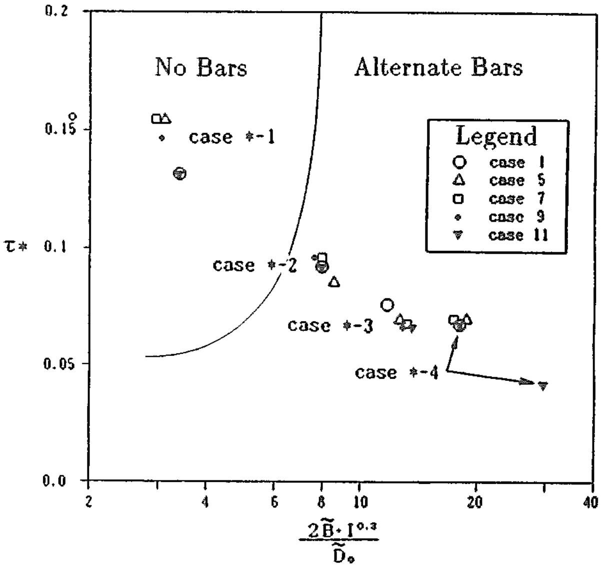

Figure-1 Experimental Conditions with the Domain Diagram by Kuroki and Kishi

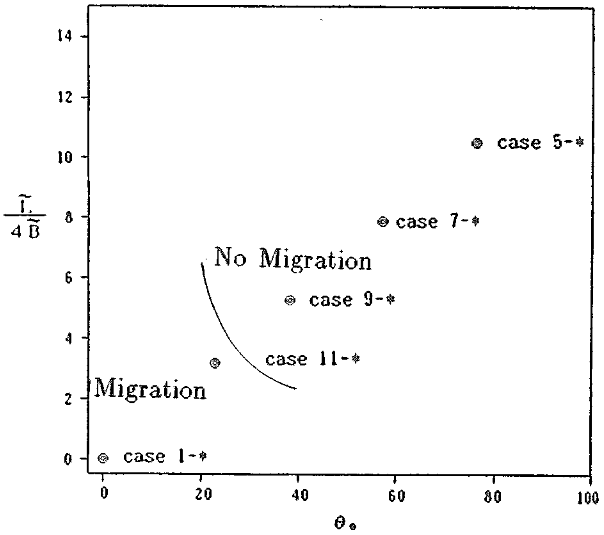

Figure-2 Experimental Conditions with the Domain Diagram by Kinoshita and Miwa

This study adopted the general domain diagram represented by $\tau_* \sim \widetilde{D_0}/\widetilde{d_s}$, like Ashida and Michiue et al.$^{7)}$, and it also set the drag force τ_* as larger than the critical drag force τ_{*c}= 0.05. Figure-3 plots these experimental conditions, and there are no cases where the lower regime cause sand ripples and dunes. Considering subcritical flows in rivers, the Froude number was given to be below 1. Comparing the results of experiments and the conditions of scour in the main rivers of Hokkaido, the ratio of river-width to water depth β was set between 5 and 40, based on actual rivers conditions. Sufficient water depth was determined by the resistance rule of Equation (3) unaffected by the viscosity of bed materials, and also to satisfy the various conditions mentioned above. Here $\widetilde{u_*}$ is the shear velocity and $\tilde{u}$ is the mean flow velocity.

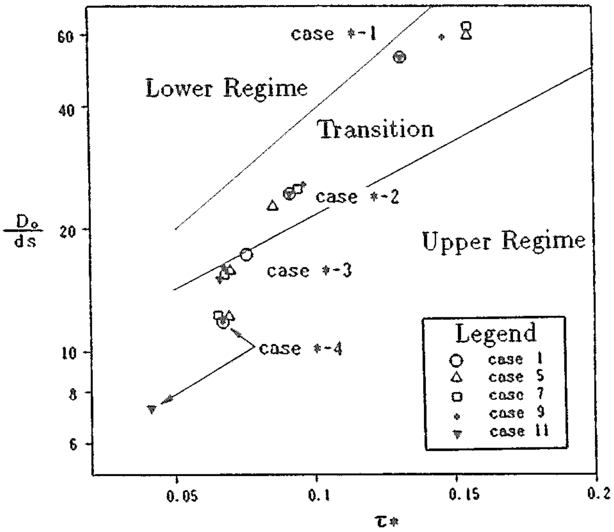

Figure-3 Experimental Conditions with the Domain Diagram by Ashida and Michiue

$$\frac{\widetilde{u_*^2}}{\widetilde{u_*}} = \frac{1}{\{6 + 2.5ln(\frac{\widetilde{D_0}}{2.5d_s})\}^2} \tag{3}$$

The flume shape and hydraulic figures were set to satisfy the above conditions and to enable the amplitude to fit in the experimental installations. Here 20 experiments were performed using one straight flume and four meandering flumes with different λ , for four different β . Table-1 shows particulars of the experiments, the bed material is quartz sand No.5.

Actually, the influence of the particle size of the river bed material also had to be considered, but it was disregarded in these experiments, due to the small differences in the dimensionless grain size $d_s = \widetilde{d_s}/\widetilde{D_0}$.

Table-1 Particulars of Experiments

case	Meander wavelength $\widetilde{L}(cm)$	Dis-charge $\widetilde{Q}(\ell/s)$	Measured flume slope I	Average water depth $\widetilde{D_0}(cm)$	Bed material $\widetilde{d_s}(mm)$	Angle of meander θ_0	λ	ν	β	d_s	τ_0	η
01 − 1	−	3.97	1/243	2.96	0.553	−	−	−	5.1	0.019	0.134	0.255
01 − 2	−	1.46	1/161	1.36	0.553	−	−	−	11.0	0.041	0.093	1.458
01 − 3	−	0.79	1/138	0.96	0.553	−	−	−	15.7	0.058	0.077	2.477
01 − 4	−	0.56	1/106	0.65	0.553	−	−	−	23.1	0.085	0.068	3.623
05 − 1	628.00	3.99	1/241	3.33	0.568	38.217	0.15	0.10	4.5	0.017	0.151	1.508
05 − 2	628.00	1.47	1/161	1.27	0.568	38.217	0.15	0.10	11.8	0.044	0.087	2.898
05 − 3	628.00	0.81	1/138	0.87	0.568	38.217	0.15	0.10	17.3	0.064	0.069	3.958
05 − 4	628.00	0.55	1/106	0.65	0.568	38.217	0.15	0.10	23.0	0.085	0.068	3.266
07 − 1	471.00	4.01	1/244	3.35	0.568	28.662	0.20	0.10	4.5	0.016	0.151	1.595
07 − 2	471.00	1.60	1/160	1.37	0.568	28.662	0.20	0.10	10.9	0.040	0.094	2.585
07 − 3	471.00	0.80	1/138	0.85	0.568	28.662	0.20	0.10	17.7	0.065	0.068	3.979
07 − 4	471.00	0.56	1/106	0.65	0.568	28.662	0.20	0.10	22.9	0.085	0.068	4.008
09 − 1	314.00	4.02	1/243	3.29	0.568	19.108	0.30	0.10	4.6	0.017	0.149	1.406
09 − 2	314.00	1.50	1/161	1.41	0.568	19.108	0.30	0.10	10.7	0.039	0.096	2.339
09 − 3	314.00	0.80	1/138	0.86	0.568	19.108	0.30	0.10	17.5	0.064	0.069	3.749
09 − 4	314.00	0.55	1/106	0.66	0.568	19.108	0.30	0.10	22.9	0.084	0.068	3.879
11 − 1	188.40	4.01	1/243	2.96	0.568	11.465	0.50	0.10	5.1	0.019	0.134	0.890
11 − 2	188.40	1.51	1/161	1.36	0.568	11.465	0.50	0.10	11.0	0.041	0.093	2.230
11 − 3	188.40	0.81	1/138	0.83	0.568	11.465	0.50	0.10	18.1	0.067	0.066	2.863
11 − 4	188.40	0.55	1/106	0.40	0.568	11.465	0.50	0.10	37.3	0.138	0.042	6.891

Experimental Installation

Figure-4 is a diagram of the experimental installation. The table is 25m long and 3m wide, with 0.3m-wide meandering and straight flumes, and sand was placed according to the design. The meandering flume was made of lauan plywood (completely waterproof, 24mm thick) cut to the shape of the flume on the table, and by fixing the 30cm-deep sidewall with a vinyl chloride plate (colorless, transparent, 5mm thick) to fit to the base shape of the flume. Supports were placed to prevent deformation of the sidewall due to the weight of sand. In addition, 2cm diameter vinyl chloride pipes were buried in the sand to prevent deformation of the river bed form when draining water after stopping the discharge, and to promote drainage.

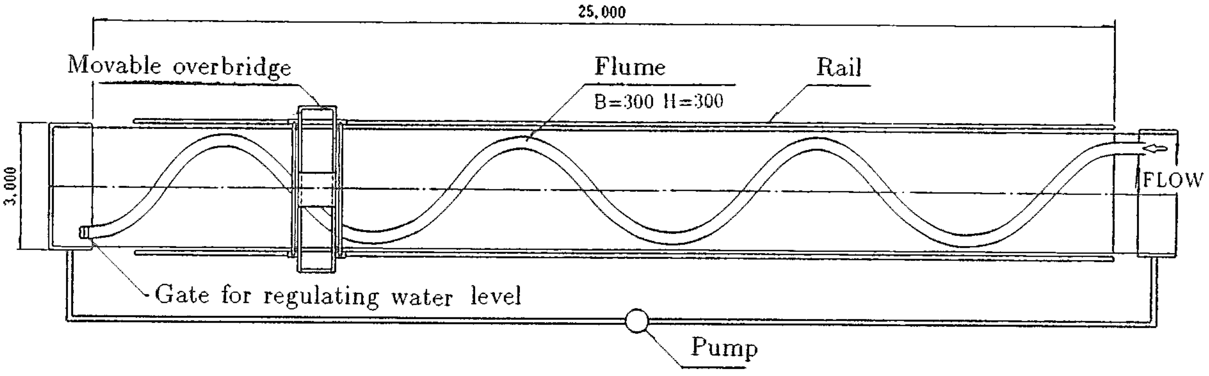

Figure-4 Diagram of Experimental Installation

At the start of the experiments, the flume was first flooded to prevent rapid bed variations, and then the water level and discharge were set to the design values. When the bed became stable after discharge of the water, water levels were quickly measured. Later, water was drained, taking care not to affect the bed, and the bed height was measured after completion of the drainage. Measurements used a non-contact automatic reader of the river bed with an optical sensor.

Results

Figure-5 shows the longitudinal variations in the deepest river bed in each meander experiment. The ordinate shows the sediment amount on the average bed made dimensionless with the average water depth negative values indicate scour, and the abscissa is the downward distance made dimensionless with 1/2 of the meander wavelength of the flume (the start is the crest of the curve in the meander flume). The average height of the river bed in each cross section is also added. In Case*-1, without sand bars, scour tends to be large at the curve crest, and small where the curve turns. This shows that river bed forms are affected by the shape of flume. In experiments with sand bars like cases-9, -2, -3, and -4 and 7-2, and -3 where sand bars are fixed and the wavelength of sand bars and meander of the flume are sufficiently equal, river bed forms also depend on the meander shape. In case 11-2, -3, and -4, 7-4, and cases 5-2, -3, and -4 where the wavelengths of sand bars and meander are different, scour tends to be large at the top of curves, but is independent of the meander shape. In cases 5-2, -3, and -4, sand bars were expected to remain fixed as in Figure-3, but movement did take place. This supports research by Shimizu et al.[3] that movement of sand bars depends on the wavelength as well as the angle of meandering.

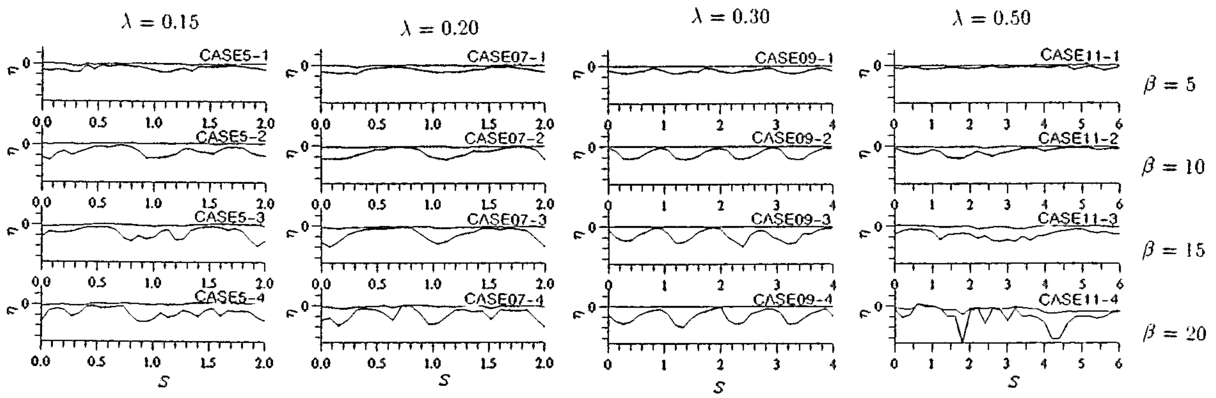

Figure-5 Longitudinal Bed Variations of the Maximum Height in Each Experiment

The following outlines the results of the experiments for typical cases with the contour chart of the river bed.

Figure-6 shows contour charts of the bed for case 11 with the shortest wavelength of meander from experiments with (case 11-2) and without (case 11-1) sand bars. Case 11-1 without sand bars showed straight flows, sedimentation on the concave bank, erosion on the convex bank, and a dimensionless maximum depth of scour of 0.89, nearly equal to the water depth. In case 11-2, with sand bars and the same shape of meander, formation of sand bars causes meandering, and the deepest bed develops at the front of bars. The wavelengths of bars and meander are different, and scour and sedimentation is independent of the shape of the flume. When the meander length is short and sand bars do not develop, scour and sedimentation occurs in places different from those generally expected.

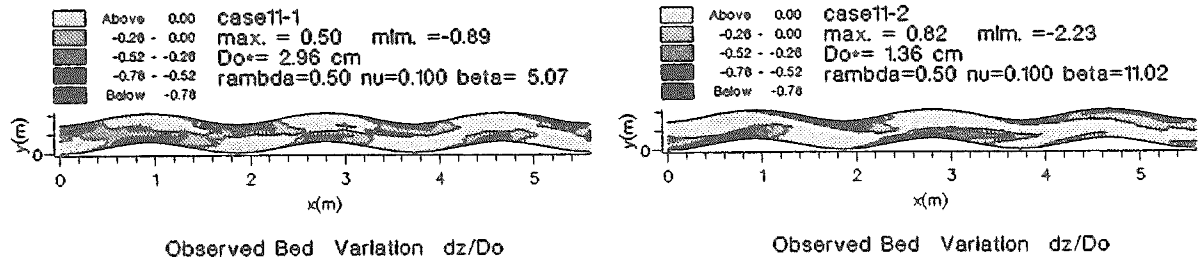

Figure-6 Contour Charts of River Beds in Case 11-1 and 11-2

Figure-7 shows contour charts of the experiments with (case 9-4) and without (case 9-1) sand bars in case 9 where the wavelength of meander and sand bar are equal. Both cases show similar river bed forms. The dimensionless maximum depth of scour in case 9-1 is 1.4 times the water depth, and in case 9-4 it is four times the water depth. It was established that much scour occurs when the wavelengths of sand bars and meander are equal.

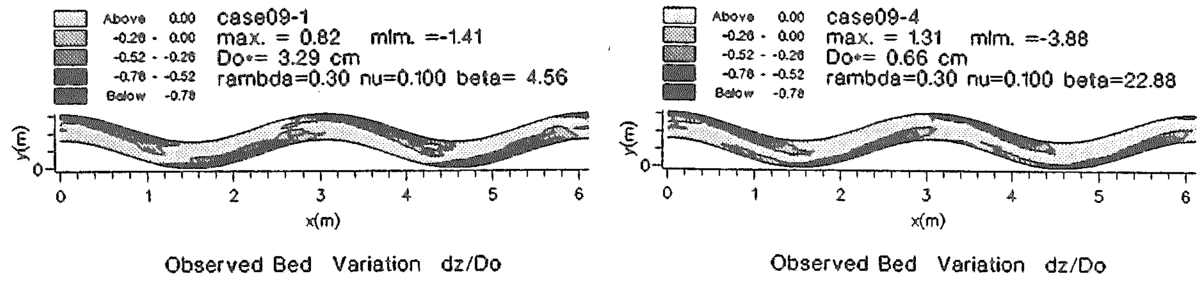

Figure-7 Contour Charts of River Beds in Cases 9-1 and 9-4

Figure-8 shows the results of experiments with different dimensionless wavenumbers of meander λ for the same β parameter of sand bar formation: the contour charts of case 7-3 is with a short wavelength of meander and case 5-3 is with a long wavelength. Case 7-3 indicates that movement of sand bars does not correspond to the meander of the flume. Case 5-3 shows that movement of bars takes place between inflection points of a meander: sand bars trailing away from the inflection point vanish upstream of the top of the curve, and new sand bars extend downstream and this behavior is repeated. In this case, two pairs of alternating bars occurred with one meander wavelength, and the wavelengths of meander and sand bars were different. Figure-2 indicated that bars did not move in either experiments, but that movement of bars was confirmed in case 5-3 with the long meander wavelength. In the movement of sand bars, it is necessary to consider the relation between wavelengths of sand bars and meandering, as well as the meandering angle of the flume.

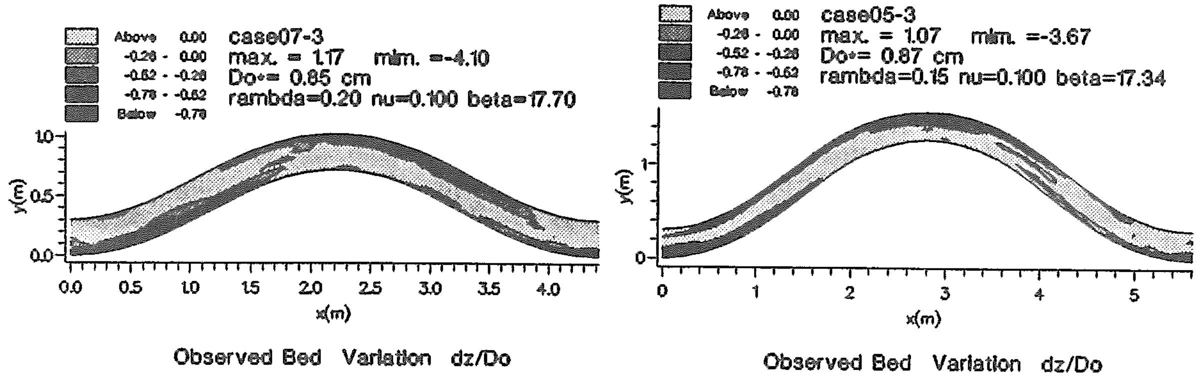

Figure-8 Contour Chart of River Beds in Cases 5-3 and 7-3

SIZE AND PLACE OF SCOUR OF RIVER BEDS

In revetment design, it is necessary to determine penetration depth to prevent damage by determining the places and amounts of scour. The most effective arrangement is also needed to preserve the ecosystem and establish water-access as has been advocated recently. Here, the establishment of place and amount of maximum bed scour focuses on meandering river channels with sand bars.

Amount of Bed Scour

Figure-9 shows the relations between the maximum of the dimensionless depth of bed scour η and the ratio of river-width to water depth β using the dimensionless wavenumber of meander as the parameter. It indicates that η increases with β for all λ , and that the depth of bed scour depends largely on β, the dominating parameter of sand bar formation. Figure-10 shows the relations between the maximum value of dimensionless depth of bed scour η and the dimensionless wavenumber of meander λ by interpolating from the values in Figure-9 and using β as the parameter. For every β value, the plotted η indicates a maximum between 0.15 and 0.30 λ and shows that it moves upward in parallel as β increase. In the experiments with λ between 0.15 and 0.30, the wavelength of sand bars agrees with the wavelength of meander of the flume, which is considered the condition causing resonance between sand bars and the shape of flume. That is, the experiments corroborate conventional investigations1)2)3) that the maximum scour depth increases in the domain of resonance of sand bars and shape of flume.

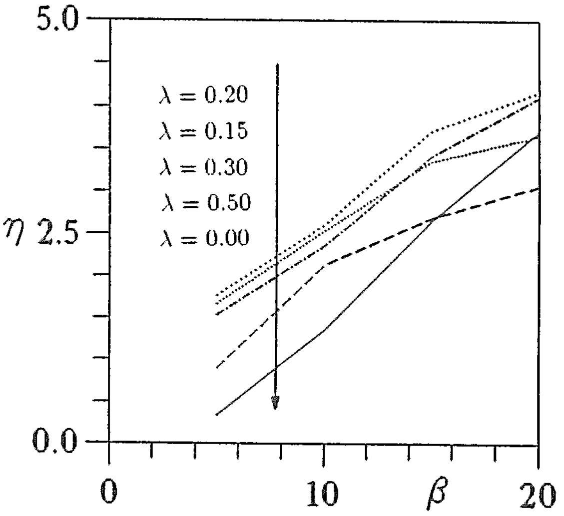

Figure-9 The Relation between the Maximum Dimensionless Depth of Bed Scour & β

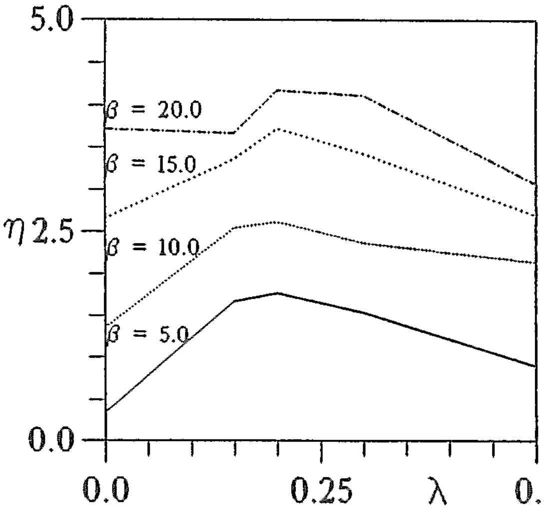

Figure-10 The Relation between the Maximum Dimensionless Depth of Bed Scour & λ

3-2 Position of Maximum Scour

Figure-11 shows where the maximum scour depth with one wavelength of each meander changes with time by expressing the discharging time of water (minutes) as the ordinate and the dimensionless phase difference δ as the abscissa (δ is given by making the distance from the concave bank of the top of the curve of the meandering flume to the maximum height of river bed dimensionless with 1/2 of the wavelength of meandering, and the upperstream is positive.) The maximum scour depths developing at the concave and convex banks of the top of the curve of the flume provide the dimensionless phase differences of 0 and 1. In cases 9-2,-3, and -4, and 7-2,-3, and -4 with fixed bars, the deepest river bed with one wavelength per meander develops in a specific phase. Cases 5-1, 7-1, 9-1, and 11-1 without sand bars, and 11-2, -3, and -4 with movement of bars, show that the deepest bed did not form at a fixed place, but that it may occur anywhere in the bed. In cases 5-2, -3, and -4 with movement of sand bars, movement of place of scour due to sand bars does not appear in the figure because of the large amount of scour around the top of the curve of meander. This may be because the influence of the meander is larger than that of bars: case 5-1 with the same dimensionless wavenumber of meandering and no sand bar indicates that the deepest river bed forms at a specific place, though other cases without bars show it to develop in different places. These results indicate that in cases with the same ratio of river-width to radius of curvature, river bed forms are possibly more dominated by sand bars than by the meander shape of the flume, as the dimensionless wavenumber of meandering increases. Further investigation will be necessary to verify this.

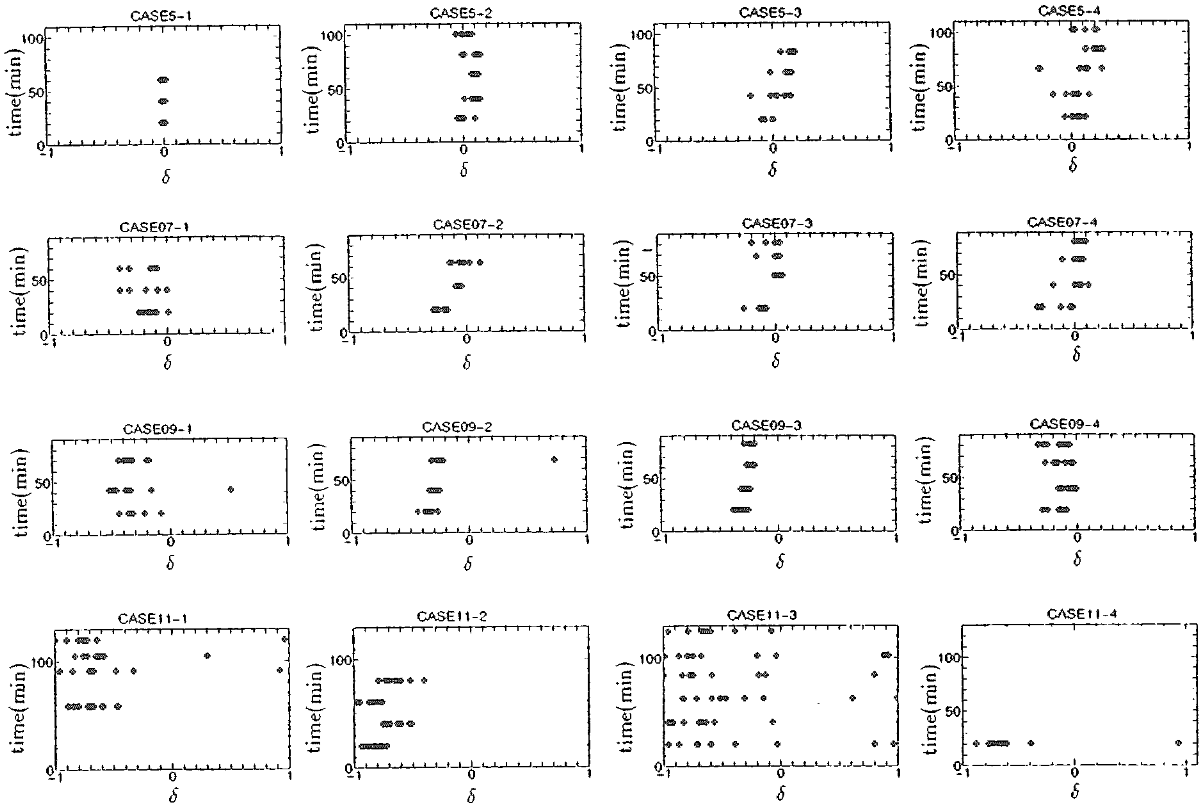

Figure-11 Variation in Dimensionless Phase Differences with Time

Summary

Experiments were performed on the resonance between sand bars and meander of flumes, and the results are:
1) Movement and disappearance of sand bars are affected by the meandering angle of the flume and the relation between the wavelengths of sand bars and meandering.
2) Large scour develops with both sand bars and meander of flumes.
3) The dimensionless maximum depth of scour increases with the ratio of river-width to water depth β, and reaches a maximum value at a specific dimensionless wavenumber of meander λ.
4) At the same ratio of river-width to radius of curvature, river bed forms are more affected by sand bars than by the meandering shape of the flume. This is increasingly so when the dimensionless wavenumber of meandering increases.

Further investigation is necessary to establish the conditions of resonance to establish maximum scour of the river bed and details of bar formation. Further experiments are also needed with different ν and ds values.

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