Experimental Study on Stream Channel Processes in Alluvial Rivers

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Abstract

In order to elucidate fluvial processes of alluvial rivers, experiments were carried out in the 7.5 m wide flume of Experimental Facilities for Research of River Disaster in Ujigawa Hydraulic Laboratory of the Disaster Prevention Research Institute.

In the beginning of the experiments, the stream channel was widened uniformly in longitudinal direction and the channel bed was raised by depositing eroded sand from side banks, and after a while, signs of alternating bars appeared on the bed. And then, channel widening and bed variation were affected by boundary conditions to have a obvious longitudinal change, though planform of channel was still straight, while alternating bars kept on developing and traveling. But channel processes after that became considerably different from each other, being governed largely by experimental conditions which were classified into three groups, and consequently, three kinds of channel patterns were formed, that is, meadering channel, braiding channel and straight channel with armor coat.

In addition, it was indicated that there were not a few common aspects in fluvial processes to every experiment under different conditions, and based on these aspects, a diagram explaining the stream channel processes under fundamental conditions was presented.

1. Introduction

Rivers have formed alluvial plains, conveying sediment and changing their courses freely without artificial restraints in early stages of human activities, and even at present the change of river channels have caused enormous flood hazards. In order to protect human life and property from these river disasters, people have made many efforts to clarify the whole feature of river channel variations in alluvial plains and to find out a rational criterion for designing a secure river course and a stable channel. For these aims, studies and investigations on river mechanics and fluvial hydraulics have been carried out and clarified various aspects of river channel processes. In spite of this progress, it is possible to predict only theoretically longitudinal variation of mean bed elevation, hence it is necessary to introduce two-dimensional analysis of stream channel variation into river mechanics on the basis of elucidation of the phenomena in the channel processes. But stream channel variations, especially channel lateral shifts, occur almost always during extreme floods, and therefore, these processes can hardly be observed and surveyed directly, because people evacuate far from the rivers or engage in flood-fighting. Even if a hydraulic observation of channel variations during a flood would be planned systematically, extreme dangers of losing lives prevent people from obtaining sufficient results on the machanisms of the channel processes. Then, it seems practically impossible to execute the direct observations of the channel processes and this impossibility is regarded as one of the limits of present technics in hydraulic observation. Accordingly, traces of river metamorphorsis are the sole guide for the processes and the causes of channel changes, but results obtained from them are restricted and not accurate. For these reasons, the observations must be replaced by well-managed fundamental experiments in which channel processes and hydraulic conditions can be measured precisely in detail.

For the purpose of the elucidation of stream channel processes, many experiments[1)-19)] have already been carried out as shown in **Table 1.** In almost all of these experiments, reflecting the scarcity of knowledge on the processes of channel variation, the aim has been to clarify fundamental properties of the processes by use of bank erodible stream channels. Experimental procedure and contents of measurement are different from each other, and the purpose of experiments are classified into three groups as follows:

1. To grasp characteristic feature of the processes qualitatively.
2. To elucidate dominant phenomena of the processes based on hydraulics.
3. To find out stable channel conditions.

Though it is difficult to classify the experiments completely since these subjects are related mutually, as to the experiments in Table 1, early studies by Friedkin,[1)] Nagai,[2)] Sawada,[4)] Kinoshita,[5)] Ackers,[8)] Rozovskii et al[9)] and Ackers-Charlton[12)-14)] belong to the first group, those by Aono[3)] Hasegawa et al[10)] and Adachi-Nakato[11)] are included within the second group, and the third group contains those of Wolman-Brush's[6)] and Stebbings'.[7)]

Characteristics of the processes of stream channel change have been made clear gradually by the above experimental studies. Most of these studies are, however, in the qualitative stage and insufficient to consider the mechanisms of the processes and to predict the channel variation, because previous experiments by means of small sized channels caused whole processes to finish in an instant, while those by large sized channels needed great efforts to be carried out and were too difficult to control experimental conditions. As present hydraulics in sedimentation has progressed through detailed experiments and profound considerations, it is indispensable to conduct experiments by means of large sized channels under well controlled conditions and with accurate measurement. Accumulation of data in such experiments is also significant to establish a similarity law of the fluvial processes of river channels, comparing with other results of experiments in small sized channels.

Table 1. Previous experiments on stream channel process with bank erosion.

Experimentalist (year)	Dimension of experimental flume Width×Length	Bed mateaial Diameter (mm)	Initial stream channel Width and Shape (cm)	Initial bed slope	Inlet angle	Discharge (l/sec)	Depth (cm)
Friedkin[1] (1945)	4 m×14.6 m 11.6×36.6	silt, sand d_{50}=0.02~1.5 mainly sand/silt=2/1	10~50 trapezoid	1/333~1/111	0, 30°~90°	0.28 ~12.2	1.5 ~ 9.0
Nagai[2] (1955)	2.2×18.0	sand d_{50}=1.0	10~40 trapezoid	1/50	0, 45°	0.6 ~ 1.2	0.4 ~ 0.9
Aono[3] (1957)	2.2×18.0	sand d_{50}=0.51	8~20 trapezoid	1/50~1/500	0	0.2 ~ 1.6	0.5 ~ 2.0
Sawada[4] (1958)	2.2×18.0	sand d_{50}=0.51	10 trapezoid	1/100~1/200	15°~45°	0.2 ~ 1.2	
Kinoshita[5] (1959)	0.8× 3.6	silt, sand d_{50}=0.0015~0.8 mainly sand d_m=0.77	3.0~13 rectangular	1/9~1/30	0, 45°	0.05 ~ 0.11	1.0 ~ 2.5
Wolman[6] Brush (1961)	1.2×15.6	sand d_{50}=0.67 2.0	12.8~25.6 trapezoid	1/141~1/1000 1/100~1/416	0	0.28 ~ 1.9 0.90 ~ 7.9	
Stebbings[7] (1962)	0.9× 8.1	sand d_{50}=1.0	5~40 rectangular	1/72~1/677	0	0.052~ 4.17	0.5 ~ 2.7
Ackers[8] (1964)	30 ×90	sand d_{50}=0.16 0.34	76~297 trapezoid	1/348~1/2439	0	11.1 ~148.3	5.4 ~20.6
Rozovskii[9] Eremenko Bazilievitch (1967)	6 ×36	sand d_{50}=0.40	47, 100 trapezoid, rectangular	1/143	0	steady 20 unsteady 0.5~8, 1.3~9	
Hasegawa, Kudo,[10] Yamaoka (1968)	0.5×11.5	sand d_m=0.46	10 rectangular	1/30~1/100	0	0.04 ~ 0.25	
Adachi[11] Nakato (1969)	2 ×25	sand d_m=0.43		1/115~1/14	0	1.0 ~ 2.4	1.0 ~ 2.0
Ackers[12)~14] Charlton (1970)	10.4×91.4	sand d_{50}=0.15		1/700~1/303	0	6 ~90	2.19~ 7.80
Schumm[15] Khan (1972)	7.3×30.5	sand d_m=0.7	30.5 rectangular	1/50~1/1000	0, 40°	4.25	1.65~5.18
Hickin[16] (1972)	1 × 3.7	quartz sand d_{50}=0.454 d_m=0.499	8.5	0.0087~0.070	0	0.0193~0.153	0.2 ~ 0.7
Bordas[18] (1973)	15 ×28	sand d_m=0.22	20~200 60	1/167 1/100~1/500	0	4	
Yamaoka[17] Hasegawa (1975)	0.8×15	sand d_{50}=0.26	11 triangle	1/50~1/100	0	0.235~ 0.4	
Ikeda[19] Nakamura (1976)	1 × 5	sand+clay sand d_{50}=0.4	6 trapezoid	1/50~1/15	0	1.08 ~ 1.38	

(Remarks: d_{50}=the median diameter, d_m=the mean diameter)

From the viewpoint stated above, fundamental experiments were carried out,[20)-24)] using the largest flume in Ujigawa Hydraulic Laboratory of the Disaster Prevention Research Institute. This flume composes a part of Experimental Facility for Research of River Disaster,[25)] and these experiments were conducted by Ashida, Narai, Shioiri, Tanaka and authors since 1969. In this paper, most of the essentials of the experiments are described as well as equipment, conditions and procedure of the experiments.

2. Experiments

2.1 Experimental equipment

Experiments were carried out by using the river course part of the Experimental Facility for Research of River Disaster in Ujigawa Hydraulic Laboratory. Experimental equipment for this part consists of a flume made of reinforced concrete, a sand scraper, a carriage for measurement, a sand injector and water supplying systems.

The flume is 7.5 m in width, 1.5 m in depth and 243 m in length, the indoor part of which is 135 m, and its bed is horizontal. The upstream end is connected to a regulating tank while the downstream end to a sand receiver (**see Fig. 1**). Rails of 15 kg/m are laid on the top of both side walls for running of the scraper, the carriage and the sand injector. (**Photo. 1**)

The sand scraper is used to form an initial shape of the stream channel. It has a blade of full width of the flume and a shovel which rotates and moves laterally, on the both apparatus we can put attachment plates of initial cross-sectional shape. They can also rise and fall by clutch operation, in linkage to and independent of the scraper's traveling. Six kinds of slopes can be shaped, that is, 1/2000, 1/1000, 1/700, 1/500, 1/300 and 1/200, by operating this linkage system. In addition, a photographic measuring stage is installed on the scraper for picture analysis and video-recording of the stream channel processes. (**Photo. 2**)

The carriage for measurement has two large-sized point gages mounted on their own traversing devices. Vertical range and accuracy of the point gage measurement are 0–120 cm and 0.1 mm respectively and the traversing device can be equipped with various kinds of sensors to detect channel geometry and flow conditions. (**Photo. 3**)

The large-sized sand injector is an apparatus of rotary feeder type, that has a hopper of 2 m^3 and supplies sand at a rate of 0.01–1 m^3/hr/m into any position of the flume in both longitudinal and lateral direction, because it also has a traveling function and the hopper is divided into 15 partitions at intervals of 50 cm in lateral direction. The wide range of sand supplying rate is attained by rotating a rubber-coated drum intermittently (0.5 sec period) by reciprocation

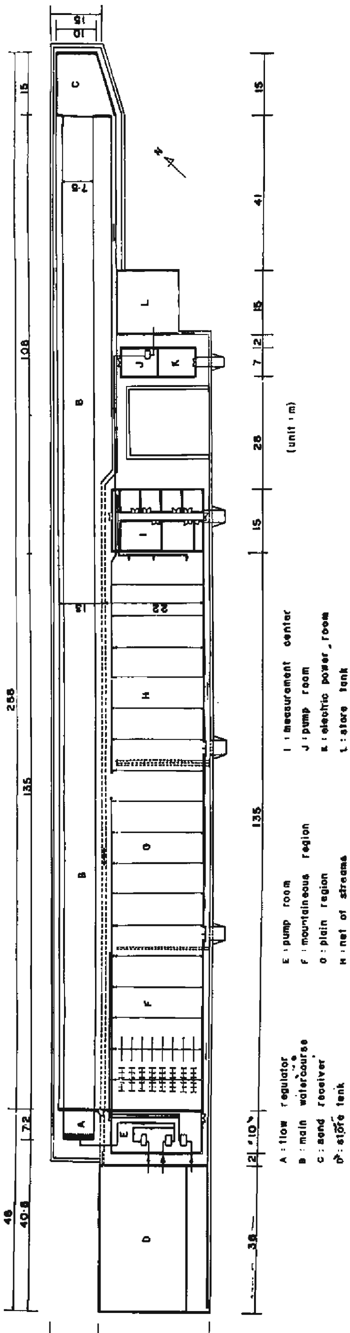


Fig. 1 Plan of Experimental Facility for Research of River Disaster.

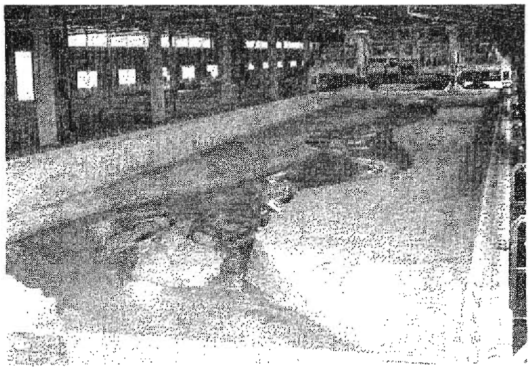


Photo. 1 Experimental flume and stream channel (Exp. XIII).

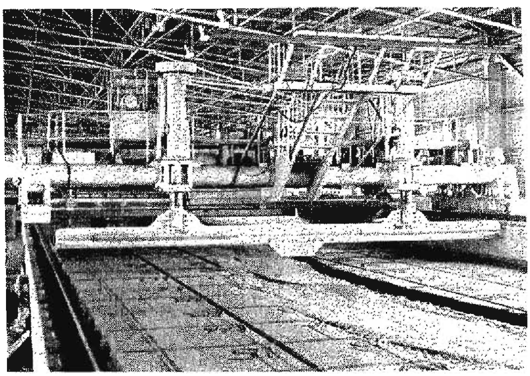


Photo. 2 Sand scraper.

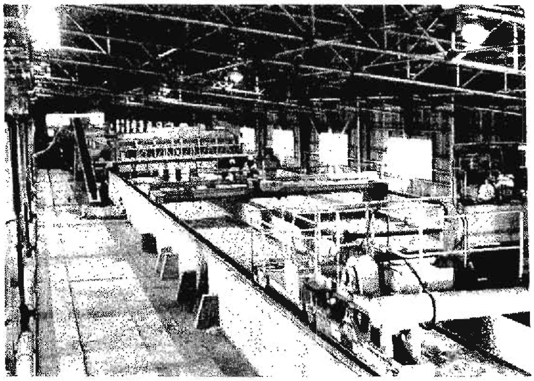


Photo. 3 Carriage for measurement. (center).

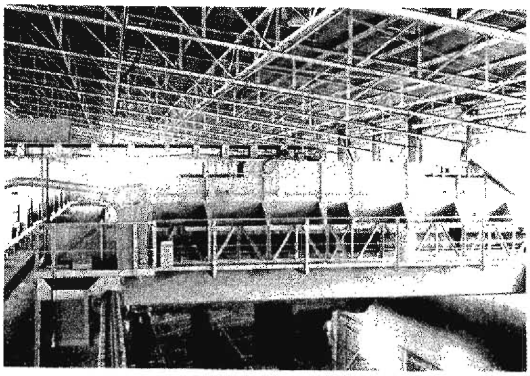


Photo. 4 Large-sized sand injector.

of a fan-shaped gear with a one-way clutch driven by a rack gear, the stroke of which is adjusted by an eccentric wheel to control the supplying rate. There were no detectable influence of this intermittency on the processes of channel variation. (**Photo. 4**)

Three water supplying systems can be used. Capacities of these systems are 500 l/sec, 250 l/sec and 50 l/sec respectively. The flow discharge is remote-controlled automatically to keep a constant value or produce a certain hydrograph by orifice or electro-magnetic flow meters and air valves from the measuring room, where discharge and the operation are monitored. In the experiments, only the third system is used because of relatively small discharge of 6 to 30 l/sec.

2.2 Experimental conditions

Sand used in the experiments is the product of the Yodo River at Hirakata. Its grain size distribution is shown in **Fig. 2** and its median and mean diameter are $d_{50}=0.61$ mm and $d_m=0.88$ mm respectively.

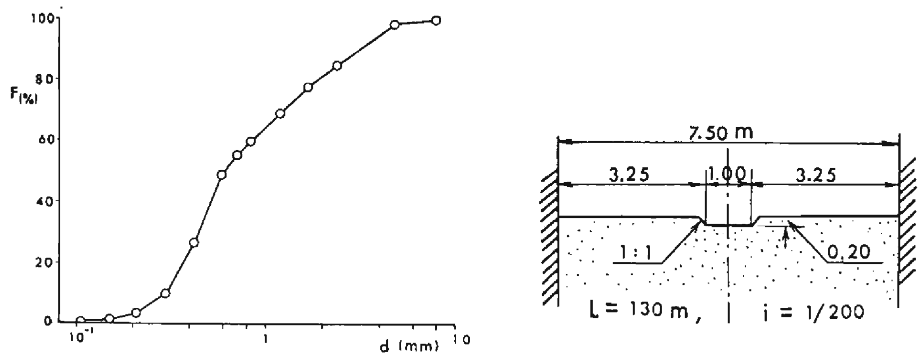


Fig. 2 Grain size accumulation curve of sand used and cross-section of initial channel (Exp. II).

Table 2. Initial conditions of experimens

Exp. No.	Cross section of channel (Trapezoidal shape) Bottom width (cm)	Side slope	Depth (cm)	Bed slope	Stream length (m)	Discharge (l/s)	Flow duration (hr-min)	Notation
I-1 I-2	100	1 : 1	20	1/200	130	7.5 15.0	100-00 30-19	
II	100	1 : 1	20	1/200	128	15.0	28-41	
III	50	1 : 2	10	1/200	120	6.0	71-26	
IV	50	1 : 2	10	1/200	110	15.0	25-00	
V U.R. D.R.	50	1 : 2	10	1/200 1/500	110	6.0	55-30	Two step slope
VI U.R. D.R.	50	1 : 2	10	1/200 1/500	110	15.0	37-30	〃
VII	50	1 : 2	10	1/200	110	6.0～30.0	31-00	Varying flow
VIII	25	1 : 2	5	1/200	110	5.0	22-00	
IX	50	1 : 2	10	1/200	110	15.0	30-00	Left side: loose Right side: rigid
X	100	1 : 2	20	1/200	42.3	20.0	17-21	Sand supply
XI	50	1 : 2	10	1/200	42.8	15.0	12-07	〃
XII	50	2 : 1	40	1/200	42.4	15.0	44-35	〃
XIII	50	1 : 1	20	1/200	42.8	15.0	15-40	〃

(Remarks: U.R.: Upstream Reach, D.R.: Downstream Reach)

Discharge Q and initial geometry of stream channel are summarized in **Table 2.** In Exp. X–Exp. XIII, experimental reaches were shortened and sand was fed at the inlet in order to let the reaches be equivalent to the downstream reaches in Exp. I – Exp. IX. Reference discharge was 15 l/sec and most of initial channel width was about 0.7 m. The experiments are classified into the following three groups

1. Experiments under prismatic initial channel and constant discharge without sand supplying ·····························Exp. I – IV and VIII.

Table 3. Duration of each discharge in Exp. VII.

Flow duration T (hour)	0-5	5-8	8-10	10-12	12-15	15-21	21-31
Discharge Q (l/sec)	6	10	15	30	20	10	6

2. Experiments under prismatic initial channel and constant discharge with sand supplying ··Exp. X – XIII.
3. Experiments otherwise with some additional conditions····················
··Exp. V – VII and IX.

Experimental conditions of the third group are explained here briefly. Exp. V and Exp. VI were both fundamental experiments corresponding to the processes near the transition point from steep slope to mild slope, such as downstream ends of alluvial fans, and initial bed slope was formed to be 1/200 in a upstream reach of $x=0$–60 m while 1/500 in a downstream reach of $x=60$–110 m. Exp. VII was conducted to clarify the influence of unsteady discharge on fluvial processes, where discharge was varied step like, shown in **Table 3**, simulating a hydrograph during a flood. In Exp. IX, it was aimed to find out a restraint effect of a one side bank revetment or to consider characteristic features in channel processes when bank erodibility is different from each side bank. Then the right side bank was stabilized by setting tin plates coated with sand grains along the bank slope.

2.3 Experimental procedure

The initial shape of the stream channel was formed, as shown in **Fig. 2**, into a given cross-section and slope by the blade of the sand scraper. On the top planes of both side banks, lines at 1 m intervals were drawn by the shovel in both longitudinal and lateral directions to detect channel shifts. The sand slope at the upstream end of experimental reach was shaped into about the angle of repose of the sand used and the upstream part of the flume from this slope forms a stilling basin with a capacity of more than 60 m^3. Filling up this basin by water, the sand bed of experimental reach could be almost saturated before the beginning of the experiment. On the other hand, the sand bed was fixed at a constant level by a sill and water fell freely over it at the downstream end, except for Exp. I where the bed surface was coincident to the flume bottom at the end. Sediment washed out from the downstream end was trapped and measured to estimate the sediment transport rate.

Experiments were closed according to the channel variation, that is, if it was intense, an experiment would be finished when the stream channel reached either of the side walls; while if it was gentle, when little change in the stream channel was detected. Flow conditions and channel geometry were measured at suitable time intervals. Water surface level was measured at 2 to 4m intervals each just before breaking the flow, while detailed measurement of bed profile, bed configuration, change of bed materials and sediment transport rate was carried out during the break of flow. Moreover, plane picture sequences of the stream channel were taken at rather short time intervals to measure channel geometry and migration of bars and meandering bends using potasium permanganate as a tracer of bed configuration.

The coordinate system for measurement was as follows: the x-axis was longitudinal direction and $x=0$ m at the upstream end of the stream channel, the y-axis was lateral direction from right to left and $y=4$ m at the center-line of the flume, and the z-axis was upward vertically.

3. Results of experiments

3.1 Fluvial processes in the experimental stream channel

Characteristic features of stream channel processes in the experiments are described in this section, concerning changes of channel patterns and bed configuration. Especially, the processes are explained on the basis of the results of Exp. II in fair detail, because the most essential phenomena of the processes seemed to occur in this experiment. Results of the other experiments are described comparing them with those of Exp. II.

(1) Experiments under prismatic initial channel and constant discharge

(a) Experiments without sand supplying

Plans of stream channel variation in Exp. I-2 and Exp. II is depicted in **Fig. 3(a)** and **(b)** by the results of photo measurement respectively, and changes of channel width B and bed elevation Z in Exp. II are shown in **Fig. 3(c)** and **(d)** respectively. **Fig. 3(d)** shows changes of profiles of water surface level H and energy head H_0 also. According to **Fig. 3(b)** and **(c)**, uniform channel widening (in longitudinal direction) was found in mid-and-downstream reach at $T=0$ - 10hr39′, but after $T=17$ hr, channel width showed wavy variation in $x=55$-95 m and $x=110$-130 m reaches, corresponding to channel meandering. At $T=23$ hr 20′ - 23 hr 40′, that channel meandering propagated from the upstream reach became clear even in $x=95$-110 m reach, while the longitudinal variation of stream channel width showed the same wavy shape as in the final state. On the other hand, channel widening ceased rapidly in a upstream reach of $x=0$-25 m till $T=3$ hr 40′. Such a ceasing of channel widening extended downstream slowly to $x=55$ m at the final state.

The stream channel bed was raised by sand deposition due to bank erosion except for the upstream reach of $x=0$-25 m and the aggradation was remarkable from mid to downstream reach. By not supplying sand at the inlet, the bed

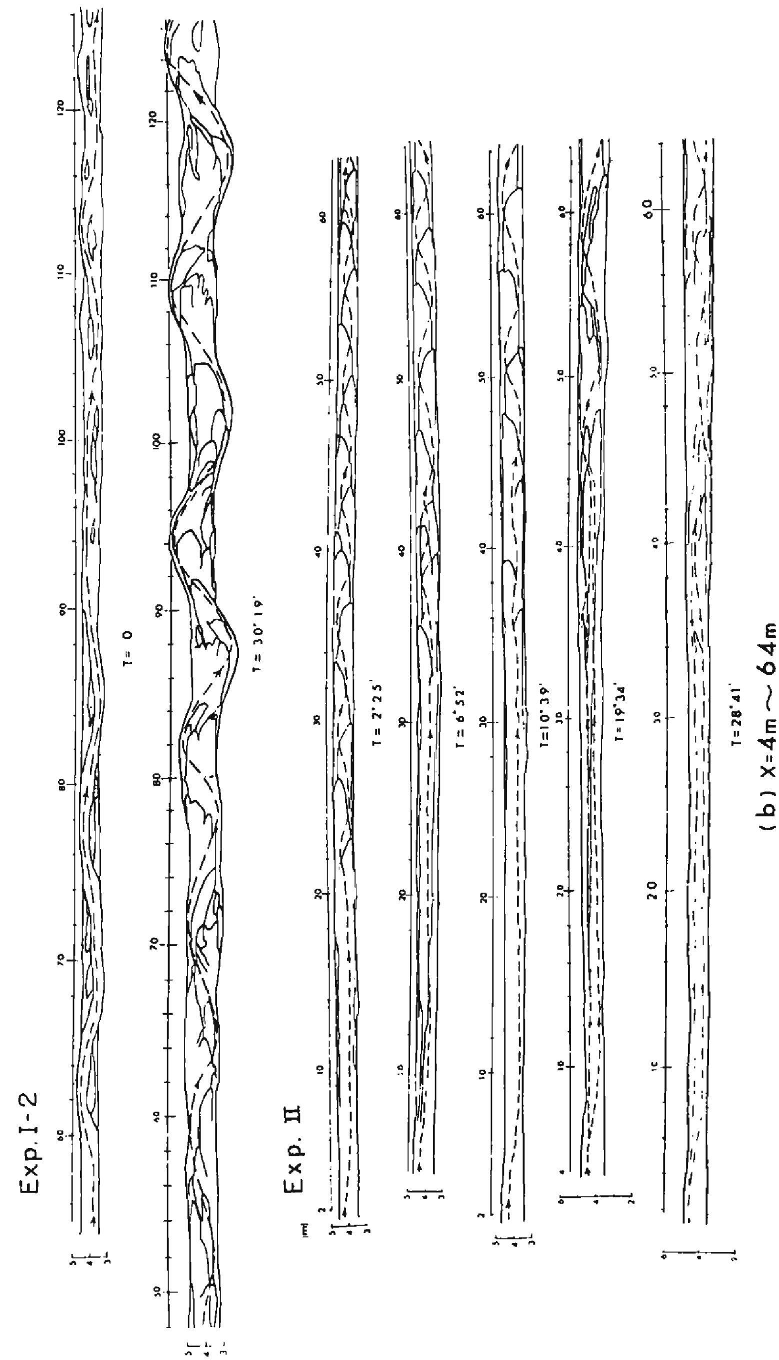
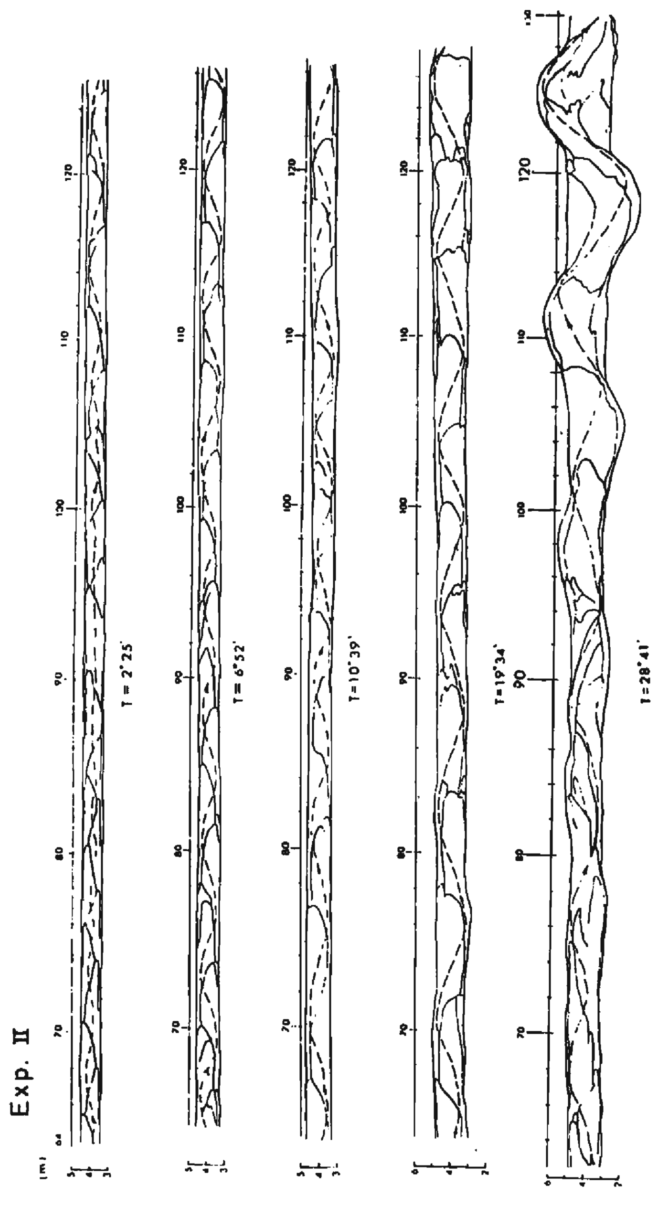


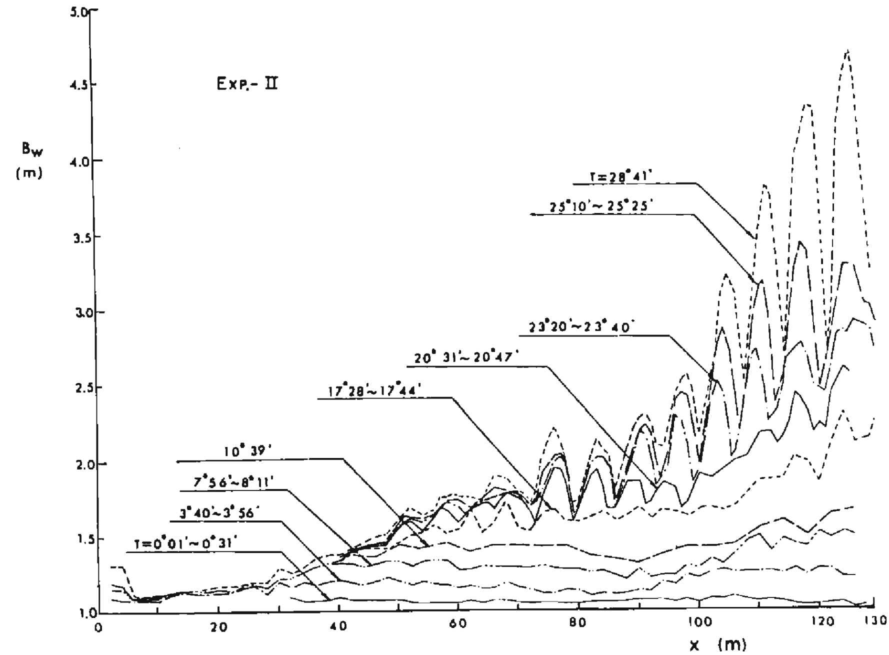
Fig. 3 (a), (b) Developing processes of bed configuration with time in Exp. I—2 and Exp. II.



(b') x = 64m~128m

Fig. 3(b)' Developing processes of bed configuration and channel meandering in Exp. II.

(c)



(d)

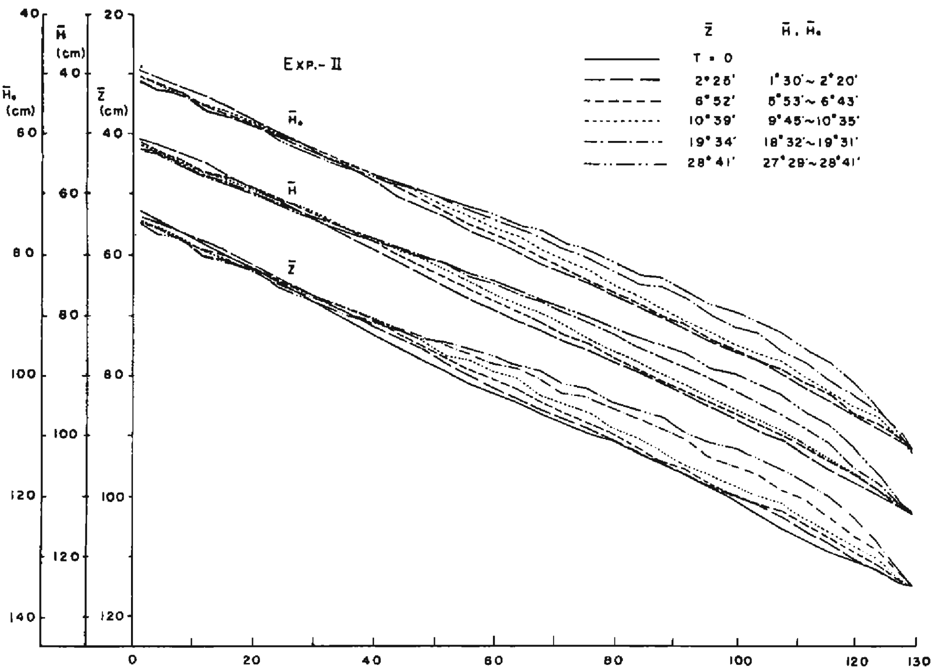


Fig. 3 Variation of water surface width of stream (c), and that of bed profile, water surface profile and energy head line (d) with time (Exp. II).

degraded from the upstream end. The degradation reach stretched to $x=50$ m at the final stage. But near $x=50$ m, the bed level at the final state was higher than the initial level, since degradation in the midstream reach was much smaller than the preceding aggradation. Just before the end of Exp. II, the reach of $x=0$–20 m was judged to have attained a static equilibrium, because bed degradation was not detectable and channel widening ceased within that reach. In the downstream reach, meanwhile, the bed slope became steeper due to the fixed level at the downstream end, and the bed profile was a wavy line similar to the water surface profile which corresponded to channel patterns and bed configuration.

The above-mentioned properties of stream channel processes were observed in other experiments under the same discharge (Exp. I-2, Exp. IV). However, at the downstream reach in Exp. I-2, the bed slope was mild, so development of meander bend was rather gradual and variation of flow pattern was gentle, because there was no abrupt drop at the downstream end. As to Exp. IV, all the fluvial processes progressed more rapidly than in Exp. II, such as, widening and aggradation in the early stage, stoppage of widening in the upstream reach and meander development in the mid-and-downstream reach, since initial width and depth of channel cross-section were both about a half of those in Exp. II (**Photo. 5**).

→Flow

(a)

(b) ①

②

③

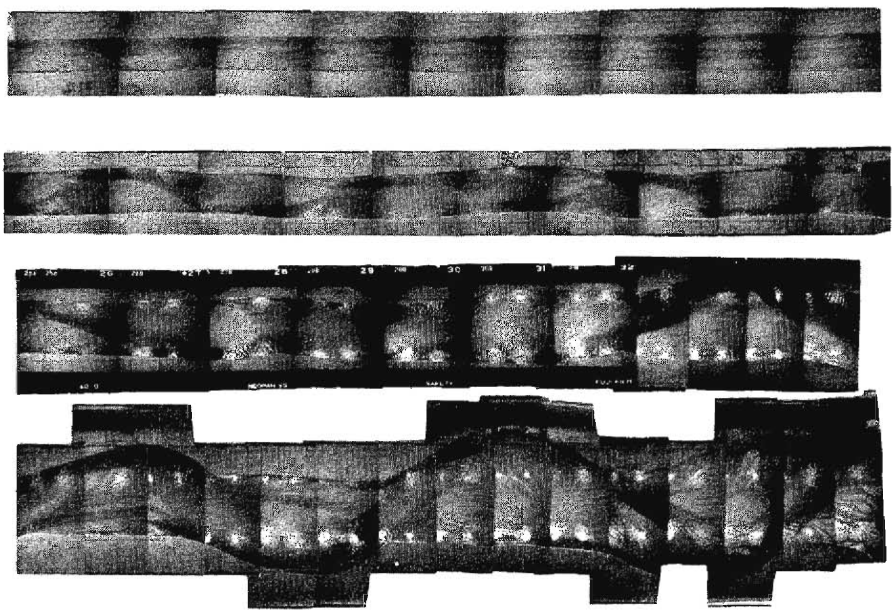


Photo. 5 Armor coat, alternating bars and channel meander in Exp. IV.
(a) Armoring in $x=1\sim28$ m reach ($T=15^{hr}$)
(b) Alternating bars and meander in $x=67\sim96$ m reach
① $T=8^{hr}20'$ ② $T=16^{hr}40'$ ③ $T=22^{hr}50'$

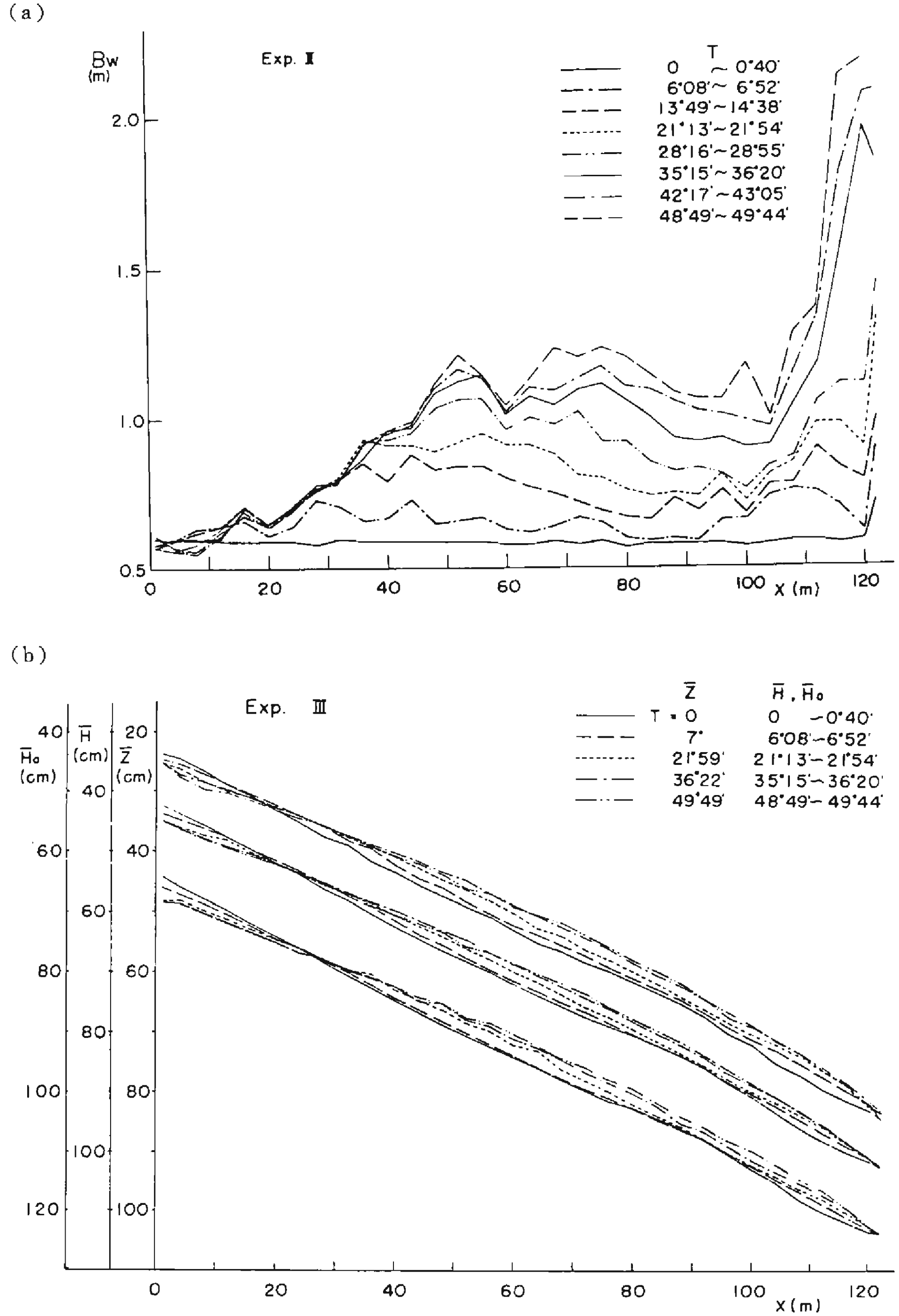


Fig. 4 Variation of water surface width of stream (a), and that of bed profile, water surface profile and energy head line (b) with time (Exp. III).

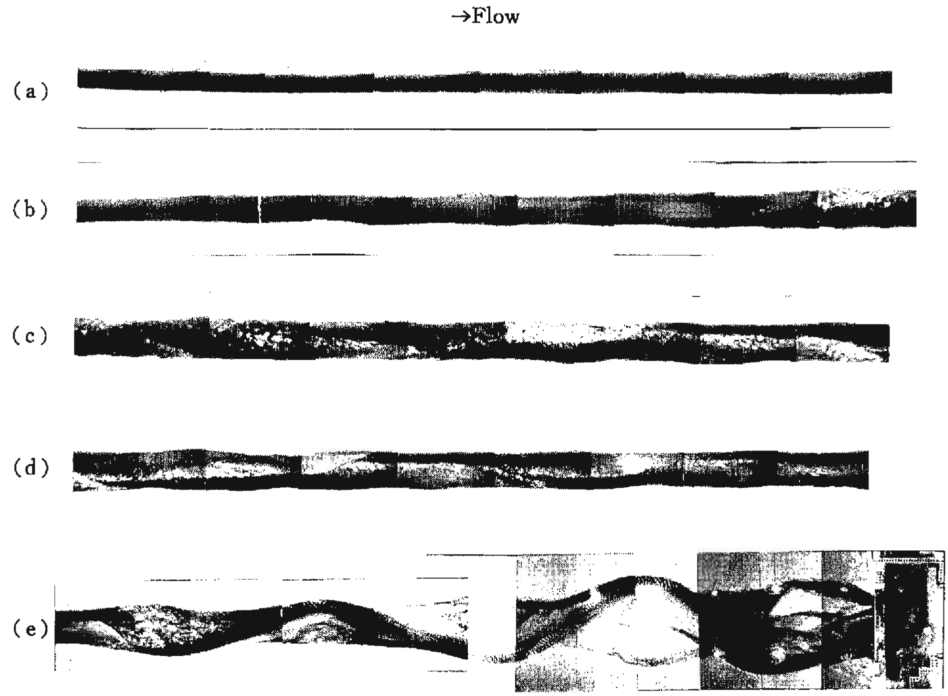


Photo. 6 Final state in Exp. III.
(a) $x=1\sim24$ m (b) $x=24\sim48$ m (c) $x=48\sim72$ m
(d) $x=72\sim96$ m (e) $x=96\sim130$ m

Changes of channel geometry in Exp. III are shown in **Fig. 4** as a example of small discharge experiments. Widening of channel ceased in the early stage at the upstream reach, while uniform widening in the midstream reach succeeded to the final stage. In addition, widening by meandering bend occurred only in the downstream reach of $x=100$–130 m (**Photo. 6**). Bed profile became convex upward as in Exp. II, suggesting degradation in the upstream reach and aggradation in mid-and-downstream reach. Rates of the widening and bed variation, however, were much smaller than Exp. IV, which was different only in discharge from Exp. III. On the other hand, in Exp. VIII, where initial width and depth of cross-section were both about a half of those in Exp. III, stream channel continued uniform widening till the end of the experiment, except for a upstream reach of rapid propagation of bed degradation from inlet, and channel meandering did not appear in the whole reach (**Photo. 7**). Therefore, it is presumed that a critical discharge for channel meandering, given an initial channel slope of 1/200, may be between 5 l/sec and 6 l/sec for such a bed material as the sand used.

In all experiments above-mentioned, distinctive alternating bars were observed to play a leading role in the processes of channel variation and to have a great influence on stream channel patterns. According to an observation of bed forms in Exp. II, the relation between the alternating bars and the channel planform is described in the following.

As soon as water was introduced into the stream channel, the bed was covered with rather fine sand and innumerable small standing waves appeared on it, but at $T=5\text{-}6'$ many oblique streaks were formed on the bed in a downstream reach from $x=6$ m. The wave length of these streaks was 1-3 m and stream meander was not discernible yet at this stage. At $T=20\text{-}30'$, sand grains increased in size and the armoring process began in $x=0\text{-}3$ m reach near the inlet, while a meandering tendency with wave length of 4 to 6 m was noticed in rows of standing waves at the middle part of the stream in a downstream reach from $x=20$ m. In addition, in the $x=4\text{-}16$ m reach between the above two reaches, rows of sand waves were straight. This meandering flow was caused by alternating bars. After this state, alternating bars developed largely in mid-and-downstream reach, but they advanced rapidly downstream and then the channel was widened uniformly without distinctive local bank erosion till $T=15\text{-}16$ hr. About $T=17$ hr, already developed alternating bars began to migrate slowly enough to cause local erosion of both side banks by turns and to change the straight channel into meandering one. In accordance with the development of meandering bends, sediment eroded from banks deposited mostly on bars just downstream and these bars turned their planform triangular into rectangular, thrusting out their edges toward opposite banks and dividing other part of edges facing downstream into a few patches. Furthermore, after $T=23$ hr, meandering bends in $x=93\text{-}130$ m reach developed enough to change migrating alternating bars into fixed bars just like point bars in curved channels.

→Flow

(a)

(b) ①

②

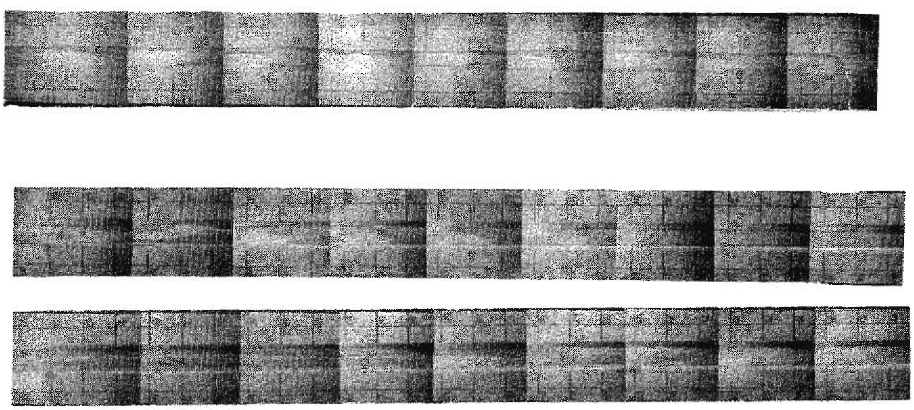


Photo. 7 Small alternating bars with armor coat in Exp. VIII and Exp. V.

(a) Exp. VIII $x=68\sim95$m ($T=22^{hr}$)

(b) Exp. V $x=50\sim77$ m ① $T=6^{hr}30'$ ② $T=50^{hr}30'$

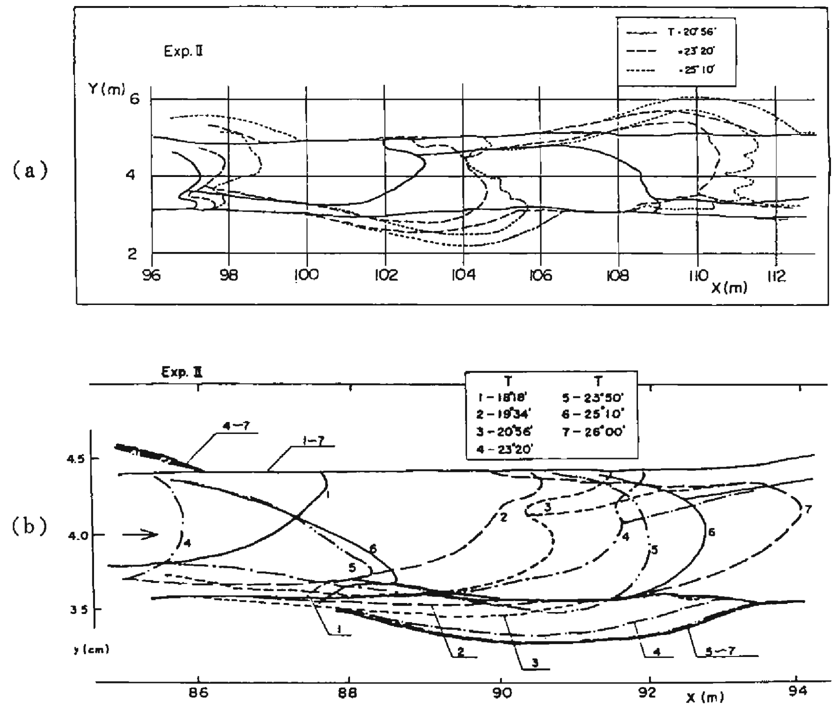


Fig. 5 Development of bars and meanders in phase (a) and out of phase (b).

But, if the other developed bars come into these reaches from an upstream reach, phase differences arise between flow meanders and channel meanders to cause new local erosion at the other positions on the side bank and to form a irregularly meandering channel or 8-figure shaped channel observed, for instance, in a reach near $x=90$ m in Exp. II.

The above two processes of meander formation are illustrated in detail in **Fig. 5 (a) and (b)** from photographic records. **Fig. 5 (a)** demonstrates a coincident case of alternating bar and channel meandering, while **Fig. 5 (b)** a case where an alternating bar does not correspond to a meander bend. In **Fig. 5 (a)**, banks were eroded locally on both sides and bars thrust out their edges toward opposite banks during $T=20$ hr 56′ - 23 hr 20′, and migration velocity of the bars decreased rapidly by $T=25$ hr 10′. The planform of bar edges at this time were smooth in a part along the opposite bank where flow and sediment were concentrated, while they were irregular in another part facing downstream, where the flow was weak and only fine sediment could be in motion. Increase in meander amplitude caused an intense flow across the channel bed in front of a bar to flush away the sediment which had deposited just downstream of the bar edge and had contributed to bar migration, hence the migration velocity decreased rapidly. This process seems to be similar to the ceasing of bar migration in curved channels. Consequently, after meander amplitude had increased, the bars migrated following the progress of downstream erosion of meander bends. The most intense meandering erosion due to alternating bars occurred in the middle part between an apex of the bend and the front of the corresponding bar. This location moved downstream rather rapidly when the amplitude was small. Though water surface and energy slopes along the main stream decrease according to the development of meanders, a meandering pattern may not become stable because of flow concentration and an effect of curvature. Actually, no steady meandering channel was observed in any experiments.

In case of **Fig. 5(b)**, the same process as **Fig. 5(a)** was also observed till $T=$ 24 hr 50′, but after this another bar entered into the upstream part of this bend, changing flow direction from lateral to longitudinal. Hence, the formerly occupied bar ceased to thrust out its edge laterally and stopped local bank erosion, moreover, returned its planform almost into that at uniform widening stage and began to travel downstream again. Accordingly, the relative position of the bar front to the apex of bend changed, and an irregular meander pattern appeared with unequal wave length when the upstream bar caused local bank erosion.

Such a ill-balanced meandering bend is caused by a difference between development of a meander in the upstream reach and that in the downstream reach and this difference occurs with propagation of boundary conditions at the both stream ends. Lack of uniformity is usual in natural rivers and is regarded as one of main reasons why meandering rivers have complicated features.

The same processes of meandering channel were recognized in Exp. I-2 (**Fig. 3(a)**) and Exp. IV aforementioned, and even in Exp. III, being accompanied with noticeable ripples, the development of alternating bars led to the formation of a meandering channel (**Photo. 6**). But in Exp. VIII, mentioned above also, in spite of the existence of distinct alternating bars, the bars traveled downstream too rapidly to cause local bank erosion by the end of the experiment at $T=22$ hr. Such a large difference in the processes between Exp. III and Exp. VIII, despite a rather small discharge difference of 1 l/sec (20%), was ascribed to the fact that erosion rates at bed and bank became much smaller when tractive force decreased even a little in the cases of such small values of tractive force near the critical one. Hence the side bank was protected easily by an armor coat, because of fairly wide distribution of grain size of the sand used. In fact, after uniform widening, scour holes along bar edges were found to be covered with coarse sand in Exp. VIII, where stream flow could presumably not remove this armor coat to commence local scouring (**Photo. 7**).

(b) Experiments with sand supplying

It is very difficult in general to carry out experiments in bank erodible channel with feeding sand, because however carefully sand is fed to keep uniformity in a lateral direction, even a very small deviation in the inlet flow, the crosssectional shape or the rate of sand feeding causes the local deposition and scour near an injecting point. The deviation makes the upstream end just like an inlet with an attack angle due to the local erosion of one side bank, or it divides the inlet flow into two parts to bring about arcuate erosion of both side banks at the injecting point and a constricted planform by flow concentration appears at an immediate downstream section from the injecting point. Though the large-sized sand injector used in the experiments was designed with due regard for such difficulty, it was unavoidable that the inflow was biased locally more or less near the injecting point. Besides, all four experiments described here, being considerably shorter than the others, were affected more intensely by boundary conditions at both stream ends.

As to the prescribed conditions in **Table 2**, initial cross-sectional shape in Exp. X is the same as in Exp. II but the former discharge was a little larger. The conditions in Exp. XI were the same as in Exp. IV, furthermore, those in Exp. XII and Exp. XIII were the same as in Exp. XI except for initial bank heights which were four times and twice of that in Exp. XI, respectively. These three experiments were conducted to elucidate effects of bank height on the processes of stream channel variation also. All experiments showed distinctive features of the channel processes reflecting the difference of the conditions including the flow deviation due to sand injecting too. These characteristics are mentioned in the following, based on the changes of channel width and bed profiles shown in **Fig. 6** - **Fig. 9.**

In Exp. X (see **Fig. 6, Photo. 8**), the channel bed aggraded intensely to make its profile convex upward by $T=1$ hr and then the change of bed profile almost stopped. Though oblique streaks running across each other from both side banks at $T=1$ hr seemed to be unified into a series of alternating bars at $T=3$ hr, characteristic feature of bars in squamation remained in channel bed, and thereafter, bars in single row and those in double row or those in squamation

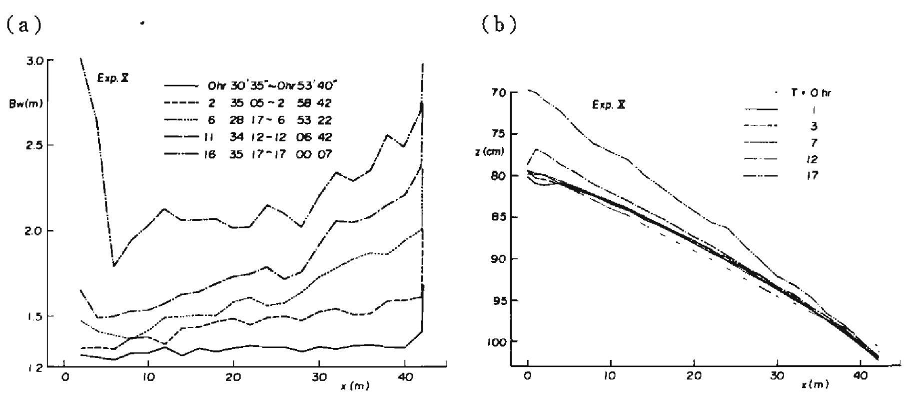


Fig. 6 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. X).

→Flow

(a)
(b)
(c)

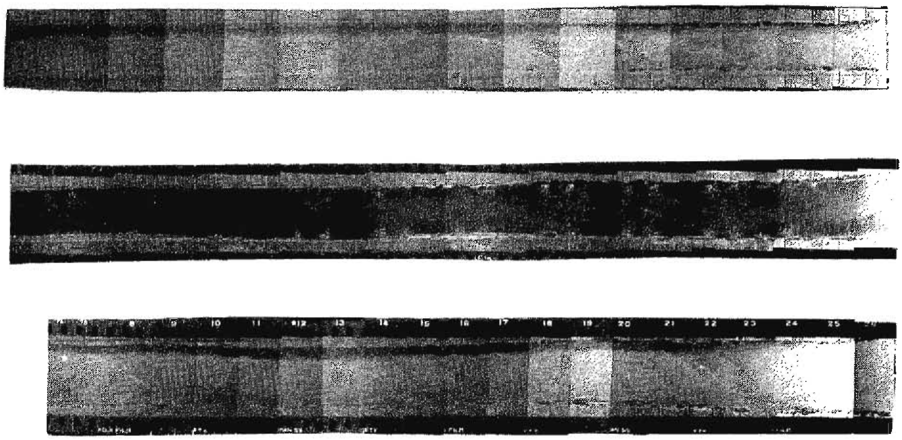


Photo. 8 Variation of bed configuration with time in Exp. X (x=11-42.5 m reach).
(a) $T=3^{hr}00'$ (b) $T=10^{hr}28'\sim30'$ (c) $T=17^{hr}01'$

appeared and disappeared in turn on the bed. Consequently, all bars were small in height and traveled downstream rapidly enough to widen the channel fairly uniformly and neither local bank erosion nor meander bend occurred by the end of the experiment. In the final state at T=17 hr, channel width increased longitudinaly corresponding to increase of tractive force in the same direction caused by the bed slope change. Bed configuration was considered as a braiding stream because the main stream diverged irregularly on the bed, though bars did not emerge from the water surface obviously.

In Exp. XI (see **Fig. 7, Photo. 9**), distinct alternating bars formed before T=3 hr migrated rapidly enough to cause uniform widening of the channel while the bed profile was a straight line showing large aggradation in the upstream reach. After T=6 hr, local bank erosion, just as observed in the mid-to-downstream reach in Exp. II, began corresponding to the developed alternating bars and the channel width change became wavy in longitudinal direction. Similarly, the bed profile was also observed to become a faint wavy line. The wavy pattern of width change advanced downstream and increased in amplitude gradually, according to the formation of a typical meandering channel. In the meandering reach, bed aggradation was remarkable by deposition of sand eroded from the side banks. As the bed was fixed at the downstream end, the bed slope increased along longitudinal distance, hence meander amplitude also increased downstream, so as in Exp. II and in Exp. IV.

In Exp. XII (see **Fig. 8, Photo. 10**), because of the large slope angle of the initial bank, 63°, both side banks collapsed down into stream and deposited on the bed as soon as water was introduced into the channel. Thus, in a reach of x=0-26 m, the bed aggraded uniformly about 13-15 cm height, while in x

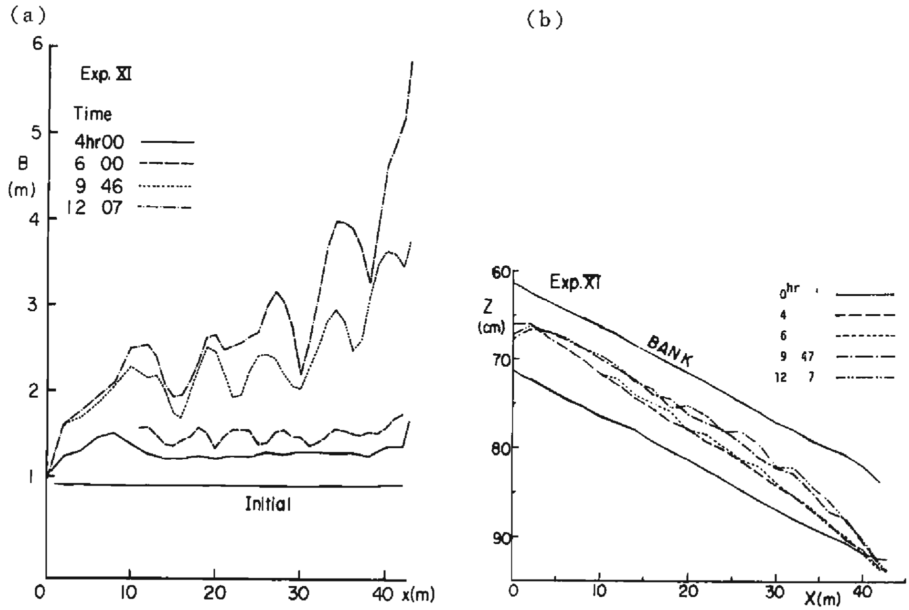


Fig. 7 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. XI).

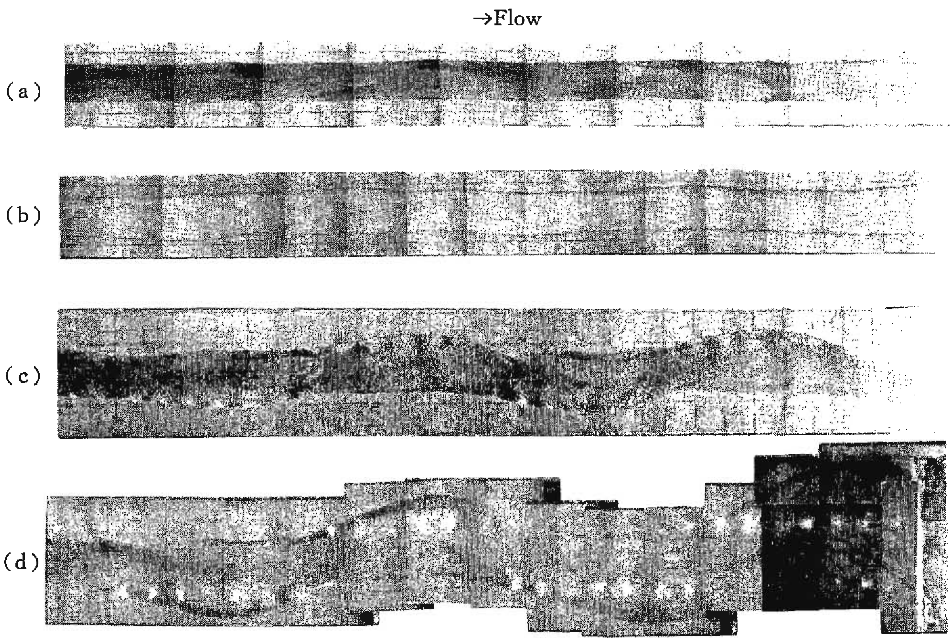


Photo. 9 Developing process of channel meandering in Exp. XI (x=14–42 m reach).
(a) $T=4^{hr}29'\sim32'$ (b) $T=6^{hr}00'$ (c) $T=7^{hr}40'\sim43'$ (d) $T=10^{hr}47'\sim51'$

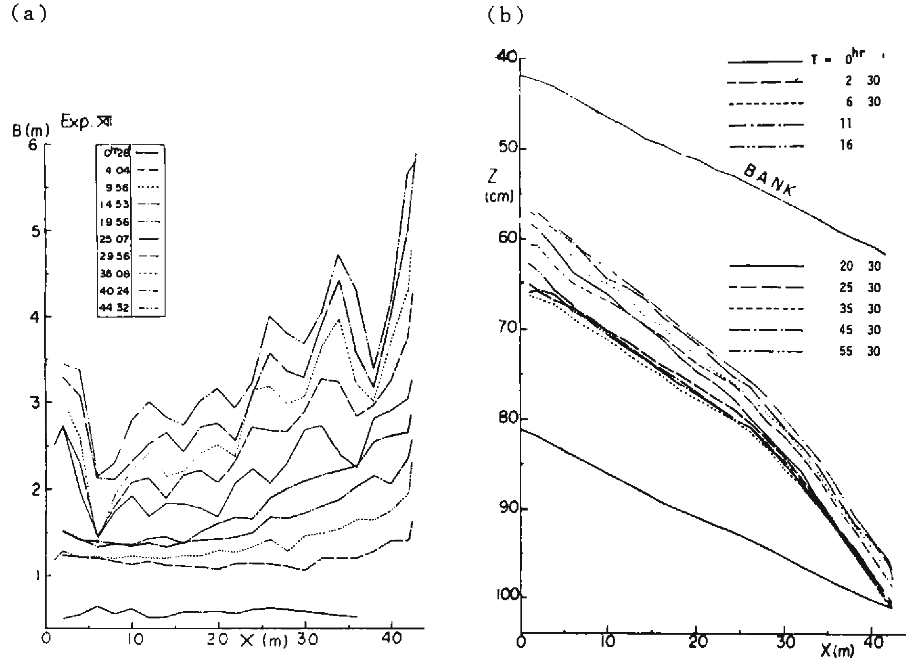


Fig. 8 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. XII).

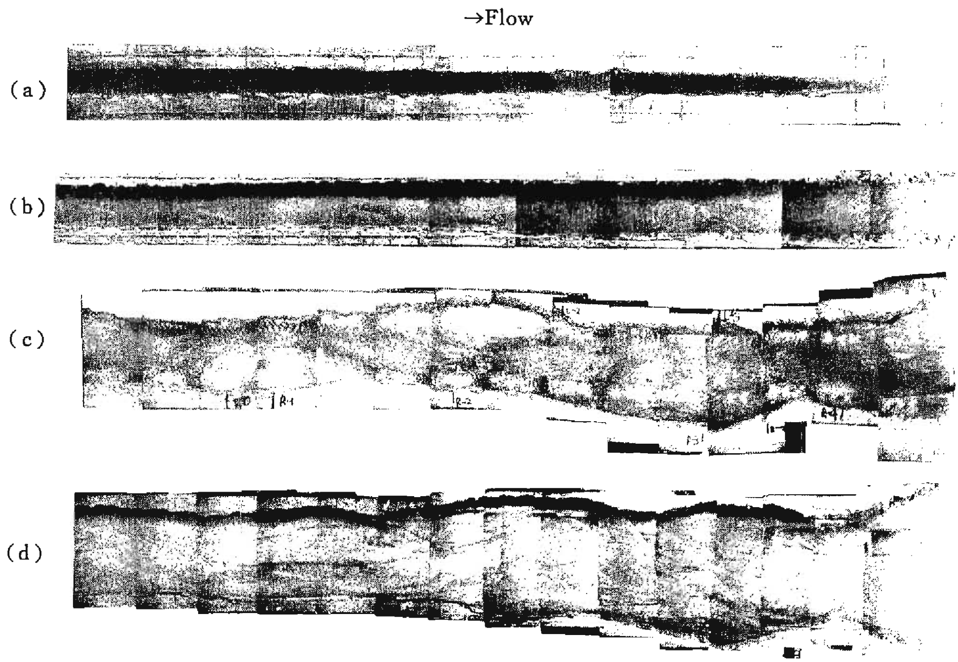


Photo. 10 Stream channel process toward braiding channel in Exp. XII (x=12–42 m reach).
(a) $T=0^{hr}43'\sim47'$ (b) $T=15^{hr}00'$ (c) $T=35^{hr}27'\sim32'$ (d) $T=44^{hr}35'$ (Final state)

$=26$–42 m reach the bed slope increased to 1/80 because of the constant bed elevation at the downstream end. A transition point from mild slope to steep slope which was, therefore, formed at $x=26$ m remained till the final state, though average bed slope kept on increasing by continuation of gradual bed aggradation. By $T=20$ hr, the planform of the stream channel was approximately straight without local bank erosion as in Exp. X. But after this, since the inlet angle occurred by the deviation of flow due to sand injecting, local bank erosion was caused in the upstream reach and was propagated downstream alternately to make the channel pattern slightly sinusoidal. The amplitude of this pattern increased apparently in the longitudinal direction reflecting the change of channel width which was caused by the increase in tractive force in the same direction corresponding to the bed profile. But, even in these meander bends, local erosion continued on both side banks. After rectification of the inlet flow by controlling the sand injecting, another meander was formed out of phase to the previous one and the planform of the channel turned into an 8-figure shape in the final stage at $T=44$ hr.

Thus, the channel process in Exp. XII was much different from that of the meander formation aforementioned. Such a process in Exp. XII was owing to a lack of concentrated flow toward the opposite bank by distinct alternating bars which were not able to develop in the process above.

As to bed configuration in Exp. XII, bars in single row and those in double row repeated by turns to appear and disappear till $T=20$ hr just as in Exp. X, but after $T=20$ hr bars in single row did not appear any longer and small bars in squamation with irregular edges varied complicatedly on the bed, being influenced by the faint meander of the channel. Furthermore, the main flow was divided into small branches and some bars emerged from the water surface during $T=32$–44 hr, and channel pattern became a braiding stream one. This bed configuration was judged to be similar to that in the Ohi River or the Johganji River from the comparison of the pictures of dry bed in the experiment with aerial photographs of these rivers.

Finally, in Exp. XIII (see **Fig. 9, Photo. 11**), the bed profile showed a intermediate variation between that in Exp. XI and in Exp. XII and had a transition point of slope the same as in Exp. XII at $x=25$ m, which remained by the end of the experiment. Before $T=8$ hr $30'$, channel widening was rather quick in the upstream reach where bed aggradation was large. On the other hand, the bed configuration consisted of irregular bars like those in Exp. X before $T=4$ hr, but at $T=6$ hr clear alternating bars were formed in $x=10$–32 reach. These bars started local bank erosion at $T=7$ hr, the more intensely in the more upstream reaches. In the downstream reach of $x=30$–42 m, local bank erosion was propagated alternately to the downstream end, however, bars corresponding to the local erosion remained still obscure till $T=8$ hr $25'$. But according to development of the meandering bends, stream flow across the

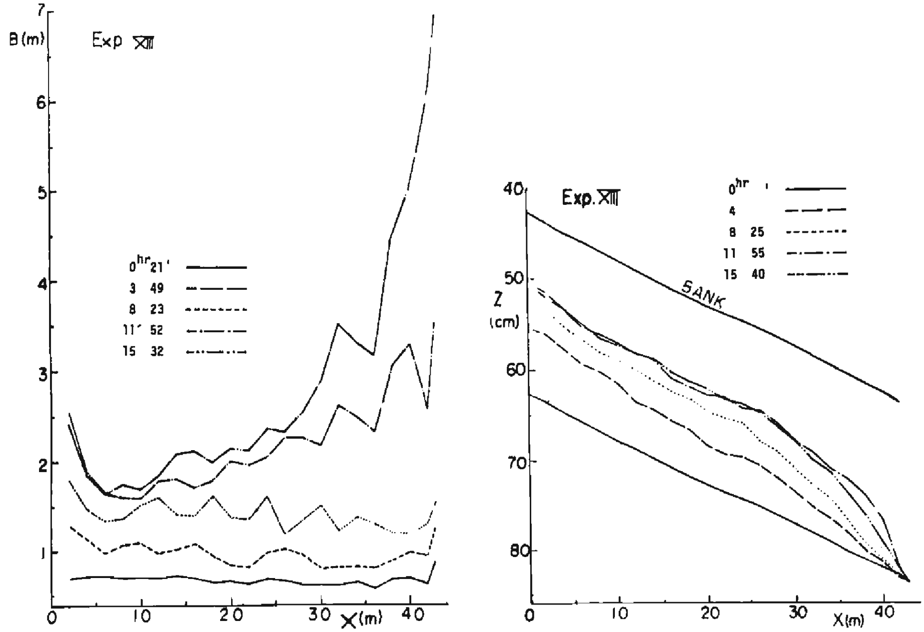


Fig. 9 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. XIII).

Flow→

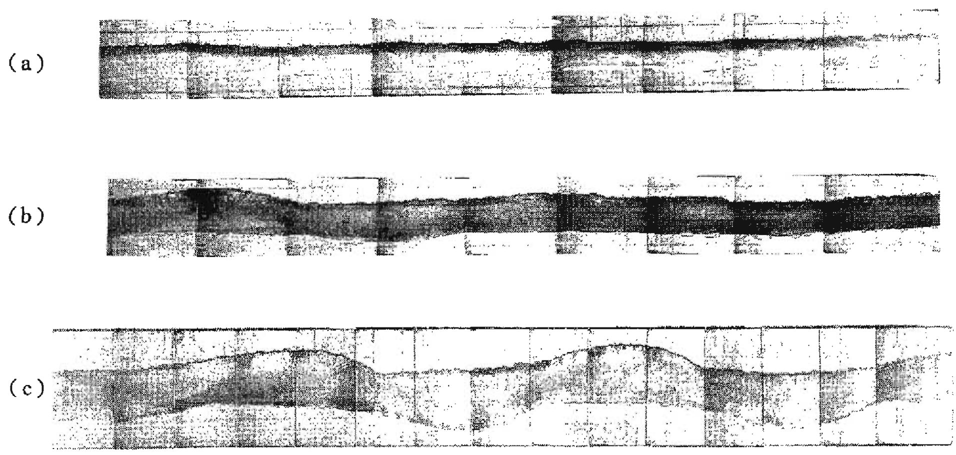


Photo. 11 Propagationof meander bends in Exp. XIII (x=11–42 m reach).
(a) $T=4^{hr}00'$ (b) $T=7^{hr}22'\sim7^{hr}25'$ (c) $T=9^{hr}30'\sim9^{hr}34'$

channel bed became strong enough to increase local erosion of opposite bank and made bed bar-like form in the downstream reach. Through this process, a meandering channel was also formed in $x=30$–42 m reach. Meanwhile, in the up-to-midstream reach of $x=9$–14 m, a meander bend appeared first ceased local bank erosion at $T=8$ hr 36′, since another bar entered there from the upstream reach. The influence of this bar was propagated to the next bend at $x=16$–22 m, and therefore channel width was enlarged by erosion of the bank opposite to the former eroded bank. Thus, meandering development is easier to continue in the downstream reach than in the upstream reach when the channel is connected to a straight channel at the upstream end. In addition, on the basis of picture analysis of alternating bar propagation during $T=6$–10 hr in Exp. XIII, it is concluded that a deviation of sand supplied from the upstream reach promotes alternating bar formation considerably. Accordingly, it is regarded that upstream boundary conditions have a great effect on fluvial processes of stream channel.

(2) Experiments with additional conditions

(a) Experiments with two step initial slope

Two experiments, that is, Exp. V and Exp. VI were conducted under same initial channel geometry and cross-sectional shape was same as in Exp. III and Exp. IV, but discharge in Exp. V was fairly smaller than that in Exp. VI.

In Exp. V (see **Fig. 10, Photo. 7**), because of small tractive force the influence of the initial geometry of the stream channel lasted to the end of the experiment and the bed profile was kept concave upward for a long time. Channel widening almost stopped in $x=0$–40 m reach by $T=1$ hr and in $x=80$–100 m reach by $T=1$ hr. But gradual channel widening continued in a reach near $x=60$ m where bed caused noticeable aggradation. On the other

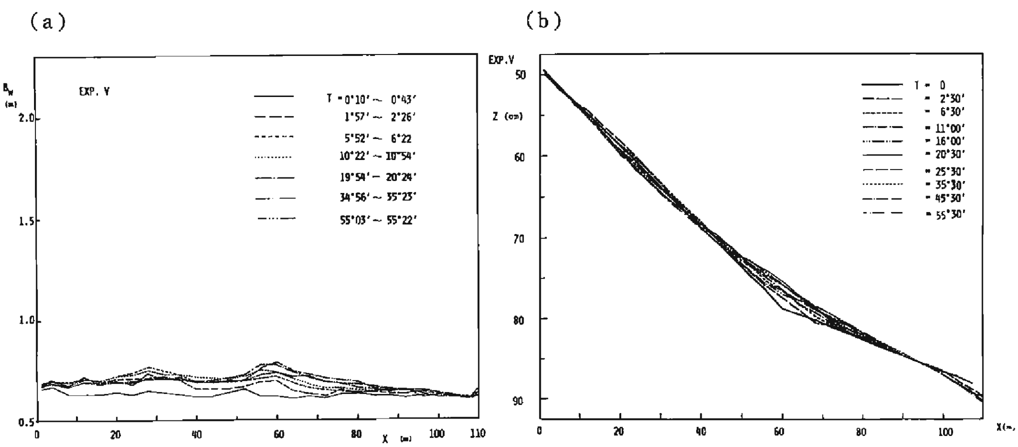


Fig. 10 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. V).

hand, a series of alternating bars were formed in $x=22$-45 m reach by $T=1$ hr 40′ and they migrated into $x=30$-65 m reach at $T=4$ hr 30′ stretching their length. But after this, since the bars decreased their migration velocity in the forefront while supplied sand became insufficient from the upstream reach because of bed degradation and armoring phenomenon, the bars reduced their extent, moving downstream and they disappeared in a little while after arrival at $x=82$-91 m reach. In the reaches where bars did not occur, sand grains on the bed increased in size continuously from the feet of both side banks enough to form a static stable channel. In addition, the formed bars above were so small in height that stream flow was not concentrated toward the side banks and consequently, local bank erosion did not occur anywhere by the end of the experiment at $T=55$ hr 30′.

In Exp. VI (see **Fig. 11, Photo. 12**), the stream channel could be divided

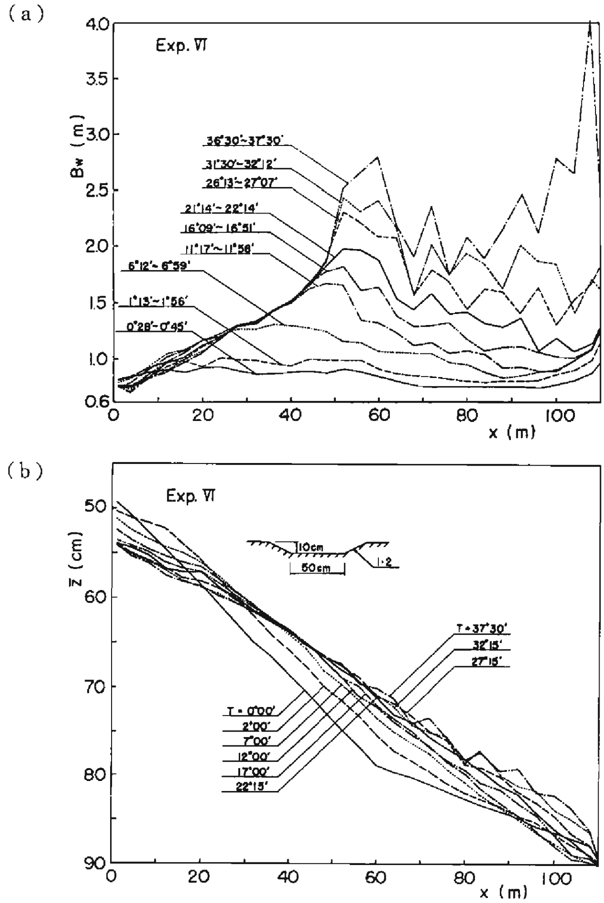


Fig. 11 Variation of water surface width of stream (a) and that of bed profile (b) with time (Exp. VI).

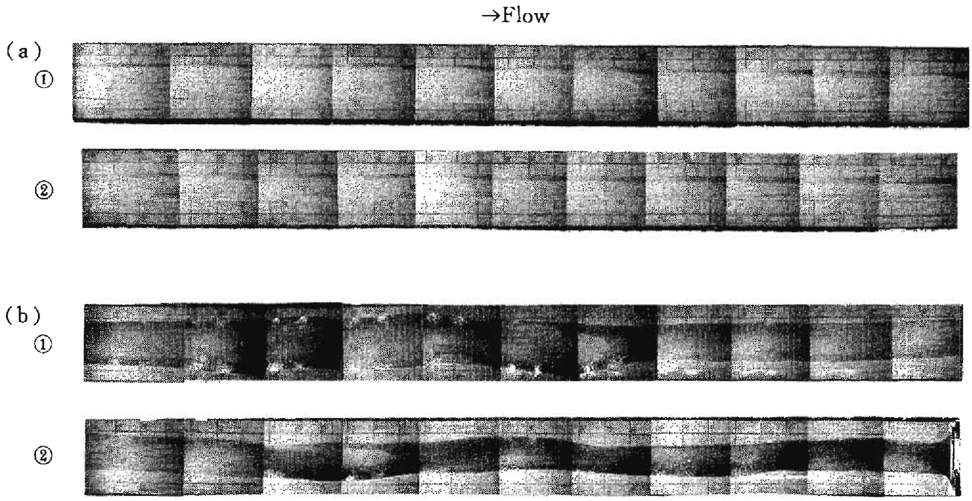


Photo. 12 Propagation of alternating bars (a) and beginning of meanders in two reaches (b) in Exp. VI.

(a) $T=7^{hr}$ ① $x=32\sim65$ m ② $x=65\sim98$ m
(b) $T=23^{hr}$ ① $x=47\sim78$ m ② $x=77\sim110$ m

into two noticeable reaches which were an upstream reach of $x=0$–40 m and a downstream reach of $x=50$–110 m. In the former reach once raised bed lowered again remarkably, while in the latter reach aggradation only was distinguished. Dominant deposition occurred in a reach near $x=60$ m before $T=7$ hr and the transition point from steep slope to mild slope in the initial bed profile became undiscernible. In the $x=0$–40 m reach with degradation tendency, channel widening almost stopped before $T=10$ hr, and in the most degraded reach of $x=0$–20 m, water surface width even decreased very gradually with time and sand grains became considerably coarser. Immediately after the beginning of the experiment alternating bars were formed in a upstream reach from $x=60$ m. The bars developed their size and advanced downstream to cause local bank erosion in $x=50$–60 m reach with the most raised bed, and meander bends were formed the same as observed in Exp. XI. These meander bends acted as an inlet angle toward the downstream reach and extended channel meandering to $x=65$–75 m reach through a fairly similar process to that in the downstream reach in Exp. XIII. Independently of these meanders, however, another series of meander bends were caused by developed alternating bars in $x=80$–90 m reach and led the downstream channel to meander similarly. Accidentally, these two meanders, independent of each other, were so in phase that they formed a series of well-ordered meanders after $T=25$ hr when the upstream meander was propagated to the downstream one. This meander continued developing even in the final stage.

(b) Experiment under varying flow conditions

Exp. VII was the only experiment carried out under unsteady flow conditions employing a step-like change of discharge (see **Table 3**). Characteristics of stream channel process in Exp. VII are described in the following.

In the rising stage of discharge, because of the rather short duration of each discharge, the alternating bars which appeared had short wave lengths about twice of the channel width (the wave length of stream meander was about four times of channel width) and they migrated downstream rapidly in insufficient development (**Photo. 13**). According to the above behavior of bars, the stream channel increased in width uniformly, as shown in **Fig. 12**. These processes, the same as observed in the early stage of steady flow experiments, remained even in the first phase of lowering discharge of $Q=20\ l/\mathrm{sec}$ except that the bars elongated their wave length a little by successive decrease of the migration velocity from the upstream reach. Therefore, no distinct meander bend appeared at the end of this stage. When discharge was lowered to 10 l/sec, meandering flow became clear being governed by the alternating bars formed under previous discharge. But, since there was a considerable phase difference of meander between two reaches divided by a reach of $x=72$–78 m where the wave length of bars was excessively short, these two distinct meanders produced complicated stream bed configuration in their competing reach of $x=80$–90 m. However, at the final state of the discharge of $Q=10\ l/\mathrm{sec}$, another meander with longer wave length was propagated from the upstream reach and dominated to form new meander bends with apexes at $x=100$ m and $x=106$ m. Introducing 6 l/sec discharge into this stage of stream channel, the flow meandered along thalweg, which is a curved line linking the lowest position in each cross-section, in 45–78 m reach where a meander in a phase had appeared. On the other hand, in the downstream reach from $x=80$ m, where meanders in various phases had occurred, the stream flow tended to form its own course for lack of a dominantly low part on the channel bed. For example, near the end of the experiment, a curved course turned into a straight stream again with lowering water surface to leave the previous bed a flood plain like as in river terrace formation in a reach of $x=96$–108 m (**Photo. 13**).

(c) Experiment with a rigid side bank

In Exp. IX, the right side bank was stabilized by inserting tin plates along the bank slope. Rate of channel widening in this case was considerably smaller than that in Exp. IV where initial channel geometry and discharge were identical, and stabilized section of channel widening reached even $x=65$ m at the final stage of the experiment. In the early stage, alternating bars appeared and traveled downstream similarly to the case where both side banks were erodible, and the channel became wider uniformly because of fairly high migration velocity of bars (see **Fig. 13**, **Photo. 14**). This process lasted to $T=13$–14 hr, but after $T=15$ hr alternating bars showed asymmetrical development, that is, bars having their fronts along the right side bank increased in

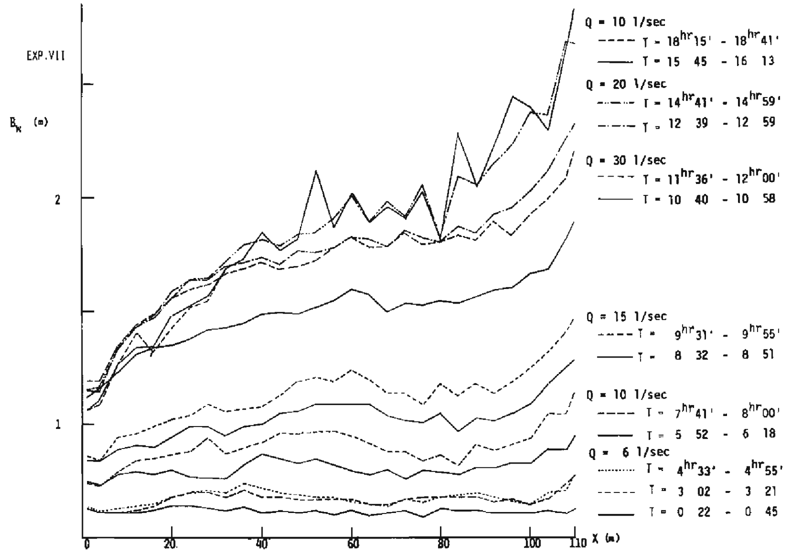


Fig. 12 Variation of water surface width of stream with time (Exp. VII).

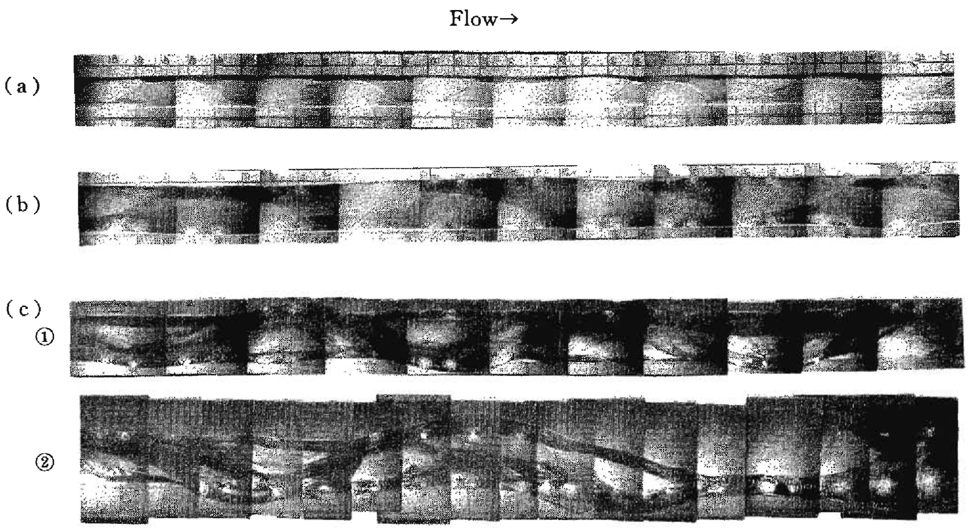


Photo. 13 Alternating bars with short wave length in rising stage (a), (b) and water course at low discharge (c) in Exp. VII.

(a) $T=10^{hr}00'$ ($Q=15\,l$/s) $x=44\sim77$ m

(b) $T=14^{hr}30'$ ($Q=30\,l$/s) $x=44\sim77$ m

(c) ① $T=30^{hr}10'$ ($Q=6\,l$/s) $x=44\sim77$ m ② $x=77\sim110$ m

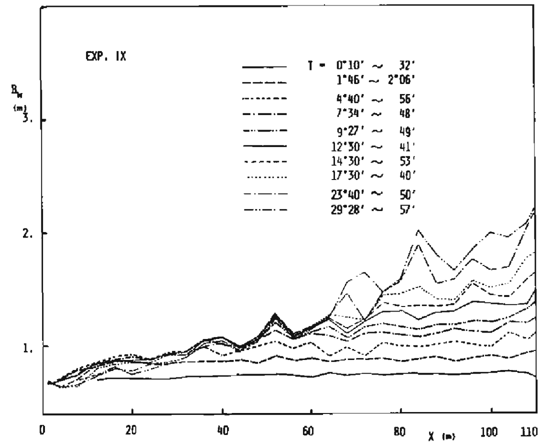


Fig. 13 Variation of water surface width of stream with time (Exp. IX).

→Flow

(a)
(b)
(c)

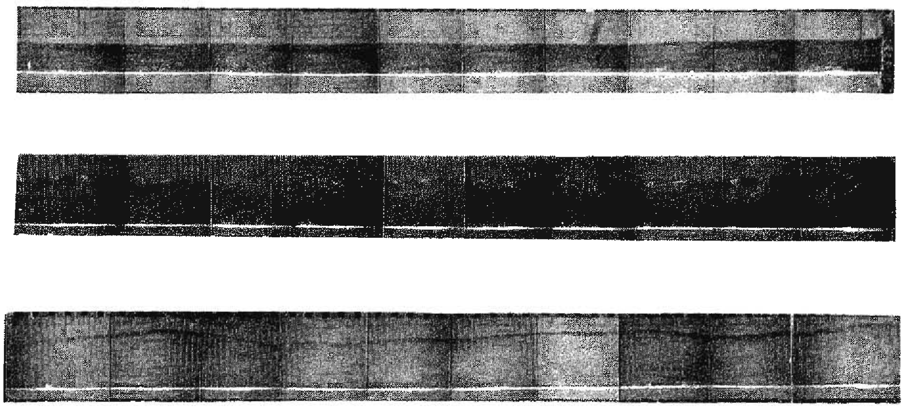


Photo. 14 Symmetric bars in early stage (a), asymmetric bars (b) and local bank erosion (c) in Exp. IX (x=80–100 m reach)

(a) Symmetric alternating bars ($T=7^{hr}10'$)
(b) Asymmetric alternating bars ($T=23^{hr}07'$)
(c) Local bank erosion ($T=30^{hr}00'$: Final state)

wave length longer than those of the other side and they thrust out their edges toward the left side bank. Simultaneously, the state of bank erosion changed from uniform widening to local erosion of the left side bank and meander bends were about to be formed in this bank. But flow direction of the main stream did not turn so laterally as in the case where both side banks were erodible, hence channel meandering did not occur even at the final stage.

As mentioned above, in the experiments where some particular conditions were added, characteristic processes appeared as variations of stream channels according to each condition. But even in these processes, it could be found out that there were very similar properties as those in the fundamental experiments with simple conditions. Accordingly, it seems possible to presume fluvial process in a experiment with particular conditions by considering the results of basic experiments and their combination. Therefore, it is regarded important to clarify the essential features of fluvial processes on the basis of fundamental experiments.

3.2 Hydraulic characteristics

In the experiments mentioned in **3.1**. a stream channel can be divided into three or four reaches corresponding to longitudinal variation of bed elevation and channel width and to bed configuration. Hydraulic quantities were calculated about each measurement by use of given discharge and measured values of water surface level and cross-sectional shape of a stream channel, and the calculated values were averaged in each reach above-mentioned. These averaged quantities are listed in **Appendix**, as well as representative bed configuration and stream channel patterns. In this section, changes of these hydraulic quantities in the fundamental experiments are described, according to the results of Exp. IV, Exp. VIII, Exp. XI and Exp. XII. Exp. IV and Exp. VIII represent the experiments of large and small discharge respectively carried out in the long stream reach without sand supplying, while Exp. XI and Exp. XII are examples of experiments of meandering and braiding channels respectively in the short stream channel with sand supplying.

Fig. 14 shows the variation with time of mean flow velocity U, shear velocity U_*, Manning's roughness coefficient n and Froude number Fr. The

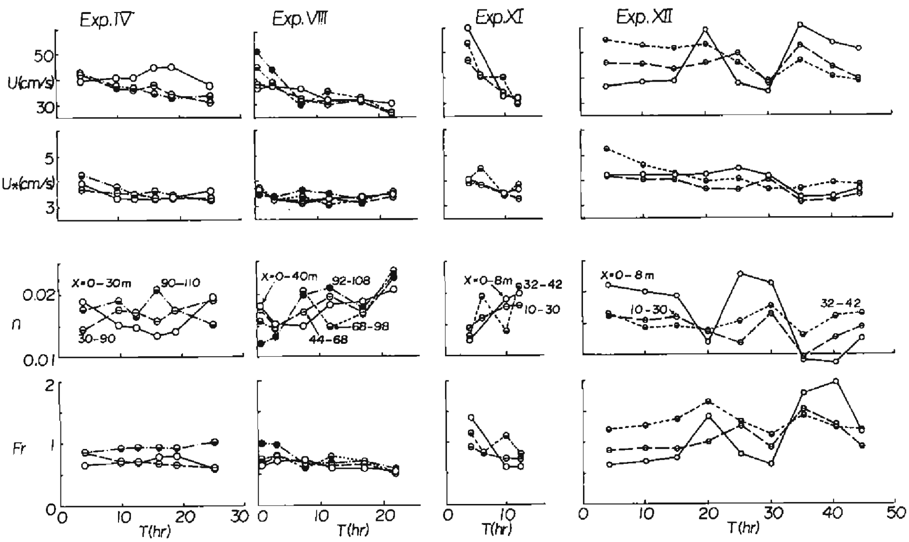


Fig. 14 Variation of averaged hydraulic quantities with time.

ranges of these values shown in **Fig. 14** almost cover those of all the experiments in this paper.

Mean flow velocity decrease with time to suggest increase of flow cross-sectional area with channel widening, except for the upstream reaches in Exp. IV and Exp. XII. The velocity is generally low in Exp. VIII of small discharge while it is the highest in Exp. XII with remarkable aggradation. However, most values were in the range of $U=30\text{-}50\,\mathrm{cm/sec}$ in all experiments. As to shear velocity, its time changes show a gradual diminishing trend in Exp. IV, Exp. XI and Exp. XII, but in Exp. VIII, it keep approximately a constant value as in Exp. III of $T=0\text{-}30\,\mathrm{hr}$ when meander had not yet appeared. It is presumed that increase of form drag due to sand waves of micro scale, described in **3.1** (1), maintain a constant value of shear velocity, since Manning's roughness coefficient tend to increase simultaneousely in Exp. VIII and Exp. III of small discharge. Manning's coefficient have a slight increasing tendency in Exp. IV and Exp. XI where meandering channels appeared, while it decrease with time in Exp. XII of braiding channel. Finally, Froude number is in general smaller than unity except for Exp. XII and have an inverse tendency for Manning's coefficient.

As to time change of sediment transport rates measured at the downstream end, total sediment discharge per unit time increased gradually when a meandering channel was formed; on the other hand, it diminished in case that meander did not develop, including the case of braiding channel formation. But converting these values into those per unit width, they all showed a diminishing tendency, in accordance with the change of shear velocity above-mentioned. The rates of sediment transport per unit width were compared with Ashida-Michiue's[26] bed load formula by using hydraulic quantities in the most downstream reach. As a result of comparison, the observed values showed rather wide scattering around the predicted ones. One of the main reasons for this scattering was attributed to arbitrariness in determination of representative hydraulic conditions, such as flow width, tractive force, and sand grain size, caused by stream channel patterns and bed configuration of meso scale, as well as the accuracy of bed load function.

Additionally, sediment balance was considered, by comparing measured value of total volume washed out from the downstream end and those estimated from each volume of side bank erosion, bed variation and sediment supplied from the upstream end. It was proved that sediment balance evaluated by the above way showed a good agreement and that sediment load could be estimated at each section by iterative calculation from either the upstream or the downstream end.

4. Summary and discussion

In this chapter, the fluvial processes described in chapter 3 are summarized at first, secondly the properties common to all these processes are pointed out and finally, a diagram explaining the processes of stream channel variation and the formation of channel patterns is proposed, based on these properties.

The experiments with uniform slope and constant discharge were conducted in the long stream channels without sand supplying, and it was observed that bed degradation was propagated from the upstream reach and stream channel ceased widening its course simultaneousely. In the degradation reach, sand grains became coarser from the upstream end and from the feet of both side banks, presumably matching the critical tractive force to the flow stress and reducing bed erosion. On the other hand, in mid-and-downstream reaches where bed degradation was not propagated at all, the stream channel kept widening and alternating bars continued to develop and advance downstream. Thereafter, channel processes diverged into two cases according to the magnitude of the discharge. The first was the case that channel widening and development of bars progressed enough to lower the migration velocity of bars and to cause local bank erosion, and then a meandering channel was formed. The second was another case that channel widening was slow and alternating bars stopped developing before a mature stage, and therefore, no meandering channel appeared. Exp. I-2, Exp. II, and Exp. IV were included within the first case, while Exp. I-1 and Exp. VIII belonged to the second. Moreover, Exp. V and Exp. VI were observed to cause the same channel processes as the second and the first, respectively.

The experiments with uniform slope and constant discharge were carried out in the short stream channel, injecting sand at the upstream end. The degradation reach covered with armor coat was not observed in anywhere.

The characteristics of fluvial processes are summarized as follows:

1. The case that a series of alternating bars in uniform development caused meandering bends simultaneousely and caused increasing local bank erosion to form a meandering channel ······························ Exp. XI
2. The case that local bank erosion caused by a few particularly developed alternating bars propagated meander bends downstream with formation-of bars in the bends ··· Exp. XIII
3. The case that dominant bar did not appear and the channel remained approximately straight but both side banks were eroded to and fro, and consequently flow diverged into several streamlets irregularly to form a braiding channel or similar one ······ Exp. X and Exp. XII

Among the three cases above, the first case was the same as observed in the downstream reaches of Exp. II and Exp. IV, while the second case was similar to the phenomenon in Exp. VI where meander bends were propagated from the transition point of slope into the downstream reach.

In the experiments with the transition point from steep slope to mild slope, meander was easy to occur in the aggradation reach near the transition point and it was propagated downstream, but when independent meander was formed by developed alternating bars in the downstream reach, the two meanders often conflicted with each other to produce a very complicated stream pattern.

Under a step-like change of discharge, flow duration of each discharge at the rising stage was so short that alternating bars did not develop sufficiently to cause local bank erosion. But in the recession stage, since a relatively large discharge to that at peak lasted for a rather long duration, a meandering channel was formed and was maintained when discharge became small in the case that the alternating bars developed orderly. Otherwise, a flow of small discharge was apt to form its own stream channel.

Even in a channel with one rigid side bank, it was found at an early stage that alternating bars, as well as uniform channel widening, occurred similarly as in the channel with erodible banks of both sides. But these bars turned into asymmetrical planform in due course, bringing about local erosion of the unfixed bank, hence distinct channel meandering did not appeared.

As summarized above, in alluvial channels with non-cohesive materials such as these experiments, the fluvial processes of stream channel variation are changes of planform rather than that of longitudinal profile, in other words, mainly bank erosion process rather than bed variation, and the latter acts as a factor of suppression or promotion to the former process. For example, the great aggradation near the transition point of slope accelerated the formation of meandering channel, while the degradation in the upstream reach resulted in the cessation of channel widening.

The widening of a straight channel, being restricted under the conditions that alternating bars do not appear or they migrate rapidly, seems to link weakly to remarkable channel variation such as channel meandering. But this phenomenon occurs inevitably under simple and fundamental conditions, besides the lowering of migration velocity of alternating bar can hardly occur before uniform widening of initial channel. Accordingly, elucidation of the uniform widening process in straight channel is regarded as a first step to clarify more complicated phenomena in the processes of stream channel.

On the other hand, it was proved in the experiments that not only the alternating bar plays a leading role in the process of meandering channel formation as indicated in previous studies but also other type of stream channel processes and channel patterns are mostly determined according to the behaviors of bars, such as development and migration of bars.

Based on the above summary, it is attempted to illustrate the stream channel processes briefly under the simple conditions of initial prismatic channel and constant discharge. The result may be seen diagram in **Fig. 15**, in which the

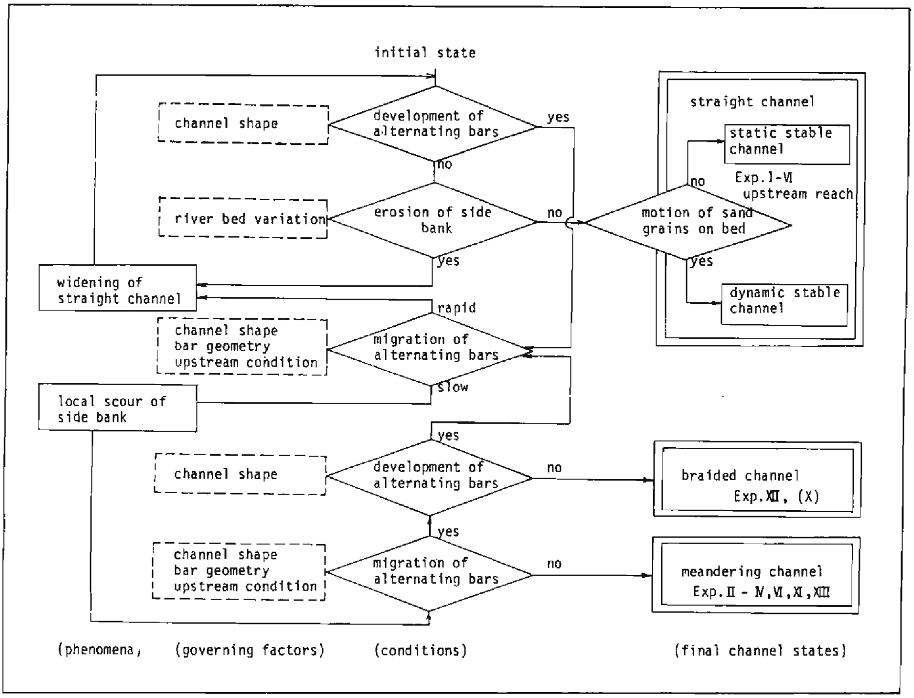


Fig. 15 A diagram explaining the processes of stream channel variation and channel pattern formation.

behaviors of alternating bar are regarded as a main pivot, and the phenomena progress according to the diverging conditions enclosed by lozenges and reach the final channel patterns shown by double frames if each condition is fulfilled successively. The final states of the experiments presented in this paper are also written into this diagram by Exp. No's corresponding to their channel patterns. However, there were a particular cases where the governing factors, enclosed by broken lines, happen to change so that phenomena cannot escape from the loop of diverging conditions, and the channel process in Exp. X seemed to be close to this case.

5. Conclusion

Large-scale experiments were conducted under various conditions, in order to clarify the fluvial processes of alluvial river channels in macro scale, which are practically impossible to observe.

At the early stage in all experiments, bank erosion and bed deposition progressed uniformly in longitudinal direction, and succesively signs of alternating bars appeared on the bed. Then, though the stream channel remained still in straight planform, channel width and bed elevation began to change longitudinally by propagation of boundary conditions both at the upstream and the downstream ends while alternating bars kept on developing and migrating in most of the experiments. These phenomena, such as channel widening, bed variation and bar behavior were governed by initial conditions and changes of hydraulic conditions in the experiments. Consequently, characteristic processes of channel variation were observed and several kinds of channel patterns, for examples, straight channel with armor coat, meandering channel and braiding channel were formed, corresponding to the experimental conditions.

Based on the results of the experiments, a diagram depicting the fluvial processes of stream channel variation was presented showing particularly the simple and fundamental conditions with prismatic initial stream channel and constant discharge. It was also indicated that channel processes under somewhat complicated conditions have considerably common aspects to those under simple conditions and can be presumed from the results of the basic experiments and their combination.

Starting from these experiments, many hydraulic aspects of stream channel processes in alluvial rivers have been clarified already.[27] The authors will present the results of these investigations in future as to the advance and the extention of the study on the problem of river channel variation.

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Appendix

Hydraulic conditions in the experiments

Exp. No.	Reach x m	Time T hr min	Dis-charge Q l/s	Flow width B cm	Mean depth h cm	Hydraulic radius R cm	Mean velocity U cm/s	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U_* cm/s	Velocity coeffici-ent U/U_*	Bed load per unit width q_B cm^2/s	Stream channel pattern	Bed configuration
I-1	0-130	2 00	7.5	104	2.25	2.04	33.4	0.78	4.83	3.02	11.4		—	—
		7 00		107	1.98	1.91	37.1	0.75	4.79	3.11	10.8		—	—
		95 40		98	1.60	1.24	—	—	4.53	2.73	—		—	—
I-2	0- 50	30 16	15.0	133	3.25	3.10	36.7	0.64	3.73	3.40	10.8		Straight	No bar
	50-100	〃 〃		205	2.64	2.57	29.5	0.61	4.20	3.24	9.5		Meander	Do
	100-130	〃 〃		273	1.60	1.58	36.8	0.97	5.94	2.98	13.0		Do	Do
II	0- 10	2 25	15.0	112	3.16	2.99	42.2	0.76	3.77	3.30	12.8		Straight	No bar
	0- 30	6 52		118	3.22	3.05	39.5	0.70	4.15	3.56	11.1		Do	Do
	0- 35	10 39		120	3.05	2.90	41.7	0.77	4.05	3.37	12.4		Do	Do
	0- 40	19 34		122	3.08	2.93	40.8	0.75	4.00	3.36	12.1		Do	Do
	0- 50	28 41		126	3.06	2.91	41.0	0.78	3.79	3.24	12.7		Do	Do
	10-100	2 25		117	2.71	2.59	47.9	0.94	4.79	3.47	13.8		Do	Alternating bars
	30-100	6 52		127	3.05	2.91	39.2	0.72	4.70	3.66	10.7		Do	Do
	35-100	10 39		138	2.83	2.72	39.4	0.76	4.61	3.49	11.3		Do	Do
	40-100	19 34		166	2.62	2.54	36.2	0.75	4.24	3.22	11.2		Straight ~Meander	Do
	50-100	28 41		196	2.32	2.26	35.6	0.79	3.78	2.87	12.4		Meander	—
	100-130	2 25		123	2.55	2.45	48.4	0.97	5.36	3.58	13.5	0.179	Straight	Alternating bars
		6 52		141	2.51	2.56	43.5	0.90	5.88	3.69	11.8	0.227	Do	Do
		10 39		156	1.97	1.91	50.7	1.19	6.05	3.34	15.2	0.336	Do	Do
		19 34		215	1.43	1.41	52.9	1.50	7.16	3.07	17.2	0.188	Straight ~Meander	Do
		28 41		355	1.50	1.48	30.1	0.86	8.80	3.28	9.2	0.126	Meander	—
III	0- 20	0 41	6.0	59.2	2.25	2.09	45.4	0.97	5.07	3.22	14.2		Straight	No bar
	0- 20	7 00		62.2	2.52	2.33	38.5	0.78	4.19	3.09	12.6		Do	Do

($dm=$ 0.5 mm on the bed)	0- 20	14 43		63.0	2.66	2.46	36.0	0.71	4.00	3.10	11.7		Do	Do
	0- 35	21 59		66.4	2.56	2.37	36.2	0.73	3.97	3.02	12.0		Do	Do
	0- 40	28 59		68.0	2.64	2.44	34.7	0.69	4.02	3.09	11.4		Do	Do
	0- 40	36 22		68.5	2.83	2.60	31.9	0.61	3.95	3.17	10.2		Do	Do
	0- 40	43 10		67.8	2.64	2.44	34.9	0.70	3.80	3.01	11.7		Do	Do
	0- 45	49 49		73.3	2.53	2.36	34.4	0.71	4.07	3.06	11.5		Do	Do
	0- 65	61 17		85.5	2.72	2.55	27.8	0.54	4.13	3.20	8.8		Do	Do
	0- 70	71 26		88.9	2.58	2.42	28.3	0.53	4.15	3.13	9.2		Do	Do
	20-100	0 41		58.5	2.15	2.00	48.1	1.06	4.87	3.08	15.7		Do	Do
	20-100	7 00		65.2	2.44	2.26	38.2	0.79	4.86	3.28	11.8		Do	Ripples
	20-100	14 43		76.5	2.37	2.22	34.5	0.72	4.74	3.21	10.8		Do	Alternating bars
	35-100	21 59		84.4	2.21	2.09	33.0	0.72	4.83	3.14	10.7		Straight ~Meander	Do
	40-100	28 59		93.2	2.42	2.29	27.3	0.57	4.81	3.31	8.4		Do	Do
	40-100	36 22		102.0	2.40	2.30	25.2	0.53	4.79	3.26	7.8		Meander	—
	40-100	43 10		106.8	2.04	1.97	28.2	0.62	4.71	3.00	9.5		Do	—
	45-100	49 49		114.1	1.91	1.84	28.3	0.67	4.79	2.93	9.9		Do	—
	65-100	61 17		119.9	1.83	1.78	27.8	0.65	4.92	2.92	9.5		Do	—
	70-100	71 26		127.0	1.91	1.85	28.3	0.58	4.86	2.97	8.5		Do	—
	100-130	0 41		58.6	1.88	1.77	54.7	1.28	5.01	2.93	19.0		Straight	No bar
		7 00		71.4	2.10	1.98	40.3	0.89	5.45	3.25	12.4	0.0320	Do	Ripples
		14 43		81.6	2.12	2.02	35.1	0.78	5.73	3.36	10.5	0.0439	Do	Alternating bars
(bed load $dm=$ 0.66 mm)		21 59		90.4	2.00	1.91	35.2	0.84	5.95	3.28	11.0	0.0515	Straight ~Meander	Do
		28 59		99.6	1.89	1.82	32.4	0.76	5.87	3.22	10.1	0.0434	Do	Do
		36 22		117.5	1.67	1.78	28.9	0.69	6.56	3.25	8.9	0.0481	Meander	—
		43 10		137.4	1.35	1.32	34.4	1.00	6.82	2.94	11.9	0.0437	Do	—
		49 49		141.7	1.22	1.19	35.7	1.04	6.80	2.99	13.1	0.0361	Do	—
		61 17		169.3	1.41	1.29	30.2	0.86	6.58	3.00	12.3	0.0378	Do	—
		71 26		186.2	1.67	1.54	21.6	0.57	7.25	3.37	7.4	0.0678	Do	—

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Hydraulic conditions in the experiments

Exp. No.	Reach x m	Time T hr min	Dis-charge Q l/s	Flow width B cm	Mean depth h cm	Hydraulic radius R cm	Mean velocity U cm/s	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U_* cm/s	Velocity coeffici-ent U/U_*	Bed load per unit width q_B cm^2/s	Stream channel pattern	Bed configuration
IV	0- 30	4 00	15.0	99	4.04	3.69	39.4	0.65	4.36	3.92	10.4		Straight	No bar
		9 49		105	3.63	3.37	40.7	0.70	3.51	3.34	12.3		Do	Do
		12 39		104	3.62	3.37	40.8	0.70	3.48	3.31	12.5		Do	Do
		16 00		100	3.50	3.26	44.6	0.78	3.48	3.31	13.7		Do	Do
		18 50		98	3.58	3.32	45.1	0.80	3.63	3.38	13.9		Do	Do
		25 00		96	4.18	3.84	37.5	0.59	3.54	3.65	10.3		Do	Do
	30- 90	4 00		116	2.87	2.74	41.8	0.85	5.12	3.69	12.3		Do	Alternating bars
		9 49		152	2.72	2.63	37.0	0.72	5.01	3.58	10.4		Straight ~Meander	Do
		12 39		159	2.66	2.58	36.3	0.72	4.94	3.51	10.4		Do	Do
		16 00		166	2.52	2.44	37.7	0.77	4.85	3.37	11.3		Meander	—
		18 50		183	2.55	2.50	34.4	0.65	4.69	3.35	10.4		Do	—
		25 00		206	2.67	2.57	31.0	0.61	4.61	3.34	9.3		Do	—
	90-110	4 00		139	2.54	2.45	42.8	0.86	7.73	4.27	10.1	0.398	Straight	Alternating bars
		9 49		222	1.94	1.91	37.6	0.92	8.10	3.80	10.1	—	Straight ~Meander	Do
		12 39		247	1.62	1.60	36.8	0.94	8.63	3.50	10.7	0.234	Do	Do
		16 00		313	1.58	1.56	34.7	0.94	8.92	3.63	9.9	0.160	Meander	—
		18 50		354	1.39	1.38	33.0	0.92	9.24	3.46	9.5	—	Do	—
		25 00		403	1.15	1.14	33.7	1.02	9.63	3.26	10.7	—	Do	—
V (bed load $dm=$ 0.55 mm)	0- 40	0 43	6.0	64.0	2.77	2.55	34.1	0.66	5.11	3.57	9.61		Straight	Alternating bars
		2 30		69.0	2.75	2.55	31.8	0.62	4.92	3.50	9.13		Do	Do
		6 30		71.8	2.67	2.52	31.1	0.61	4.78	3.43	9.07		Do	No bar
		11 00		71.5	2.74	2.55	30.7	0.59	4.74	3.44	8.95		Do	Do
		16 00		70.6	2.75	2.55	31.2	0.61	4.77	3.45	9.16		Do	Do
		20 30		69.8	2.89	2.66	30.7	0.59	4.81	3.51	8.78		Do	Do
		25 30		70.1	2.82	2.60	30.6	0.59	4.87	3.52	8.71		Do	Do

V		36 30		69.2	2.77	2.56	31.5	0.61	4.86	3.49	9.05		Do	Do
		45 30		69.8	2.92	2.69	29.6	0.55	4.88	3.58	8.27		Do	Do
		50 30		—	—	—	—	—	—	—	—		Do	Do
	40- 90	0 43		62.3	2.97	2.72	32.7	0.57	3.01	2.75	12.04		Do	Faint bar
		2 30		66.1	3.09	2.82	30.2	0.56	3.03	2.81	10.81		Do	Do
		6 30		67.4	3.02	2.81	29.3	0.54	3.11	2.87	10.31		Do	Alternating bars
		11 00		69.3	3.05	2.76	28.8	0.53	3.13	2.87	10.13		Do	Do
		16 00		69.8	2.90	2.68	30.0	0.56	3.15	2.85	10.58		Do	Do
		20 30		70.4	2.92	2.70	28.7	0.55	2.91	2.76	10.12		Do	Do
		25 30		71.3	3.19	2.82	26.6	0.48	3.04	2.94	9.12		Do	Faint bar
		36 30		71.5	2.90	2.70	29.2	0.55	3.01	2.80	10.50		Do	Do
		45 30		70.8	3.17	2.70	27.0	0.49	2.99	2.85	9.35		Do	Do
		50 30		69.8	3.07	2.62	28.2	0.52	3.00	2.85	9.94		Do	No bar
	90-108	0 43		61.7	3.22	2.91	30.3	0.54	2.12	2.46	12.32		Do	Do
		2 30		62.7	2.94	2.69	33.4	0.63	3.34	2.91	11.46	0.0631	Do	Do
		6 30		63.2	2.93	2.77	31.7	0.60	3.16	2.90	10.95	0.0247	Do	Do
		11 00		64.2	3.00	2.73	32.3	0.60	3.08	2.86	11.28	0.0140	Do	Do
		16 00		63.0	2.88	2.64	33.7	0.64	2.91	2.81	11.86	0.0112	Do	Do
		20 30		62.7	2.94	2.68	33.1	0.62	3.07	2.83	11.59	0.0123	Do	Do
		25 30		62.8	3.10	2.82	31.1	0.56	3.13	2.93	10.59	0.0110	Do	Do
		36 30		63.2	2.95	2.70	32.3	0.60	3.07	2.84	11.39	0.00996	Do	Do
		45 30		62.5	2.95	2.70	32.5	0.61	3.18	2.89	11.22	0.0120	Do	Do
		50 30		63.3	2.86	2.62	33.7	0.64	3.11	2.82	11.81	0.0145	Do	Do
VI	0- 30	2 00	15.0	92.5	3.71	3.41	46.4	0.81	4.29	3.73	12.6		Straight	No bar
		7 00		103.4	4.21	3.84	35.8	0.56	3.42	3.52	10.3		Do	Do
		12 00		103.0	4.37	3.99	34.9	0.54	3.26	3.52	10.0		Do	Do
		17 00		100.3	4.51	4.10	34.5	0.53	3.07	3.48	10.0		Do	Do
		22 15		98.8	4.57	4.14	34.6	0.52	2.98	3.45	10.1		Do	Do
		27 15		97.5	4.72	4.20	33.8	0.50	3.00	3.51	9.7		Do	Do
		32 15		96.1	4.82	4.33	33.5	0.49	2.89	3.45	10.1		Do	Do

Appendix

Hydraulic conditions in the experiments

Exp. No.	Reach x m	Time T hr min	Dis-charge Q l/s	Flow width B cm	Mean depth h cm	Hydraulic radius R cm	Mean velocity U cm/s	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U_* cm/s	Velocity coeffici-ent U/U_*	Bed load per unit width q_B cm^2/s	Stream channel pattern	Bed configuration
VI		37 30	15.0	96.1	4.68	4.18	34.9	0.52	2.89	3.44	10.2		Straight	No bar
	30- 58	2 00		97.0	2.96	2.79	52.3	0.97	4.62	3.56	14.6		Do	Alternating bars
		7 00		123.6	2.94	2.81	41.4	0.77	4.38	3.47	12.0		Do	Do
		12 00		150.1	2.98	2.86	34.0	0.63	4.06	3.37	10.2		Straight ~Meander	Do
		17 00		158.3	2.73	2.63	35.4	0.69	3.85	3.15	11.4		Meander	—
		22 15		166.0	2.69	2.60	34.3	0.65	3.78	3.10	11.1		Do	—
		27 15		175.0	2.63	2.54	34.1	0.69	3.66	3.00	11.5		Do	—
		32 15		178.0	2.75	2.65	32.2	0.63	3.53	2.99	10.7		Do	—
		37 30		180.3	2.85	2.75	30.7	0.58	3.55	3.09	10.0		Do	—
	58- 90	2 00		82.5	4.47	4.03	40.7	0.62	2.58	3.16	13.0		Straight	—
		7 00		97.3	4.08	3.76	38.1	0.61	3.31	3.49	11.0		Do	Alternating bars
		12 00		110.5	3.48	3.27	39.5	0.68	3.52	3.35	11.8		Do	Do
		17 00		127.8	3.40	3.22	35.3	0.62	3.61	3.37	10.6		Straight ~Meander	Do
		22 15		147.6	2.73	2.63	37.9	0.71	3.54	3.02	12.6		Meander	—
		27 15		172.8	2.74	2.65	32.5	0.64	3.28	2.91	11.4		Do	—
		32 15		190.4	2.99	2.90	28.3	0.55	3.11	2.96	14.6		Do	—
		37 30		213.1	2.69	2.62	28.2	0.59	2.97	2.74	11.0		Do	—
	90-108	2 00		86.2	4.05	3.69	44.1	0.72	3.93	3.70	11.9		Straight	No bar
		7 00		93.0	4.25	3.89	38.3	0.60	3.63	3.71	10.4		Do	Do
		12 00		94.8	4.05	3.72	39.5	0.63	3.64	3.64	10.9		Do	Alternating bars
		17 00		104.6	3.29	3.10	44.1	0.79	3.87	3.43	13.1		Straight ~Meander	Do
		22 15		115.8	2.89	2.75	45.3	0.85	4.03	3.29	13.9		Meander	—
		27 15		150.4	2.64	3.24	38.5	0.77	4.29	3.24	12.0		Do	—
		32 15		176.0	2.64	2.56	35.0	0.72	4.38	3.24	11.0		Do	—
		37 30		277.0	1.97	2.06	29.2	0.72	4.85	2.95	10.2		Do	—

VII	10– 40	0 45	6.0	62.8	2.64	2.44	36.4	0.72	5.01	3.46	10.5		Straight	No bar
		4 55	〃	67.0	2.71	2.50	33.5	0.66	5.03	3.50	9.6		Do	Do
		6 18	10.0	77.5	3.69	3.37	35.3	0.59	5.09	4.10	8.7		Do	Do
		8 00	〃	86.0	3.26	3.02	36.1	0.64	4.11	3.48	10.4		Do	Do
		8 51	15.0	93.5	4.27	3.92	37.6	0.58	4.58	4.19	9.0		Do	Do
		9 55	〃	101.3	4.00	3.70	37.4	0.60	3.49	3.54	10.6		Do	Do
		10 58	30.0	134.8	6.40	5.83	35.1	0.45	3.90	4.70	7.5		Do	Do
		12 00	〃	152.0	4.50	4.24	44.7	0.68	4.05	4.05	11.0		Do	Do
		12 59	20.0	152.8	3.40	3.25	39.1	0.69	3.74	3.43	11.4		Do	Do
	40– 90	0 45	6.0	61.3	2.45	2.27	39.5	0.80	4.95	3.32	11.8		Do	Alternating bars
		4 55	〃	67.7	2.70	2.50	32.9	0.64	5.04	3.52	9.4		Do	Do
		6 18	10.0	81.0	4.00	3.64	31.0	0.50	4.50	3.99	7.9		Do	Do
		8 00	〃	91.5	2.92	2.74	37.5	0.70	5.10	3.69	10.1		Do	Do
		8 51	15.0	103.5	4.79	4.36	31.8	0.48	4.93	4.55	7.1		Do	Do
		9 55	〃	116.7	2.86	2.72	45.2	0.86	5.60	3.86	11.7		Do	Do
		10 58	30.0	153.7	4.85	4.56	40.3	0.59	5.43	4.89	8.3		Do	Do
		12 00	〃	179.8	3.87	3.71	43.2	0.70	5.84	4.57	9.5		Do	Do
		12 59	20.0	182.7	2.92	2.83	37.9	0.72	5.43	3.84	9.9		Do	Do
	90–110	0 45	6.0	61.5	2.19	2.03	42.0	0.89	5.70	3.32	12.3		Do	Do
		4 55	〃	73.5	2.09	1.96	41.6	0.97	6.25	3.37	12.4		Do	Do
		6 18	10.0	88.0	3.08	2.86	38.4	0.72	5.46	3.79	10.1		Do	Do
		8 00	〃	102.0	2.63	2.49	38.0	0.76	6.20	3.84	9.9		Do	Do
		8 51	15.0	114.5	4.31	3.91	26.7	0.72	6.79	4.70	8.5		Do	Do
		9 55	〃	132.0	2.36	2.27	49.0	1.03	7.58	4.03	12.2		Do	Do
		10 58	30.0	174.3	3.61	3.45	50.5	0.99	8.66	5.29	9.6		Do	Do
		12 00	〃	203.5	2.95	2.86	52.2	1.01	7.96	4.63	11.3		Do	Do
		12 59	20.0	211.0	2.14	2.10	45.5	1.01	7.06	3.78	12.1		Do	Do

Appendix

Hydraulic conditions in the experiments

Exp. No.	Reach x (m)	Time T (hr min)	Discharge Q (l/s)	Flow width B (cm)	Mean depth h (cm)	Hydraulic radius R (cm)	Mean velocity U (cm/s)	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U_* (cm/s)	Velocity coefficient U/U_*	Bed load per unit width q_B (cm^2/s)	Stream channel pattern	Bed configuration
VIII	0- 42	0 36	5.0	42.18	3.18	2.83	36.4	0.64	4.83	3.66	9.98		Straight	No bar
(dm=		3 00		48.45	2.79	2.50	37.4	0.72	4.35	3.26	11.57		Do	Do
0.5mm		7 30		56.09	2.50	2.29	36.3	0.74	4.40	3.13	11.63		Do	Do
on		11 46		55.91	2.85	2.57	32.0	0.61	4.41	3.31	9.60		Do	Do
the bed)		17 00		54.64	2.93	2.64	31.8	0.60	4.49	3.39	9.40		Do	Do
		21 59		54.18	3.09	2.76	30.3	0.55	4.57	3.51	8.78		Do	Do
	42- 68	0 36		41.86	3.17	2.75	37.9	0.68	5.12	3.72	10.25		Do	Do
		3 00		58.57	2.30	2.13	37.3	0.79	5.06	3.26	11.46		Do	Do
		7 30		67.71	2.30	2.15	32.4	0.68	5.01	3.25	9.99		Do	Alternating bars
		11 46		71.43	2.38	2.23	30.1	0.64	5.02	3.30	9.24		Do	Do
		17 00		71.29	2.25	2.12	31.4	0.67	4.79	3.15	9.96		Do	Faint bars
		21 59		70.43	2.72	2.51	26.5	0.52	4.75	3.41	7.81		Do	No bar
	68- 90	0 36		41.50	2.98	2.61	40.5	0.75	5.09	3.61	11.23		Do	Do
		3 00		55.17	2.36	2.17	38.6	0.80	5.02	3.27	11.28		Do	Do
		7 30		67.17	2.39	2.37	29.8	0.60	5.07	3.42	8.40		Do	Alternating bars
		11 46		72.00	2.02	1.91	34.9	0.79	5.08	3.07	11.44		Do	Do
		17 00		72.67	2.15	2.02	32.6	0.72	5.40	3.24	10.10		Do	Do
		21 59		72.33	2.62	2.44	26.8	0.53	5.34	3.57	7.57		Do	Do
	90-108	0 36		38.60	2.61	2.30	50.1	1.00	5.44	3.49	14.34		Do	No bar
		3 00		55.20	2.11	1.96	43.6	0.97	6.04	3.38	12.98		Do	Do
		7 30		66.80	2.39	2.23	31.5	0.66	6.18	3.66	8.64		Do	Alternating bars
		11 46		80.00	2.20	2.07	31.3	0.67	6.27	3.53	8.67		Do	Do
		17 00		82.60	1.98	1.88	31.3	0.72	6.09	3.33	9.40		Do	Do
		21 59		85.20	2.26	2.14	26.6	0.57	6.06	3.55	7.55		Do	Do

IX	0- 46	0 32	15.0	71.17	4.85	4.26	43.7	0.64	4.85	4.50	9.8		Straight	No bar
		2 06		82.25	4.00	3.64	46.0	0.73	4.32	3.86	12.0		Do	Do
		4 56		88.00	4.50	4.06	38.7	0.59	4.02	3.94	9.9		Do	Do
		9 49		88.67	4.44	3.98	39.7	0.62	3.80	3.79	10.5		Do	Do
		14 53		87.17	4.88	4.34	36.6	0.54	3.69	3.91	9.4		Do	Do
		20 03		85.50	4.80	4.26	38.3	0.58	3.66	3.86	10.0		Do	Do
		24 54		82.92	4.89	4.33	38.2	0.56	3.50	3.81	10.0		Do	Do
		29 57		82.00	4.92	4.35	38.3	0.56	3.47	3.82	9.9		Do	Do
	46- 78	0 32		74.38	4.70	4.17	42.9	0.63	4.95	4.50	9.6		Do	Do
		2 06		87.88	3.88	3.57	44.2	0.73	4.96	4.15	10.8		Do	Do
		4 56		98.75	3.56	3.32	43.2	0.74	5.06	4.04	10.8		Do	Alternating bars
		9 49		113.38	3.35	3.16	39.7	0.70	4.96	3.91	10.2		Do	Do
		14 53		121.13	3.14	2.98	39.8	0.72	4.98	3.80	10.5		Do	Do
		20 03		123.63	3.25	3.08	37.8	0.67	4.87	3.83	9.9		Do	No bar
		24 54		125.63	3.18	3.01	38.4	0.70	4.96	3.80	10.1		Do	Do
		29 57		131.13	3.08	2.93	38.2	0.70	4.88	3.72	10.3		Do	Do
	78-108	0 32		75.25	4.44	3.97	45.4	0.70	5.55	4.60	9.9		Do	Do
		2 06		89.13	3.69	3.40	46.2	0.78	5.76	4.35	10.7		Do	Do
		4 56		102.75	3.31	3.11	44.5	0.79	6.01	4.27	10.5		Do	Do
		9 49		121.38	2.72	2.60	46.1	0.90	6.29	3.99	11.7		Do	Alternating bars
		14 53		143.13	2.88	2.77	37.4	0.72	6.10	4.04	9.4		Do	Do
		20 03		160.63	2.78	2.69	33.9	0.65	6.06	3.99	8.6		Straight ~Meander	Do
		24 54		167.75	2.36	2.29	40.2	0.88	6.20	3.69	11.4		Do	Do but asymmetric
		29 57		187.25	2.19	2.13	38.0	0.84	5.92	3.49	11.1		Do	Do
X	0- 10	1 00	20.0	126.5	3.54	3.36	44.7	0.76	4.04	3.64	12.3		Straight	No bar
		3 00		133.6	3.60	3.41	41.2	0.70	3.78	3.55	11.8		Do	Do
		7 00		139.7	3.50	3.33	41.0	0.70	4.20	3.69	11.1		Do	Do
		12 00		154.2	2.78	2.68	46.8	0.90	5.65	3.85	12.2		Do	Do
		17 00		227.5	2.15	2.11	42.8	0.94	6.88	3.76	11.5		Do	Do

Appendix

Hydraulic conditions in the experiments

Exp. No.	Reach x (m)	Time T (hr min)	Dis-charge Q (l/s)	Flow width B (cm)	Mean depth h (cm)	Hydraulic radius R (cm)	Mean velocity U (cm/s)	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U_* (cm/s)	Velocity coeffici-ent U/U_*	Bed load per unit width q_B (cm^2/s)	Stream channel pattern	Bed configuration
X	12- 30	1 00	20.0	130.3	3.18	3.04	49.0	0.88	5.25	3.98	12.4		Straight	Faint bars
		3 00		146.1	3.25	3.10	42.8	0.77	5.26	3.98	10.7		Do	Do
		7 00		155.6	3.18	3.05	40.6	0.73	5.63	4.10	10.0		Do	Alternating bars
		12 00		170.0	2.70	2.62	43.4	0.85	5.84	3.86	11.2		Do	Faint bars
		17 00		207.7	2.11	2.07	47.3	1.06	7.31	3.83	12.7		Do	Do
	32- 42	1 00		133.0	2.95	2.82	51.7	0.97	7.34	4.48	11.6	0.525	Do	Do
		3 00		156.0	2.81	2.72	46.6	0.90	7.20	4.47	10.7	0.360	Do	Do
		7 00		186.0	2.62	2.50	41.6	0.83	7.84	4.35	9.6	0.300	Do	Alternating bars
		12 00		209.4	2.23	2.18	44.3	0.97	7.72	4.04	11.5	0.221	Do	Faint bars
		17 00		241.8	1.97	1.93	44.5	1.05	8.40	3.94	11.7	0.207	Do	Do
XI	0- 10	4 00	15.0	130.4	1.98	1.92	60.1	1.40	8.64	4.07	13.5		Straight	Alternating bars
		6 00		—	—	—	—		—	—			Do	Do
		9 47		158	3.12	2.95	33.1	0.62	5.03	3.51	9.2		Do	Do
		12 07		162.8	3.11	2.94	32.7	0.62	5.55	3.68	8.9		Do	Do
	10- 32	4 00		121	2.65	2.54	47.0	0.93	6.18	3.91	12.1		Do	Do
		6 00		146	2.51	2.42	41.1	0.83	6.20	3.83	10.8		Straight ~Meander	Do
		9 47		207	1.99	2.13	34.3	0.76	6.01	3.51	9.9		Meander	—
		12 07		243	2.03	1.89	32.0	0.74	5.74	3.30	9.8		Do	—
	32- 42	4 00		124	2.28	2.20	53.7	1.15	7.44	4.02	13.1	0.277	Straight	Do
		6 00		148	2.53	2.45	40.6	0.83	8.43	4.48	9.1	0.167	Straight ~Meander	Do
		9 47		276	1.37	1.36	40.4	1.11	9.39	3.44	12.3	0.195	Meander	—
		12 07		225	1.54	1.52	30.0	0.83	9.97	3.85	8.2	0.0986	Do	—
XII	0- 10	0 10	15.0	57	7.40	5.82	36.3	0.43	9.49	7.33	5.0		Straight	No bar
		4 10		121	3.39	3.21	36.6	0.64	5.71	4.24	8.6	1.143	Do	Do

		10 00		123	3.24	3.07	38.3	0.69	5.99	4.23	9.0	0.597	Do	Do
		15 00		142	2.76	2.66	38.6	0.75	6.84	4.22	9.2	0.422	Do	Do
		20 00		143	1.83	1.79	59.0	1.41	11.59	4.24	14.0	0.363	Do	Do
		25 00		169	2.59	2.50	37.9	0.80	8.60	4.48	8.8	0.314	Do	Do
		30 00		144	3.09	2.95	34.7	0.64	6.36	4.18	8.3	—	Do	Do
	10- 30	0 15		59	5.91	4.91	43.7	0.58	5.11	4.92	9.0		Do	Do
		4 10		113	2.90	2.76	45.8	0.86	6.56	4.20	11.0		Do	Faint bars
		10 00		128	2.61	2.51	45.4	0.90	6.66	4.04	11.3		Do	Irregular bars
		15 00		144	2.47	2.34	43.3	0.89	7.17	4.04	10.7			Do
		20 00		155	2.13	2.07	45.8	1.01	6.89	3.66	12.3		Braiding	—
		25 00		191	1.60	1.58	49.6	1.26	8.66	3.64	13.6		Do	—
		30 00		218	1.90	1.86	37.9	0.91	7.47	3.64	10.5		Do	—
	30- 42	0 20		57	4.01	3.52	66.8	1.08	4.47	3.92	17.5		Straight	No bar
		4 10		124	2.26	2.18	55.2	1.21	10.70	5.26	10.7		Do	Faint bars
		10 00		160	1.82	1.78	52.8	1.27	12.50	4.63	11.8		Do	Irregular bars
		15 00		196	1.58	1.55	51.7	1.37	12.14	4.30	12.4		Do	Do
		20 00		231	1.33	1.32	53.2	1.65	12.00	3.96	14.3		Braiding	—
		25 00		260	1.35	1.33	45.9	1.33	12.56	4.06	11.6		Do	—
		30 00		310	1.34	1.33	38.8	1.12	12.92	4.05	10.1		Do	—
XIII	0- 8	0 23	15.0	71	5.41	4.70	39.08	0.54	6.06	5.28	7.47		Straight	No bar
		4 00		112	2.43	2.33	55.73	1.15	6.16	3.73	15.00		Do	Do
		8 25		151	1.98	1.92	52.00	1.22	7.42	3.66	14.24		Do	Do
		11 55		190	1.91	1.87	42.61	1.00	6.57	3.46	12.54		Do	Do
		15 40		193	2.13	2.08	38.74	0.87	5.67	3.06	12.92		Do	Do
	10- 30	0 23		66.5	4.74	4.15	47.94	0.71	4.77	4.40	11.01		Do	Do
		4 00		96	2.69	2.54	58.93	1.15	5.83	3.79	15.75		Do	Faint bars
		8 25		145	2.05	1.99	50.89	1.15	6.02	3.40	15.39		Slight meander	Alternating bars
		11 55		182	2.10	2.05	40.05	0.90	5.27	3.31	11.76		Meander	Do
		15 40		200	2.10	2.06	36.10	0.83	7.21	3.35	11.32		Do	Do

Appendix

Hydraulic conditions in the experiments

Exp. No.	Reach x m	Time T hr min	Dis-charge Q l/s	Flow width B cm	Mean depth h cm	Hydraulic radius R cm	Mean velocity U_* cm/s	Froude number Fr	Energy slope $I\times10^3$	Shear velocity U cm/s	Velecity coeffici-ent U/U_*	Bed load per unit width q_B cm^2/s	Stream channel pattern	Bed configuration
XIII	30- 42	0 23	15.0	63.5	3.58	3.21	63.37	1.06	5.39	4.30	14.14		Straight	No bar
		4 00		88.2	2.76	2.59	62.37	1.21	8.57	4.64	13.56	0.529	Do	Do
		8 25		127	2.14	2.07	55.49	1.22	9.94	4.48	12.55	0.490	Slight meander	Do
		11 55		200	1.93	1.89	41.69	0.98	8.23	3.80	11.73	0.695	Meander	—
		15 40		187	1.69	1.66	50.73	1.28	12.63	4.50	12.13	0.761	Do	—