Environmental Research Center Papers

Number 12

1988

Environmental Research Center
The University of Tsukuba

EXPERIMENTAL STUDY OF HETEROGENEOUS SEDIMENT TRANSPORT

By Hiroshi Ikeda* and Fujiko Iseya*

(received March 5, 1988)

ABSTRACT

Although intensive observations of heterogeneous sediment transport in alluvial rivers during the past one or two decades have revealed many interesting phenomena, not enough is known about the effect of different grain size mixtures. Results of flume experiments on the transport of sediment mixtures of two grades are summarized:

(1) Slip-velocity, the relative velocity between the flow and a grain rolling along a smooth bed is proportional to local flow velocity surrounding the grain, but not to the grain density. Under a flow which is deeper than the grain size, transport velocity is proportional to grain size. It may be considered that slip-velocity is determined mainly by the viscous shear force acting on the grains rotating in a viscous fluid.

(2) Mixtures of coarse and fine sand with fines dominant are more mobile than uniform fine sand. Superior mobility of sediment mixtures can be explained by the effects of mixing on smoothing of the bed, exposure, and collision.

(3) Abrupt changes in the mobility of sand-gravel mixtures are determined by abrupt changes in bed states from smooth to congested. Sand controls the mobility of a mixture when the bed state is smooth; gravel controls mobility when the bed state is congested.

(4) Abrupt changes in the mobility of mixtures are also associated with changes in transport mode. When the coarse sand fraction exceeds a "critical mixture ratio", bedforms change remarkably and transport mode changes from mainly suspension to mainly traction.

(5) Vertical sorting caused by the development of bedforms results in sharp changes in the mobility of sediment mixtures. When the gravel content is higher than the sand content, sand grains settle among the interstices of gravel grains and the entire bed is covered by gravel. However, when the ratio of the sand exceeds the critical ratio, most of gravel grains are buried beneath sand.

(6) Some geomorphological features in alluvial rivers, such as longitudinal slope discontinuity, alternating repetition of scour and fill, and fan-head trenching, may be closely connected with the process of heterogeneous sediment transport.

* Environmental Research Center, University of Tsukuba, Tsukuba, 305 Japan

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

SYMBOL	DEFINITION
A_1	Cross-sectional area of grain
A_2	Surface area of grain
d	Grain diameter
d_{16}, d_{50}, d_{84}	Sediment diameters for which 16, 50, 84 per cent of the sample is finer
C_d	Drag coefficient
D	Mean depth of flow
F_d	Drag force
F_f	Friction force
g	Acceleration due to gravity
H_r	Ripple wave height
i_b	Bedload transport rate per unit width (immersed weight)
L_r	Ripple wave length
n	Manning's roughness coefficient
q	Water discharge per unit width
Q	Water discharge
R_e	Reynold's number
S	Water surface slope
T	Time
T_w	Water temperature
V_c	Local flow velocity
V_m	Mean flow velocity
V_p	Mean velocity of grains in motion
V_s	Surface flow velocity
V_{slip}	Slip velocity = $V_c - V_p$
W	Flume width
Y	Height above bed
μ	Viscosity of fluid
ρ	Density of fluid
σ	Density of sediment and grain
τ	Viscous shear stress
τ_0	Boundary shear stress
ω	Angular velocity of rotating grain

CHAPTER I

INTRODUCTION

We have conducted research on the transport of heterogeneous sediments in the past several years. Though this research is still continuing we wish to describe an outline of our findings.

Why does river-bed material size decrease downstream? Two interpretation have been given: (1) The grain size reduction results from wearing of individual particles by weathering and mechanical breakdown: (2) The downstream change in size is a product of selective transport and deposition (sorting), resulting from alterations in the hydraulic and morphological conditions downstream.

We would rather support the former (Ikeda, 1970; 1985), but in recent years, the latter has gained favor not only in Japan (e.g. Kira, 1982; Yamamoto, 1986) but also in the United States (e.g. Bluck, 1987). Although sorting increases rapidly in the first few kilometers downstream of a heterogeneous sediment imput and then much more slowly afterwards (Leopold *et al.*, 1964), sorting is considered to be the cause of most of the downstream decrease in grain size in alluvial rivers (e.g. Plumley, 1948; Nakayama and Miura, 1964).

In an equilibrium channel, where sediment output from the reach equals input, the sorting effect alone cannot cause an over-all reduction in grain size downstream (Statham, 1977). This is fairly apparent because all material input to the channel must eventually pass out of the channel and so ultimately the size of transported material will be the same as that of the source. Overall grain size reduction must therefore be due to wear and breakage. More field and experimental data on the transport of heterogeneous sediment are needed to understand fully the relative roles of abrasion and sorting (Pettijohn, 1957).

Let us now consider a related geomorphological feature associated with mixed sediment transport. Yatsu (1955) found that along several graded streams draining the Japanese highlands there were short reaches over which the slope of the stream and the median diameter of the bed material decreased suddenly. Gravel stream suddenly became sand stream downstream. Such slope discontinuity can be seen in rivers where granule-sized bed material is missing in the bed. Yatsu explained that this might be attributed to abrasion of sediment, involving a process of discontinuous disintegration. However he could not explain the mechanism whereby a deficiency of intermediate grain size or a bimodal grain size distribution could strongly influence longitudinal stream profiles.

There have been two opposite ideas on the cause of this phenomenon; one is that the channel slope varies directly with the mobility of bed material, and the other is that the grain size is determined by the slope. West (1978) considered that an abrupt grain size change along a stream is caused primarily by the non-arrival of the largest sizes.

It is true that fluid fows possess the ability to sort. It has been considered that there is a critical shear stress for each grain size at which it begins to move, and only particles smaller than the critical size will be moved by the flow.

Heterogeneous sediment transport processes are complex, because of added complications such as the effect of shielding of small grains by large grains (Einstein, 1950). Critical conditions for initial motion of individual sizes within a graded sediment have been proposed (e.g. Egiazaroff, 1965; Nakagawa and Tsujimoto, 1977; White and Day, 1982). However further work is required to determine the characteristics of motion of individual grain sizes within sediment mixtures (White and Day, 1982).

A direct attack to solve the problem of the downstream change in bed material size may need improved knowledge of the mobility of sediment mixtures having a bimodal size distribution and the mobility of the largest gravels in heterogeneous sediments. There have been many intensive studies on the transportation of mixed sediments (Ashida and Michiue, 1972; Fukami, 1978; Yamamoto, 1986; Parker *et al.*, 1982; Parker and Klingeman, 1982), but there have been few studies on the mobility of mixed sediments in which both large and small grains are in motion. Threrefore we examined how the grain size composition controlled the process of mixed sediment transport, e.g. bed state, transport mode, and mobility of mixed sediment that was first investigated by Gilbert (1914).

CHAPTER II

VELOCITY OF GRAINS, ROLLING ALONG A SMOOTH BED, IN TURBULENT FLOWS

Bedload transport rate is a function of the number of grains in motion and their travel velocities. Parsons (1972) measured travel velocities of fine grains in laminar flows. However, we do not have enough knowledge about the travel velocities of solid grains in turbulent flows. In order to derive a bedload transport formula for a smooth bed, Bagnold (1973) postulated that the slip-velocity of grains in motion, that is the difference between velocity of grains and flow velocity in their immediate neighborhood, is equal to the terminal fall velocity of the grains in still water.

When a large flume was constructed in 1976–77 at the Environmental Research Center of the University of Tsukuba, we had an experiment to test Bagnold's hypothesis in the flume. The results were published in 1979 in Japanese (Ikeda *et al.*, 1979). The velocity of grains is an important factor in the superior mobility of heterogenous sediment. Therefore, here we introduce briefly the results of the experiment.

2-1. Experimental methods

A steel flume (4 m wide, 2 m deep, 160 m long) was used for this study. It has smooth bed and walls. Flume bed slope is fixed at 1/100. Experimental conditions are shown in Table 2-1.

Table 2-1 Experimental conditions

Run No.	1	2	3	4	5	6	7	8
Water discharge per unit width, $m^3/sec \cdot m$	0.004	.008	.016	.032	.064	.128	.256	.400
Water temperature, °C	24.5	24.0	22.4	22.0	23.0	23.0	23.7	23.2
Surface flow velocity, m/sec	0.580	.755	.954	1.26	1.61	2.08	2.65	3.27
Mean flow velocity, m/sec	0.477	.639	.839	1.13	1.45	1.89	2.47	2.98
Calculated flow depth, mm	8.39	12.6	19.1	28.4	44.2	67.7	104	134
Measured flow depth, mm	10.0	14.1	20.3	29.2	45.6	71.1	106	146

Table 2-2 Grains for testing

Shape	Material	Specific gravity	Size (mm)	Number of sizes
balls	steel	7.8	2-51	14
balls	glass	2.5	2-30	12
columns	vinyl chloride	1.8	18-60	5
columns	plastics	1.4	3-30	11
cubes	mortar	2.0	10-70	6

Table 2-3 Travel velocity of grains (m/sec)

1) Steel balls

diameter (mm)	1	2	3	4	5	6	7	8
50.8	–	0.512	0.735	0.993	1.31	1.65	1.93	2.44
30.2	0.386	0.510	0.742	1.01	1.28	1.58	1.81	2.03
25.4	0.379	0.546	0.756	0.992	1.23	1.48	1.84	–
22.2	0.356	0.523	0.751	1.02	1.16	1.50	1.78	2.11
19.1	0.361	0.538	0.756	0.911	1.16	1.38	1.76	2.02
16.0	0.373	0.538	0.724	0.900	1.13	1.38	1.75	1.88
13.0	0.370	0.563	0.676	0.866	1.06	1.32	1.68	–
10.0	0.396	0.524	0.649	0.826	1.02	1.31	1.66	1.81
8.0	0.396	0.485	0.618	0.803	1.01	1.25	1.53	1.72
6.0	0.366	0.470	0.572	0.752	0.935	1.21	–	1.72
5.0	0.352	0.438	0.562	–	0.883	1.15	–	1.74
4.0	0.340	0.432	0.538	0.701	0.861	1.15	–	–
3.0	0.314	0.405	0.518	0.709	0.885	1:17	–	–
2.0	0.289	0.344	0.467	0.617	–	1.09	–	–

2) Glass balls

diameter (mm)								
30.0±0.5	0.386	0.561	0.795	1.04	1.25	1.55	1.96	2.22
25.0±0.5	0.391	0.566	0.799	1.01	1.25	1.51	1.96	2.16
20.0±0.5	0.398	0.566	0.769	0.953	1.22	1.51	1.83	2.11
17.0±0.5	0.403	0.568	0.756	0.939	1.17	1.47	1.87	2.11
16.0±0.5	0.399	0.566	0.765	0.900	1.15	1.45	1.86	2.08
10.0±0.5	0.409	0.522	0.693	0.873	1.09	1.37	1.67	2.11
8.0±1.0	0.408	0.528	0.680	0.849	1.09	1.44	1.75	1.94
5.61~6.68	0.390	0.498	0.629	0.816	1.07	1.38	1.75	1.83
4.69~5.61	0.377	0.467	0.613	0.796	1.03	–	1.88	–
3.96~4.69	0.369	0.455	0.568	–	0.938	–	–	–
2.79~3.96	0.352	0.457	0.604	0.743	0.987	1.32	1.48	–
1.98~2.79	0.338	0.435	0.557	0.744	0.958	1.30	1.60	–
0.99~1.98	0.311	–	–	–	–	–	–	–

3) Columns of vinyl chloride

diameter x length (mm)								
60×240	0.381	0.516	0.747	1.00	1.30	1.67	2.10	2.30
60×120	0.354	0.498	0.708	0.965	1.28	1.69	2.01	2.34
60× 60	0.330	0.472	0.663	0.903	1.24	1.66	2.05	2.26
51× 30	0.270	–	–	0.789	1.28	1.57	1.95	2.24
51× 15	–	–	–	–	1.27	1.51	2.01	2.30
38×150	0.365	0.526	0.763	1.00	1.31	–	1.94	2.18
38× 77	0.354	0.534	–	1.01	1.29	1.56	1.98	2.27
38× 38	0.324	0.497	–	0.970	1.29	1.55	2.00	2.31
31× 19	–	–	–	–	1.20	1.45	–	2.15
31× 10	–	–	–	–	1.15	1.42	–	2.07
18× 75	0.385	0.551	0.764	0.943	1.17	1.44	1.75	2.04
18× 36	0.360	0.574	0.758	0.968	1.17	1.41	1.82	2.20
18× 18	–	0.380	0.722	0.950	1.15	1.49	–	2.18
18× 9	–	0.353	–	0.947	1.16	1.46	–	2.18

4) Columns of Plastics

diameter x length (mm)	1	2	3	4	5	6	7	8
30 x 120	0.377	0.533	0.752	1.03	1.31	1.47	1.96	2.37
30 x 60	0.361	0.527	0.752	1.02	1.29	1.62	2.05	2.31
30 x 30	0.343	0.509	0.640	1.01	1.30	1.56	2.03	2.34
25 x 00	0.390	0.548	0.771	1.02	1.24	1.45	2.01	2.18
25 x 50	0.364	0.533	0.758	1.01	1.25	1.60	2.03	2.45
25 x 25	0.355	0.524	0.758	1.01	1.27	1.61	1.99	2.29
20 x 80	0.379	0.561	0.773	0.991	1.15	1.54	1.93	2.15
20 x 40	0.373	0.549	0.759	0.984	1.28	1.54	2.01	2.22
20 x 20	0.351	0.498	0.757	1.02	1.25	1.54	–	2.17
15.5 x 64	0.398	0.568	0.771	0.943	1.17	1.44	1.94	2.25
15.5 x 32	0.384	0.541	0.761	0.954	1.22	1.49	1.94	2.15
15.5 x 16	0.346	0.549	0.764	0.974	1.21	1.58	1.88	2.17
13 x 52	0.410	0.577	0.765	0.875	1.17	1.49	–	2.25
13 x 26	0.392	0.556	0.750	0.938	1.18	1.50	–	2.24
13 x 13	0.358	0.573	0.771	0.934	1.19	1.49	–	2.18
10 x 40	0.412	0.576	0.734	0.854	1.14	1.40	–	2.06
10 x 20	0.394	0.558	0.717	0.909	1.17	1.47	–	2.11
10 x 10	0.392	0.554	0.750	0.921	1.16	1.45	–	2.00
8 x 32	0.437	0.540	0.683	0.835	1.06	1.39	–	2.13
8 x 16	0.403	0.543	0.690	0.884	1.11	1.42	–	2.11
8 x 8	0.408	0.540	0.709	0.882	1.10	1.40	–	2.00
6 x 24	0.421	0.452	0.613	0.825	1.11	1.36	–	2.02
6 x 12	0.416	0.531	0.683	0.870	1.12	1.41	–	2.02
6 x 6	0.413	0.522	0.683	0.860	1.08	1.42	–	2.04
5 x 20	0.407	0.466	0.621	0.812	1.08	1.10	–	2.00
5 x 10	0.404	0.518	0.639	0.847	1.09	1.43	–	2.06
5 x 5	0.412	0.514	0.602	0.857	1.03	1.39	–	1.94
4 x 16	0.337	0.442	0.613	0.781	1.06	1.32	–	2.08
4 x 8	0.403	0.504	0.667	0.860	1.06	1.38	–	2.02
4 x 4	0.408	0.533	0.661	0.842	1.04	1.37	–	1.98
3 x 12	0.341	0.438	0.617	0.800	1.06	1.34	–	–
3 x 6	0.391	0.504	0.648	0.794	1.08	1.38	–	–
3 x 3	0.395	0.489	0.641	0.847	1.10	1.42	–	–

5) Cubes of mortar

Side length (mm)								
70						1.19	1.82	2.05
60		no motion			0.780	1.40	1.85	2.21
40				0.497	0.995	1.42	1.92	2.13
30				0.694	1.02	1.42	1.90	2.17
20			0.493	0.760	1.06	1.42	1.76	2.22
10		0.379	–	0.866	1.14	1.49	1.80	–

Surface velocity of the flow was measured by using small floats. Mean flow velocity, V_m, was measured with dye tracers. Depth, D, was calculated by water discharge, Q, over flume width, W, and mean flow velocity ($D=Q/(W \times V_m)$). Vertical distribution of flow velocity was measured by a pitot-tube. Characteristics of grains for tests are summarized in Table 2-2. Mean travel velocities of each grains were measured three times by stopwatches. Experimental results are summarized in Table 2-3.

2-2. Velocity of grains rolling along a smooth bed

Cubic and columnar particles slid along the bed under shallow flow conditions, and some small grains of low density saltated or suspended intermittently over the bed under deep and high flow conditions.

The larger the flow depth and flow velocity is, the higher is the velocity of grains rolling along a smooth bed. Under a flow which is deeper than the gain size, the larger the grain size is, the higher is the velocity of grains (Fig. 2-1). Grain velocity reaches its maximum value when grain size is equal to flow depth (Fig. 2-2).

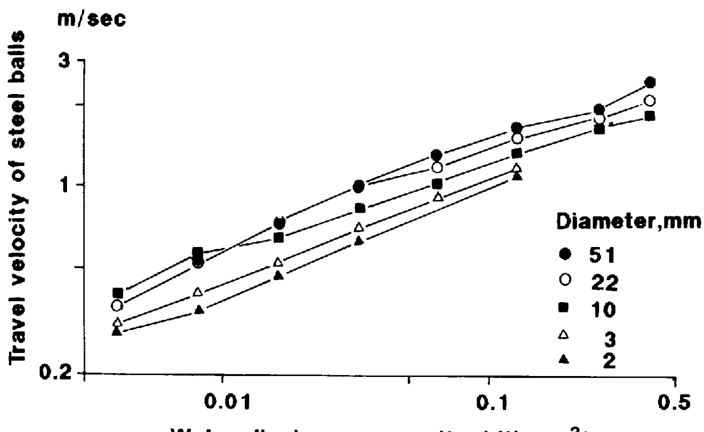


Fig. 2-1 The relation between travel velocities of steel balls to water discharge per unit width.

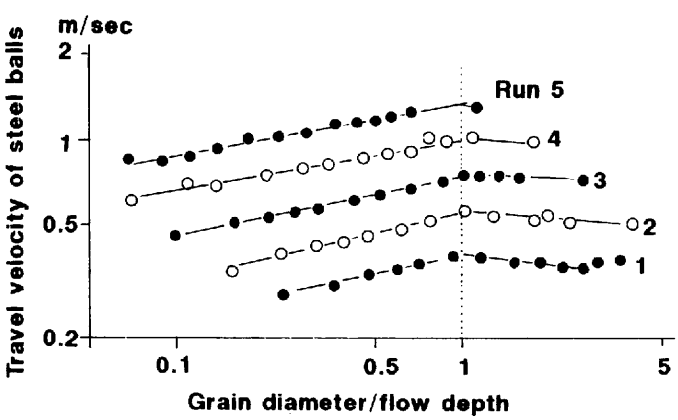


Fig. 2-2 The relation between travel velocities of steel balls to grain diameter: flow depth ratios.

The relationship between grain velocities and local flow velocities is shown in Fig. 2-3. Local flow velocities at top of each grain are obtained by vertical velocity distribution curves. When flow depth is larger than grain diameter, grain velocities are proportional to local fluid velocities. The ratio of grain velocity to water velocity is 0.8–0.9. Under these experimental conditions, density of grains has no remarkable effects on this ratio. It is reasonable to consider that V_c-V_p is nearly equal to the slip-velocity (V_{slip}) which is the relative velocity between grain and flow. Therefore, it is concluded that the slip velocity of grains rolling along a smooth bed is not equal to the terminal settling velocity of the grains in still water, but only governed by local flow velocity surrounding the grains.

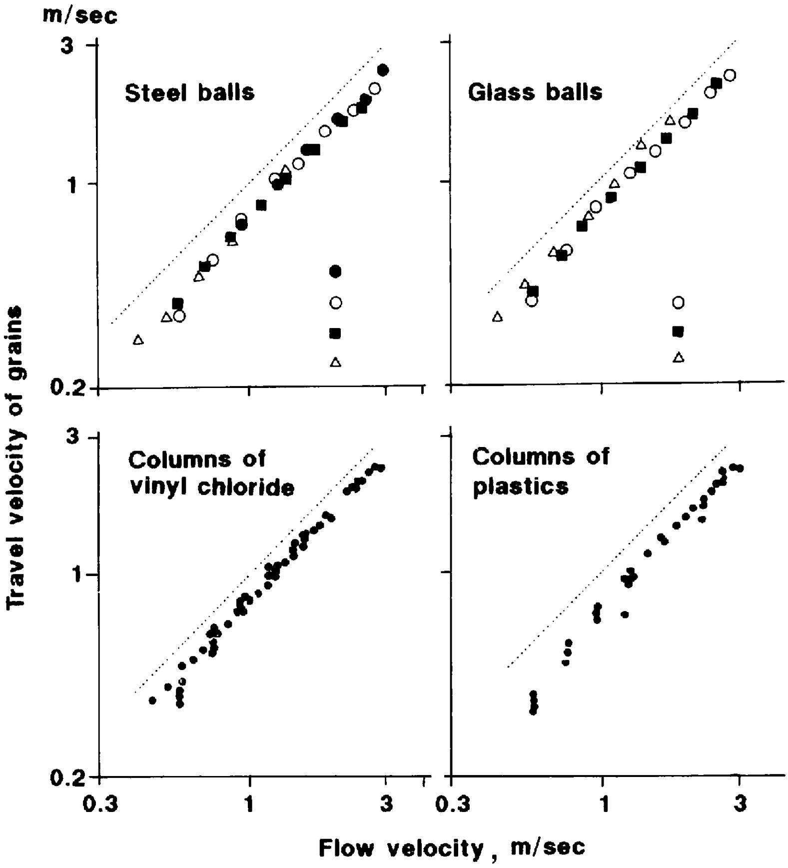


Fig. 2-3 The relation between grain velocity to the flow velocities at the top of each grain.

2-3. Slip-velocity caused by viscous shear force acting on rotating grains

Slip-velocity indicates the strength of resistant force acting on moving grains. Why is the slip-velocity not affected by grain size and density of grains, and why does the slip-velocity increase at greater flow depths or higher grain velocities? Resistant forces acting on grains in motion increase as grain velocity increases.

One resistance force acting on moving grains is the friction force between grain and bed. This friction force, however, does not increase as the grain velocity increases. On the contrary, friction force must decrease when Magnus effect imparts a lift force to rolling grains. Then we must take into account another resistant force to moving grains caused by rotation of grains in a viscous fluid.

Our experimental results show that the slip-velocity of grains rolling along a smooth bed must be determined by the viscous shear force acting on the rotating grains in a viscous fluid. The reason is as follows.

In a uniform flow, the driving force acting on a grain (F_d) is given as:

$$F_d \propto C_D \cdot \frac{1}{2} \cdot \rho \cdot V_{slip}^2 \cdot A_1 \qquad (2\text{-}1)$$

where C_d = the coefficient of drag, which is nearly constant when $R_e = 4 \times 10^2 - 3 \times 10^4$, ρ = density of fluid, V_{slip} = relative velocity between grain and fluid, and A_1 = cross sectional area of the grain.

Resistant force acting on a rotating grain in viscous fluid caused by fluid viscosity (F_f) is given as:

$$F_f \propto \tau \cdot A_2 = \mu \cdot \omega \cdot A_2 \qquad (2\text{-}2)$$

where τ = viscous shear stress, A_2 = surface area of grain, μ = viscosity of fluid, and ω = angular velocity of rotating grain. It is postulated that is proportional to the velocity gradient of flow adjacent the grain, that is dV/dY. And dV/dY is approximated as:

$$dV/dY = \tau_0 \left(1 - \frac{Y}{D}\right) / \mu \qquad (2\text{-}3)$$

where τ_0 = boundary shear stress, Y = height above the bed, D = flow depth. From eq. (2-2) and eq. (2-3), we obtain the following equation:

$$F_f = \tau_0 \left(1 - \frac{Y}{D}\right) \cdot A_2 \qquad (2\text{-}4)$$

If the slip-velocity is determined mainly by the viscous shear force acting on the rotating grain, then F_d approximately equals F_f. Then, slip-velocity can be expressed as:

$$V_{slip}^2 \propto \frac{\tau_0}{\rho} \left(1 - \frac{Y}{D}\right) \qquad (2\text{-}5)$$

Slope and density of fluid are constant in this experiment, therefore,

$$V_{slip}^2 \propto D \left(1 - \frac{Y}{D}\right) = D - Y \qquad (2\text{-}6)$$

This is true as shown in Fig. 2-4. Nakagawa *et al.* (1979) also stressed the role of viscous shear force acting on the rolling or rotating grains.

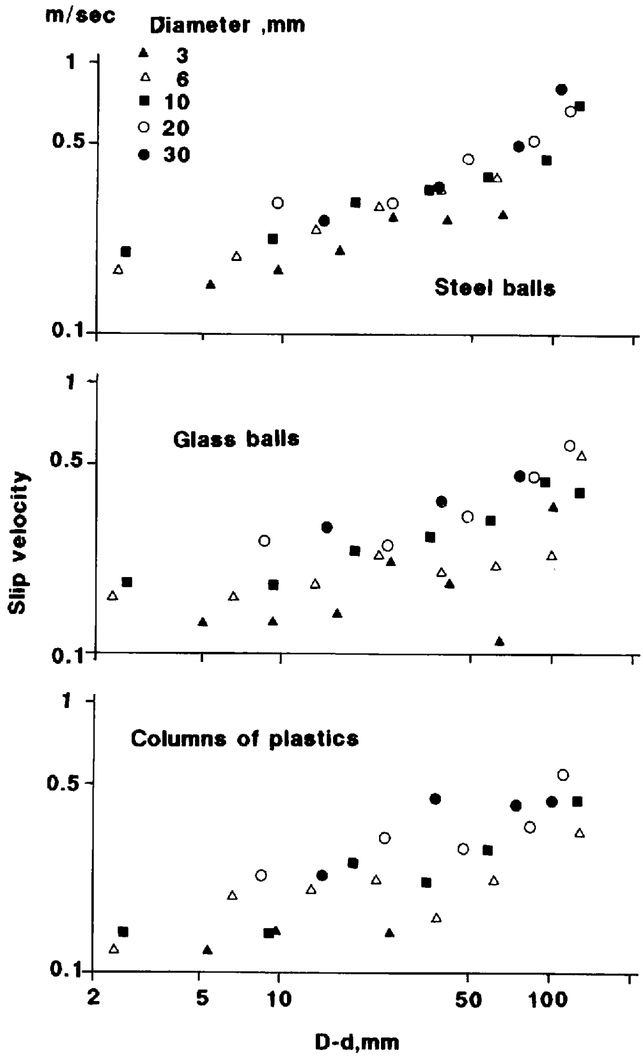


Fig. 2-4 The relation between slip velocity to the flow depth – grain diameter ($D-d$).

CHAPTER III

SUPERIOR MOBILITY OF MIXTURES OF COARSE AND FINE SAND

It has been shown that uniform coarse sand has less mobility than fine sand. The coarser the sand is, the higher is the power or shear force of the flow required for transporting the sediment. However, at some flow conditions, a mixture of coarse and fine sand is more mobile than the fine sand alone. We conducted flume experiments (Ikeda and Iseya, 1985) in order to confirm this fact that was first found by Gilbert (1914).

3-1. Experimental methods

Characteristics of coarse sand and fine sand used in this experiment are shown in Table 3-1. A small wooden flume, 10cm wide, 4 m long and 7 cm deep, has an adjustable tailgate at the downstream end that causes deposition of sediment (Figs. 3-1, 3-2). Water discharge was kept constant at 100 cc/sec for all runs. Two rotary-vane type sediment feeders were used for controlling the sediment feed rate into the flume. After equilibrium was established, water surface heights

Table 3-1 Characteristics of sands used in the experiment

	d_{16}	d_{50}	d_{84}	σ/ρ
fine sand	0.16	0.20	0.24	2.65
coarse sand	0.84	1.0	1.2	2.65

(sieve diameter, mm)

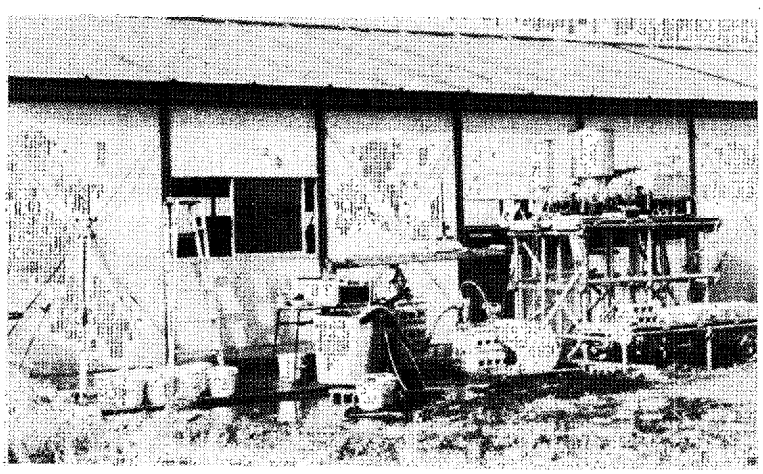


Fig. 3-1 Arrangement of devices used in the experiment.

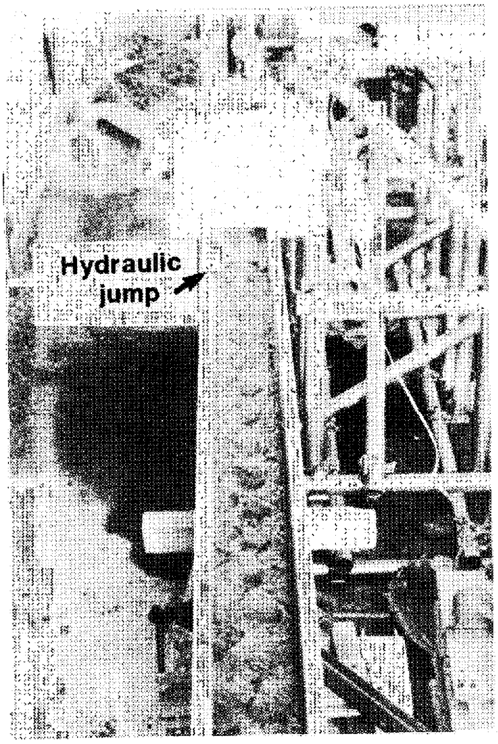


Fig. 3-2 Small wooden flume used in the experiment.

Table 3-2 Experimental results

Run No.	Dis-charge, cm^3/s	Tem-pera-ture, °C	Bedload feed rate, g/s			Bedload discharge rate, g/s			Water surface slope, %	Mean bedload velocity, cm/s	
			Total	Coarse sand	Fine sand	Total	Coarse sand	Fine sand		Coarse sand	Fine sand
1	92	20	1.3	0	1.3	1.1	0	1.1	2.9		2.0
2	102	20	2.8	0	2.8	2.6	0	2.6	4.3		0.6
3	100	19	5.0	0	5.0	4.0	0	4.0	5.2		3.0
4	100	–	9.4	0	9.4	8.9	0	8.9	7.6		11.8
6	100	20	1.4	1.4	0	1.7	1.7	0	4.3	2.9	
7	100	18	4.3	4.3	0	4.5	4.5	0	6.3	4.5	
8	100	–	6.5	6.5	0	6.1	6.1	0	7.1	6.7	
9	100	–	10.9	10.9	0	8.8	8.8	0	9.0	4.6	
10	100	19	8.1	2.1	6.0	7.8	2.8	5.0	6.5	17.1	5.4
11	100	–	8.0	3.7	4.3	7.6	4.3	3.3	6.3	10.6	2.6
12	100	–	8.1	4.6	3.5	7.5	4.5	3.0	6.1	5.7	1.6
14	100	18	8.1	5.8	2.3	7.1	5.1	2.0	6.4	20.0	3.0
15	100	19	8.3	6.8	1.5	7.3	6.0	1.3	7.0	8.7	1.3

were measured at every 25 cm along the flume in order to calculate the water surface slope. Mean bedload velocities were measured with using colored tracer grains (Table 3-2). This was done by feeding 1-2 g of tracer grains at the head of the flume, and collecting the sediment exiting the flume at ten-seconds intervals. The time required for discharge of fifty percent of the tracer grains was calculated.

3-2. Mobility of sand mixtures

Fig. 3-3 shows the relation between equilibrium slope or stream power of flow and bedload transport rate for uniform coarse sand and uniform fine sand respectively. It is clear that the coarse sand has less mobility than the fine sand. Under a given flow condition, transport rate of the fine sand is nearly 1.5 times that of the coarse sand.

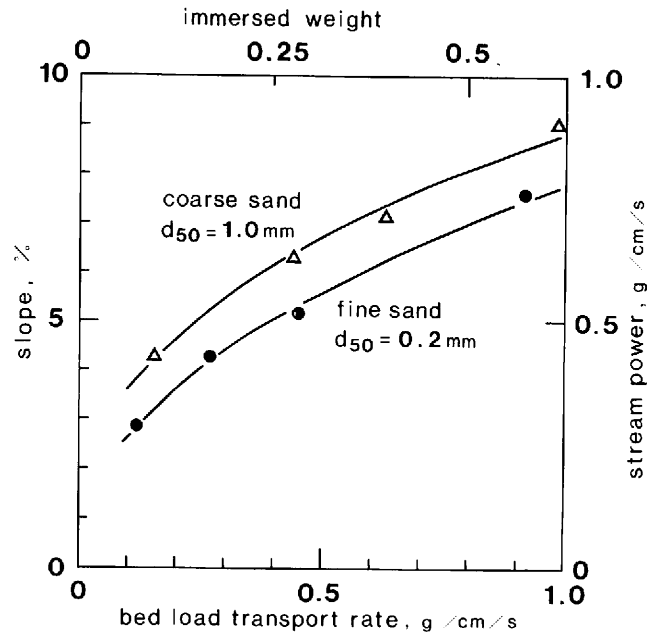


Fig. 3-3 The relation between slope or stream power of flow and bedload transport rates of the fine sand and the coarse sand

Fig. 3-4 shows how the proportions of coarse sand affect the mobility of mixtures. Total feed rate of coarse sand and fine sand is kept constant at 8 g/sec in these runs. Water discharge is fixed at 100 cc/sec. Therefore, equilibrium slope is proportional to stream power of the flow. That means slope is in inverse proportion to the mobility of mixture.

Fig. 3-4 shows that the mobility of the mixture is higher than that of uniform fine sand when the proportion of fine sand is larger than 20%. Because 7% of slope is required to transport 8 g/sec of fine sand under this hydraulic condition, but less than 7% of slope is for the same amount of mixtures. That means coarse sand in the mixture has, in appearance, higher mobility than the fine sand. When the proportion of coarse sand is larger than 50% in the mixture, stream power for transporting the mixture (solid line in Fig. 3-4) is smaller than that for transport only the coarse sand in the mixture (dashed line in Fig. 3-4). These facts indicate that mobility of coarse sand increases by mixing with fine sand.

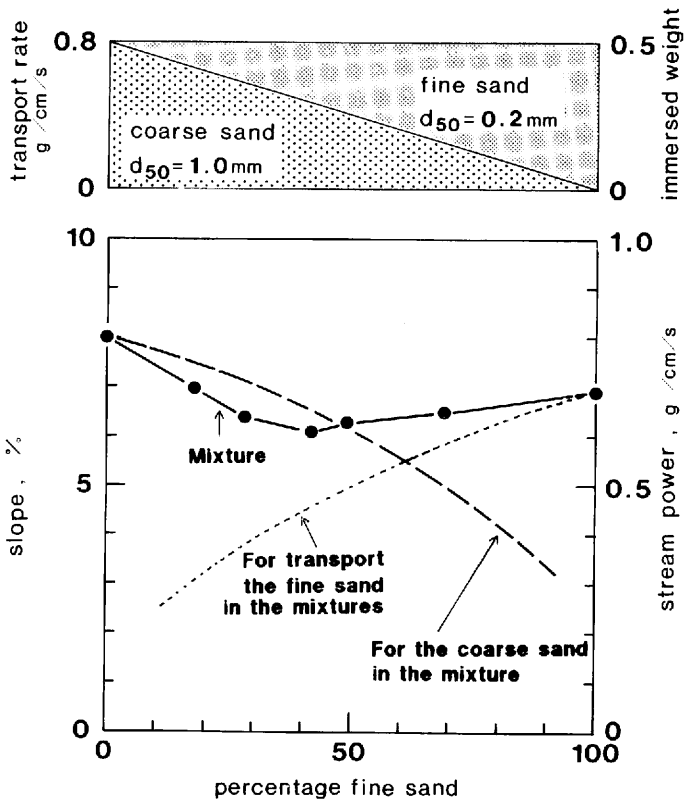


Fig. 3-4 Longitudinal slope or stream power of flow necessary for transporting a fixed amount of sediment mixtures as a function of fine sand content in the mixtures. Dashed line indicates the stream power for transporting coarse sand fractions in the mixtures. Dotted line is for the fine sand fractions.

3-3. Causes of superior mobility of mixtuers

Number of grains travelling per unit bed area (N) is expressed as:

$$N = \frac{W}{\sigma \cdot g \cdot \frac{\pi}{6} \cdot d^3}$$

$$W = \frac{i_b}{V_p}$$

here σ and ρ are density of grains and fluid, respectively, g is acceleration of gravity, d is grain size, i_b is bedload transport rate per unit width (immersed weight), and V_p is mean velocity of moving grains. The number of moving grains per unit bed area was calculated under the assumption that the sand grains were spheres (Table 3-3). Then one hundred coarse sand grains (1 mm in diameter) per square centimeter or 2500/cm^2 fine sand grains (0.2 mm in diameter) can be arranged as

Table 3-3 Number of grains in motions per square centimeter of the bed

Run No.	fine sand		coarse sand	
	W, g/s	N/cm^2	W, g/s	N/cm^2
10	0.064	9,200	0.009	10
11	0.091	13,000	0.023	27
12	0.125	18,000	0.050	58
14	0.045	6,500	0.017	20
15	0.069	9,900	0.056	65

W: weight of moving grains per square centimeter, calculated by unit transport rate/mean bedload velocity

N: number of moving grains per square centimeter

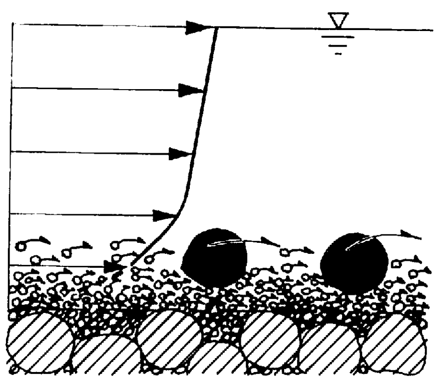


Fig. 3-5 Schematic representation of the moving bedload layer over a mixed bed of fine and coarse sand.

square pattern in a single layer. Therefore, coarse sand grains are not traveling contact with each other, but the fine sand grains are saltating in a moving bedload layer like a "cloud" (Fig. 3-5). Visual inspections of the moving bedload layer confirmed our calculations.

In this experimental condition, the mobility of a mixture reaches its maximum when the ratio of coarse sand and fine sand fed into the flume is 60:40 (Fig. 3-2). Mean travel velocity of coarse sand grains is several times that of fine sand grains (Table 3-2), when the ratio of the number of coarse and fine sand grains on the bed surface is approximately 1:3.

Fig. 3-6 illustrates diagrammatically how the mode of transport of coarse sand grains changes with mixing ratios:

1) As fine sand is added, fine sand grains fill the interstices of coarse sand beds. Therefore, the roughness of the bed surface decreases and resistance to move coarse sand grains decreases. We called this effect "smoothing".

2) Moving coarse sand grains protrude from the bed surface when it is smooth. Accordingly they are exposed to the higher velocity zone of the flow and extract more momentum from the flow. We called the effect "exposure".

3) The velocities of coarse sand grains moving on the smooth bed are always higher than those of fine sand grains. Therefore the fine grains at rest or in motion are certainly pushed by collision with moving coarse grains. We called this effect "collision". This effect must be why the mobility of a mixture becomes larger than that of uniform fine sand.

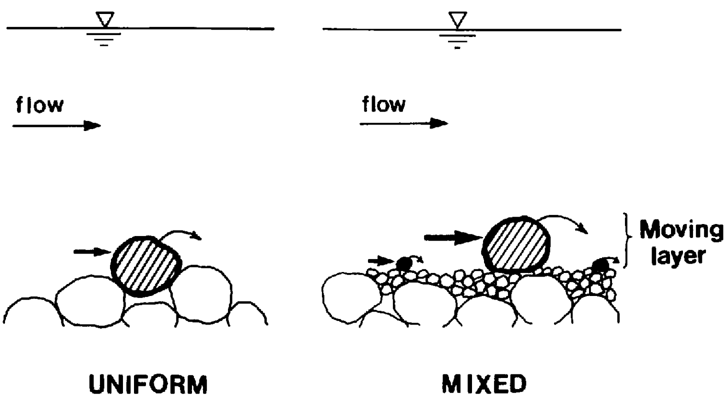


Fig. 3-6 Schematic diagram showing the effect of fine grains in mixtures.

CHAPTER IV

ABRUPT CHANGES IN THE MOBILITY OF SAND-GRAVEL MIXURES

In this experiment, two kinds of sediment, that is sand and granule sized gravel, were chosen (Table 4-1) so that the mobility of each size differed considerably (Fig. 4-1). Stream power for transporting the same amount of the gravel is nearly twice that for the sand. As a result of this experiment, a threshold in the mobility of mixtures was found. We reported these results in 1985 at the First International Geomorphological Congress held at Manchester (Ikeda and Iseya, 1987).

Table 4-1 Characteristic of sand and gravel

	d_{16} (mm)	d_{35} (mm)	d_{50} (mm)	d_{84} (mm)	d_m(mm)	$\sqrt{d_{84}/d_{16}}$	σ/ρ
SAND	0.24	0.33	0.37	0.45	0.35	1.4	2.7
GRAVEL	2.1	2.4	2.6	3.2	2.7	1.3	2.6

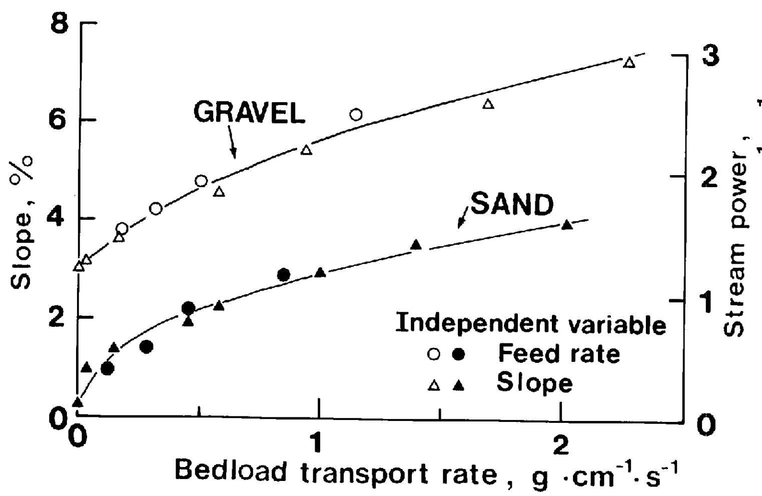


Fig. 4-1 The relations between bedload transport rate and longitudinal slope or stream power.

Table 4-2 Experimental results

Case	Run no.	Flume width	Dis-charge	Tem-pera-ture	Bedload transport rate g·s⁻¹						Water surface slope	Depth	Water surface velocity	Mean bedload velocity cm/sec			Bed state	Motion of gravel
					Feed rate			Discharge rate										
		cm	cm^3s^{-1}	°C	Total	Gravel	Sand	Total	Gravel	Sand	%	cm	$cm \cdot s^{-1}$	Gravel (a)	Gravel (b)	Sand (a)		
1	G	10	400	–	0	0	0	0	0	0	3.0	1.2	–				BM	
	C–10			–	1.7	1.7	0	0.9	0.9	0	3.8	1.0	54	0.7	0.6		A	C
	C–9			14	3.1	3.1	0	2.3	2.3	0	4.2	0.9	57	0.8	0.7		A	C
	C–8			–	5.0	5.0	0	4.3	4.3	0	4.8	1.0	59	1.3	1.1		A	C
	A–1			14	11.4	11.4	0	11.0	11.0	0	6.4	1.0	65	4.2	2.7		P~T	C
	A–2			14	16.0	11.4	4.6	13.2	10.6	2.6	5.5	0.8	61	2.1	1.7	0.9	A	C
	A–3			15	21.0	12.4	8.6	16.8	9.4	7.4	5.2	–	61	3.7	3.8	2.2	A~T	C~J
	A–4			–	23.5	11.4	12.1	15.7	10.2	5.5	4.5	0.8	67	11.1	5.4	2.4	T	J
2	S			–	0	0	0	0	0	0	0.25	1.6	–				BM	
	C–12			–	1.2	0	1.2	–	0	0	1.0	1.1	42			1	T*	
	C–11			–	2.8	0	2.8	2.2	0	2.2	1.4	1.0	–			1.0	T*	
	C–1			15	4.6	0	4.6	4.2	0	4.2	2.2	0.9	55	28		11	T*	
	B–1			–	8.5	0	8.5	8.1	0	8.1	2.9	0.8	–	32		19	P	
	B–2			–	11.0	1.6	9.4	9.7	1.6	8.1	2.9	0.8	63	30		19	P	S
	A–7			–	12.9	4.4	8.5	12.6	4.4	8.2	3.2	0.9	63	30		18	P	S
	A–8			14	14.9	6.4	8.5	12.6	5.1	7.5	3.1	0.9	63	26		21	P	S
	B–5			–	16.2	7.8	8.4	15.5	7.6	7.9	3.4	0.8	65	10	10.0	10.0	P	S
	B–4			–	18.5	10.0	8.5	16.6	9.4	7.2	4.6	0.8	57	3.3	3.1	2.0	T	J
	A–4			15	21.0	12.4	8.6	16.8	9.4	7.4	5.2	–	61	3.7	3.8	2.0	T~A	J~C
	B–6			–	23.5	15.1	8.4	13.4	10.3	3.1	6.0	0.8	–	2.0	1.8	0.9	A	C
3	C–8			–	5.0	5.0	0	4.3	4.3	0	4.8	1.0	59	1.3	1.1		A	C
	C–6			–	5.0	4.0	1.0	8.2	6.2	2.0	4.3	1.1	51	1.6	1.2	1.0	A	C
	C–5			15	5.4	3.8	1.6	4.9	3.4	1.5	3.3	1.0	51	2.4	1.3	0.7	A	C
	C–7			15	5.1	3.0	2.1	3.3	2.1	1.2	2.9	1.1	50	1.3	0.9	0.5	A	C
	C–4			–	4.5	2.7	1.8	2.4	1.5	0.9	2.5	1.1	48	1.5	1.4	0.9	A	C~J
	C–3			14	5.0	2.3	2.7	4.6	1.9	2.7	1.9	0.9	56	2.8	4.6	0.6	T	J
	C–2			–	5.1	1.7	3.4	5.1	1.8	3.3	2.1	1.0	56	8.0	8.7	4.4	T	J~S
	C–1			15	4.6	0	4.6	4.2	0	4.2	2.2	0.9	55	28		11	T*	

a) Calculated from the required time at peak of discharge of tracer grains
b) Calculated from the required time for discharge of 50% of tracer grains
c) BM: Initiation of motion, P: Flat bed, T: Transition, T*: Trains of standing waves, A: Antidunes
d) S: Smooth, J: Partially congested, C: Congested

4-1. Experimental methods

A sediment-feed flume, 4 m long, 0.1 m wide and 7 cm deep, was ued in this study. Granule-sized gravel and well sorted medium grained sand (Table 4-1) were fed into the upstream end of the flume by using vertical rotary vane feeders, which could deliver sediments at a given rate.

Water discharge was kept constant at about 400 cc/sec for all runs. After the feed rates of sand and gravel were controlled, water and sediment were introduced into the flume. After equilibrium was established, flow depth, water surface slope, and velocities of moving grains were measured. Experimental procedures of these runs are the same as those for the experiment in Chapter 3. Conditions and results of the experiment are shown in Table 4-2.

4-2. Bed states: smooth, transitional and congested

Two distinct bed states–smooth and congested–were observed when mixtures of sand and gravel were transported (Fig. 4-2). If the proportion of gravel was small, gravel grains travelled smoothly at a high speed on the plane bed surface, which was mainly composed of sand (Figs. 4-2 and 4-3). Number of moving gravel grains on the smooth bed surface increased with increasing proportions of gravel in the feed. A gravel jam occurred by chance in part of the bed (Figs. 4-2 and 4-3). The area of gravel jams expanded as the proportions of gravel increased, until the congested state appeared all over the bed (Figs. 4-2c and 4-3c, d).

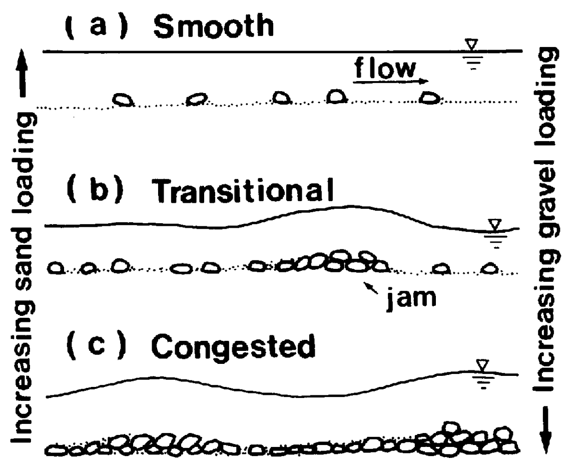


Fig. 4-2 Schematic illustration of the moving layer showing three different bed states.

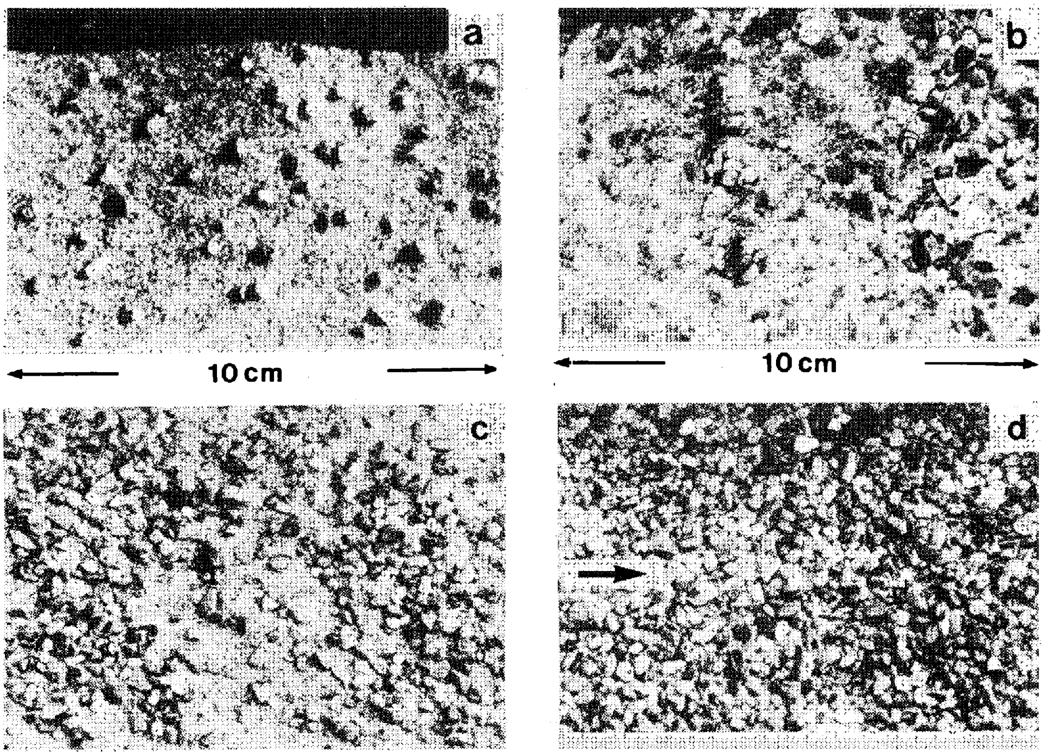


Fig. 4-3 Plan view of bed states.
a: smooth (Run C-2), b: transitional (Run C-4), c,d: congested (Run C-6)

Fig. 4-4 shows that channel slope increased with increasing feed rate of gravel (dashed line in Fig. 4-4b). When sand was added into the flume, keeping the feed rate of gravel constant, channel shope decreased with increasing feed rate of sand (solid line in Fig. 4-4b), whereas the total load increased. Similar to the results shown in Chapter 3, increasing the proportion of fines decreased the mobility of the mixture by smoothing and exposure.

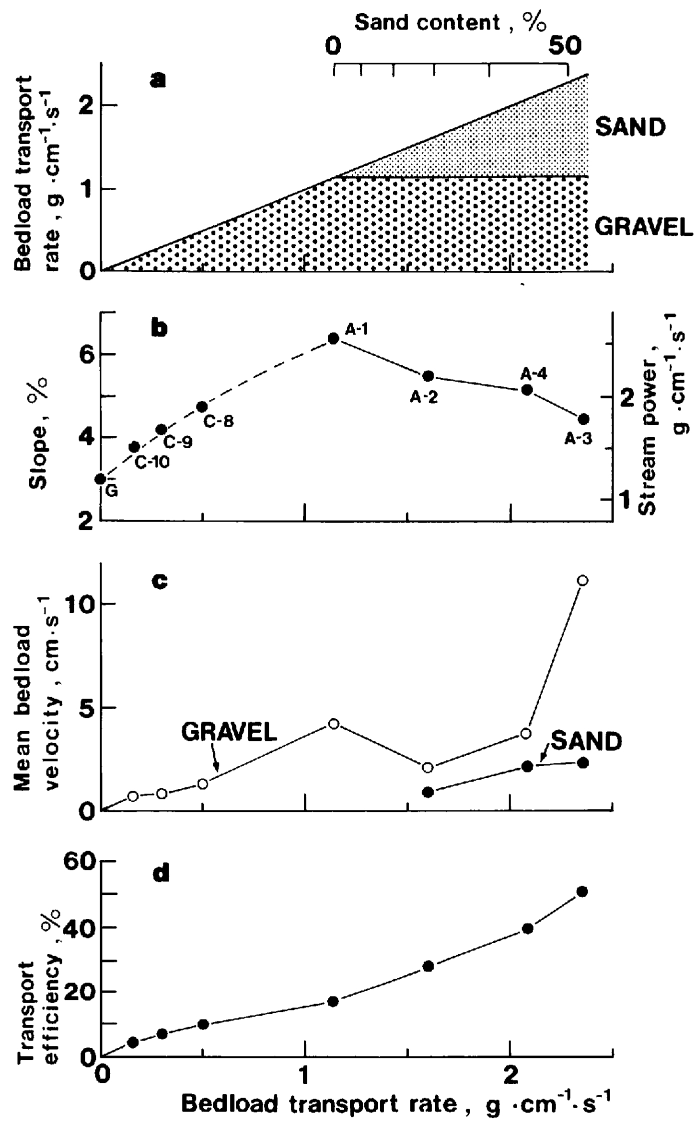


Fig. 4-4 Influence of sand on the transport of mixed sediment.

4-3. Effect of the sand: gravel ratio on mobility of sediment mixtures

Fig. 4-5 shows the influence of sand: gravel ratio on the mobility of mixtures. When the gravel content is less than 50%, the bed state is smooth or transitional and the velocities of the gravel particles moving on the smooth sand surface are fairly high. Channel slopes required to transport the mixed load (solid line in Fig. 4-5b) are nearly equal to those required to transport only the sand in the mixture (broken line in Fig. 4-5b). This indicates that gravel grains in the mixture have little effect on the mobility of mixtures.

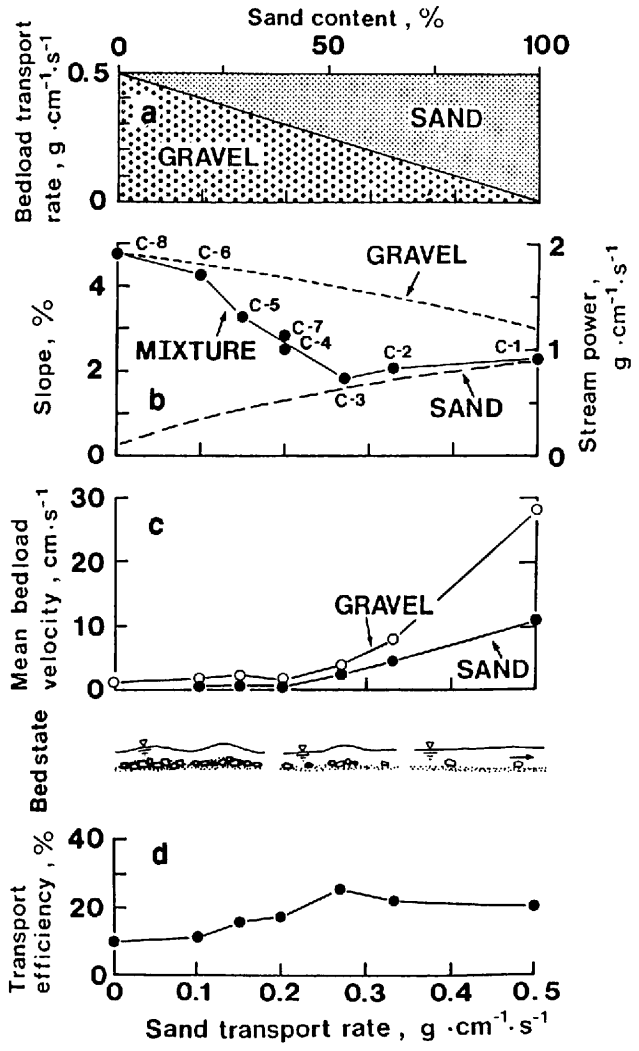


Fig. 4-5 Influence of sand: gravel ratio on the transport of mixed sediment.

4-4. Abrupt changes in the mobility of mixtures

As shown in Fig. 4-5c, when the proportion of gravel is more than 50%, gravel jams occur and the mobility of gravel particles becomes remarkably slow. The channel slope which is necessary to transport the entire mixture approaches that of gravel in the mixture.

The influence of gravel on the transportation of mixed sediment is more clearly shown in Fig. 4-6. When the proportion of gravel is less than 50%, the bed state is smooth and the channel slope to transport the mixture (sold line in Fig. 4-6b) is slightly smaller than the slope necessary to

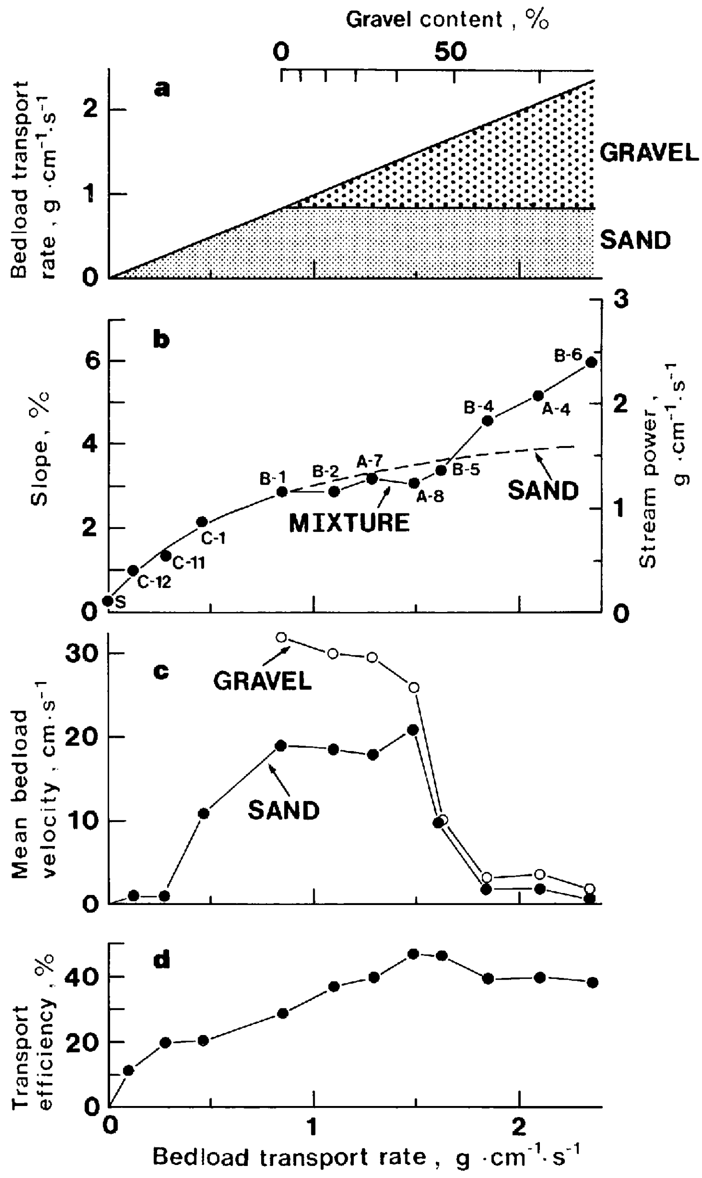


Fig. 4-6 Influence of gravel on the transport of mixed sediment.

transport the same amount of load which is composed only of sand (broken line in Fig. 4-6b). That indicates that the mobility of gravel grains in the mixture was higher than that of sand grains. When the mixture ratio of gravel is more than 50%, however, the bed state changes from smooth to congested, and the channel slope suddenly increases. Grains of sand and gravel in motion reduce their velocities to about one tenth (Fig. 4-6c).

These experimental results indicate that the mobility of the mixture is controlled by sand where the bed state is smooth and by gravel where the bed state is congested.

CHAPTER V

EFFECT OF COARSE SAND: FINE SAND RATIO ON TRANSPORT OF SAND MIXTURES: A RECIRCULATING FLUME STUDY USING FINE AND COARSE SAND MIXTURES

In this study, the effect of coarse sand on the transport of fine and coarse sand mixtures was investigated in a recirculating flume (Fig. 5-1), 9 m long, 30 cm wide and 30 cm deep (Takashima *et al.*, 1986). Two sizes of material were used in this study (Table 5-1). Water discharge, water surface slope, and thus stream power were kept constant for all runs, and only the proportion of coarse sand was varied. Bed state was observed, and mean flow depth, suspended load and total load were measured at equilibrium (Tables 5-2, 5-3).

Table 5-1 Grain size composition of sand A and sand B

	d_{16}	d_{50}	d_{84}	Standard deviation
Sand A	0.71	0.54	0.41	0.15
Sand B	0.25	0.22	0.14	0.06

(Sieve diameter, mm)

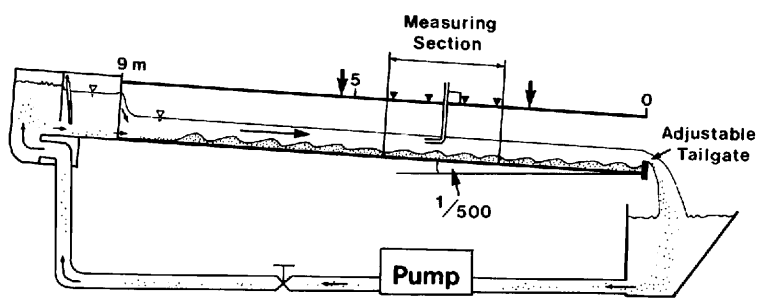


Fig. 5-1 Schematic diagram showing the recirculating flume use in the study.

5-1. Changes in bed state caused by variation in the coarse sand fraction

Fig. 5-2 to Fig. 5-5 show changes in bed state with increasing proportions of coarse sand. The higher was the proportion of coarse sand, the longer was the ripple wave length (L_r). When the coarse sand fraction reached 40%, ripple height (H_r) decreased, flow depth (D) decreased and mean flow velocity (V_m) increased (Fig. 5-6). We call the proportion of coarse sand when the bed states and flow conditions were changed abruptly as "the critical mixture ratio". This abrupt changes in the bed state may result from the effect of shielding (Einstein, 1950), that is, coarse sand grains covered the entire bed surface and the fine sand grains were shielded under the moving coarse sand.

Table 5-2 Conditions and results of experiment

Case No.	1	2	3	4	5	6	7	8
Water discharge, ℓ/sec	8.3	8.2	8.5	8.3	8.4	8.3	8.3	8.4
Water temperature, °C	18	23	19	19	16	15	14	14
Mean flow depth, cm	6.8	7.0	6.7	6.9	6.0	5.2	5.2	5.5
Mean flow velocity, cm/sec	41	39	42	40	47	53	53	51
Manning's roughness coef.	0.014	0.015	0.014	0.015	0.012	0.010	0.010	0.010
Ripple length, L_r, cm	15.3	18.4	21.5	28.4	29.6	–	35.8	20.8
Standard deviation of L_r, cm	3.5	6.0	8.5	8.2	14.6	–	21.1	8.7
Ripple height, H_r, cm	1.4	0.9	0.8	1.0	0.5	–	0.7	0.5
Standard deviation of H_r, cm	0.6	0.5	0.3	0.3	0.2	–	0.4	0.3
Ripple migration rate, cm/min	5.8	2.1	5.9	–	6.8	–	–	9.1
Sieve size of bed material, mm								
d_{50}	0.23	0.23	0.38	0.41	0.44	0.44	0.57	0.62
d_{16}	0.33	0.47	0.71	0.71	0.71	0.66	0.76	0.76
d_{84}	0.16	0.16	0.19	0.19	0.22	0.20	0.38	0.44
Standard deviation	0.09	0.16	0.26	0.26	0.25	0.23	0.19	0.16
Composition of bed material (sieve diameter), %								
Very coarse sand	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.2
Coarse sand	0.0	14.8	38.8	38.6	41.3	37.6	64.4	63.9
Medium sand	40.4	27.3	27.4	29.2	31.7	33.6	27.9	29.1
Fine sand	52.7	53.0	30.5	28.7	25.2	26.5	7.0	1.8
Very fine sand	6.9	4.9	3.2	3.5	1.7	2.3	0.6	0.0
Fall diameter of bed material, mm								
d_{50}	0.22	0.27	0.31	0.38	0.44	0.44	0.54	0.57
d_{16}	0.27	0.44	0.54	0.57	0.62	0.54	0.66	0.66
d_{84}	0.19	0.20	0.23	0.23	0.25	0.22	0.35	0.44
Standard deviation	0.04	0.12	0.16	0.17	0.19	0.16	0.16	0.11
Composition of bed material (fall diameter), %								
Very coarse sand	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Coarse sand	0.0	12.9	25.4	35.7	39.6	24.2	59.8	68.3
Medium sand	27.5	42.1	47.3	44.5	45.4	46.3	36.2	30.9
Fine sand	71.6	39.3	26.6	19.4	14.4	28.1	3.7	0.6
Very fine sand	0.9	5.7	0.7	0.4	0.6	1.4	0.3	0.2

(Flume width: 30 cm; Slope: 0.002 for all cases)

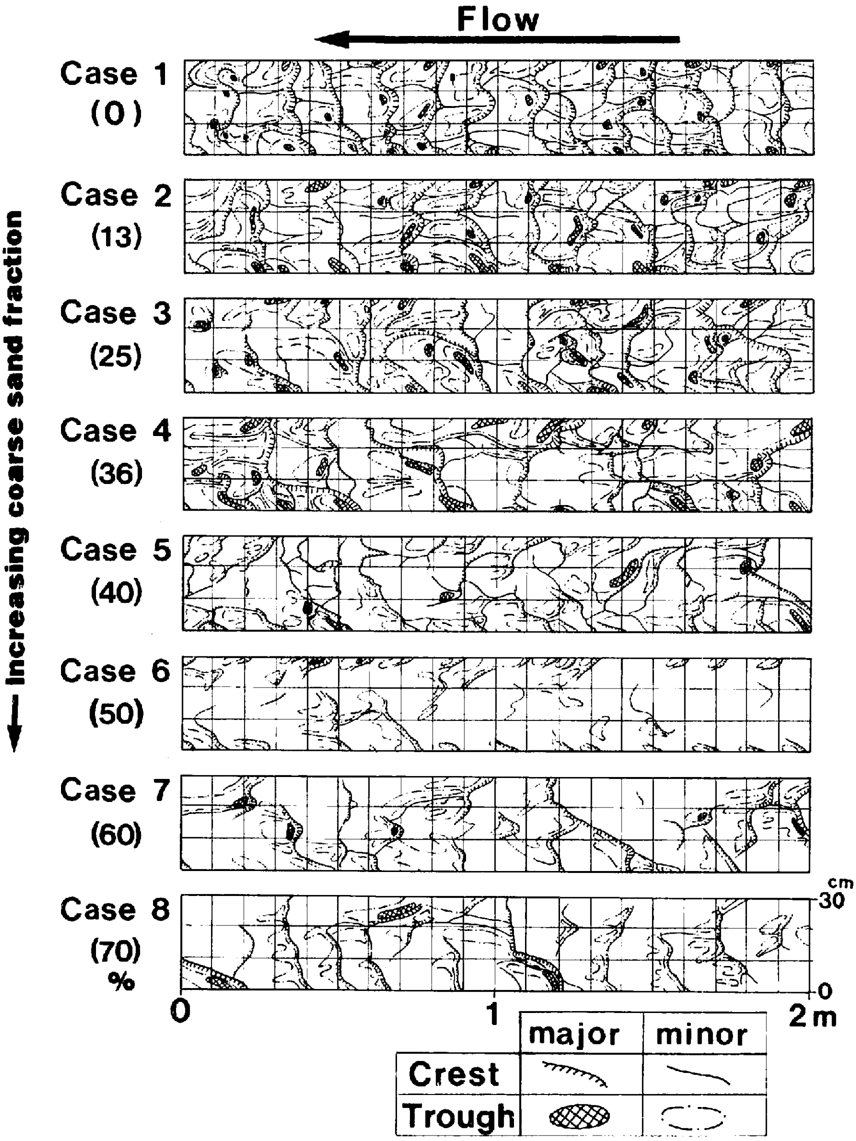
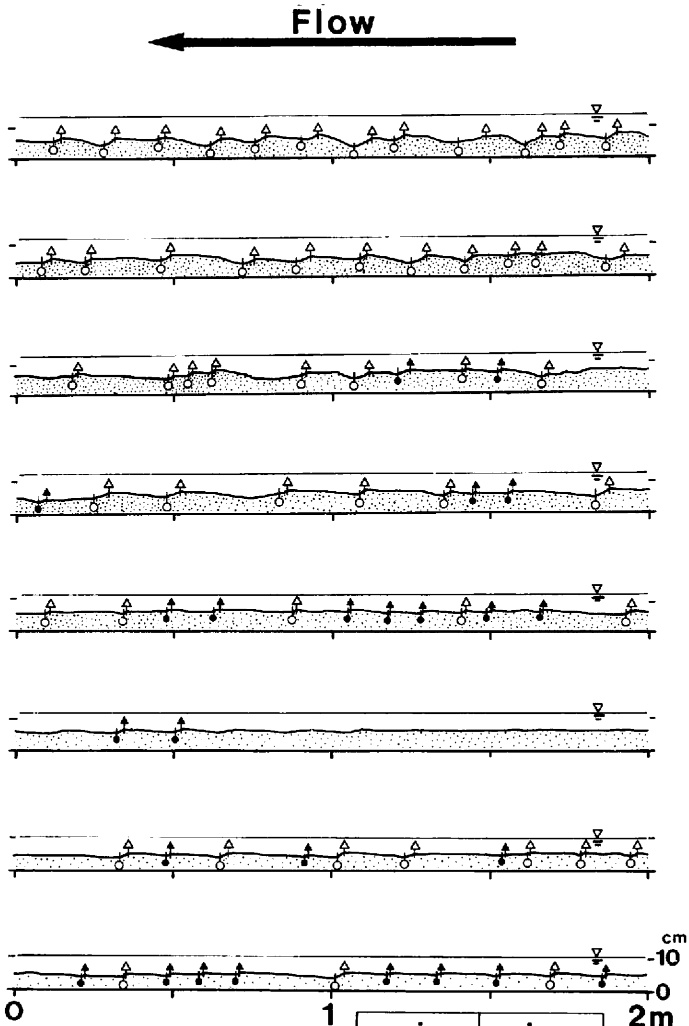


Fig. 5-2 Changes in ripple pattern with increasing coarse sand fraction.



	major	minor
Crest	△	▲
Trough	○	●

Fig. 5-3 Changes in bed profiles with increasing coarse sand fraction.

Table 5-3 Concentration of suspended and total load and their grain size composition

Case		Concentration, ppm	Content, % (fall diameter)			
			Coarse sand	Medium sand	Fine sand	Very fine sand
1	H	271	0.0	4.4	86.8	8.8
	M	686	0.0	6.3	89.0	4.7
	L	855	0.0	3.8	91.3	4.9
	T	1340	0.0	11.5	84.9	3.6
2	H	47	0.0	1.2	84.0	14.0
	M	154	0.0	2.2	91.6	6.2
	L	493	1.7	13.9	80.1	4.3
	T	514	11.3	39.6	46.8	2.3
3	H	30	0.0	3.1	91.6	5.3
	M	99	0.0	2.7	90.1	7.2
	L	397	5.2	16.4	75.1	3.3
	T	201	5.2	23.4	67.0	4.4
4	H	61	0.0	3.6	86.0	10.4
	M	81	0.0	2.7	82.4	14.9
	L	314	0.0	7.0	86.8	6.2
	T	181	2.4	7.9	83.4	6.3
5	H	53	0.0	4.3	59.1	36.6
	M	100	0.0	1.2	73.2	25.6
	L	442	0.7	5.9	82.8	10.6
	T	433	25.3	38.1	31.9	4.7
6	H	37	0.0	2.2	82.9	14.9
	M	115	0.0	1.0	72.6	26.4
	L	317	0.0	1.4	53.4	44.3
	T	1560	31.7	45.5	21.4	1.4
7	H	17	0.0	3.0	85.0	12.0
	M	61	0.0	6.4	81.8	11.8
	L	183	1.6	11.4	78.5	8.5
	T	2438	56.6	40.1	3.3	0.0
8	H	2	–	–	–	–
	M	7	–	–	–	–
	L	22	8.9	55.5	33.4	2.2
	T	1585	46.4	36.7	4.2	12.7

Suspended sediment samples were taken at 0.8D (H), 0.5D (M) and 0.2D (L).
T is the total load.

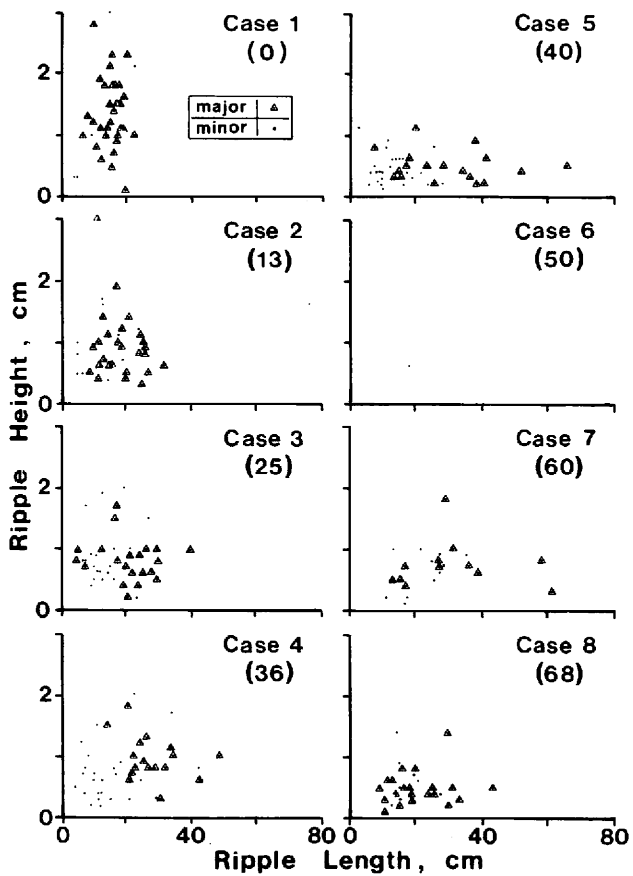


Fig. 5-4 Ripple length and height as a function of coarse sand fraction.

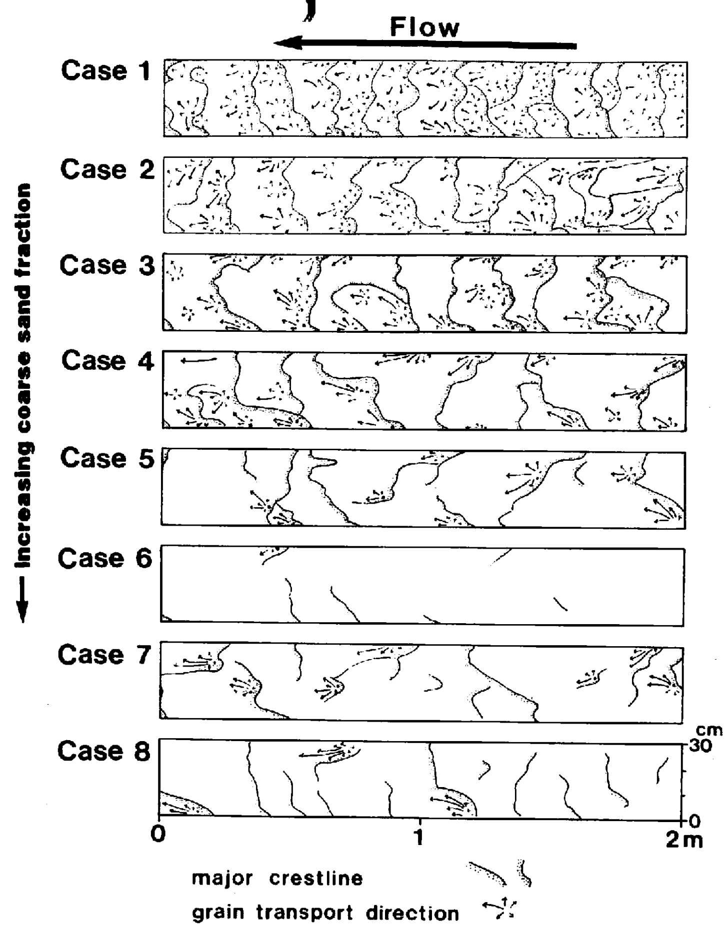


Fig. 5-5 Sketches showing sediment transport pattern on ripple bed.

5-2. Decrease of suspended load caused by mixing of coarse sand fraction

Suspended sediment concentration at each height above the bed decreased as the coarse sand fraction increased under constant stream power (Fig. 5-7). Therefore, coarse sand fraction prevented suspension of sediment, which was mostly fine sand, by shielding finer more suspendible sediment. Although increasing the coarse sand fraction to 13% caused no remarkable change in bed state (Fig. 5-6), the suspended load was reduced by half (Fig. 5-7).

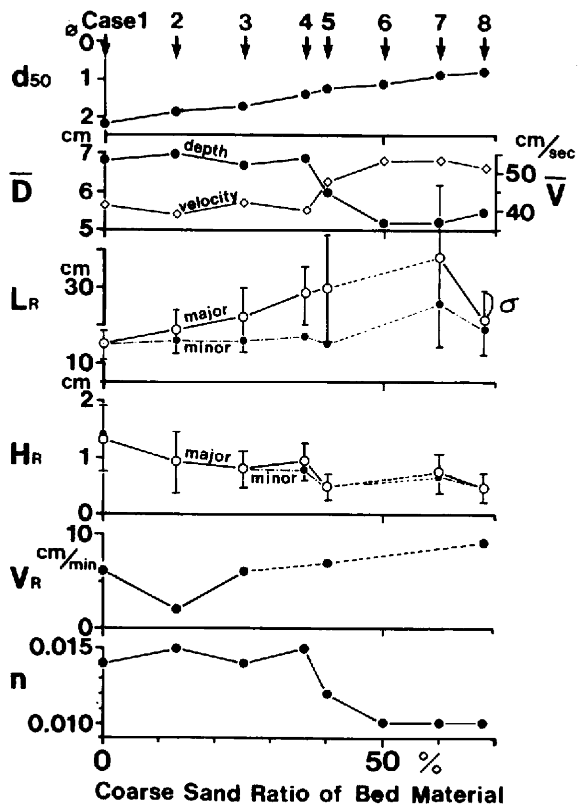


Fig. 5-6 Abrupt changes in bed state and flow conditions at the critical mixture ratio of coarse sand. d_{50}: median grain size of bed material, D: flow depth, V: mean flow velocity, L_r: wave length of ripples, H_r: wave height of ripples, V_r: migration velocity of ripples, n: Manning's roughness coefficient

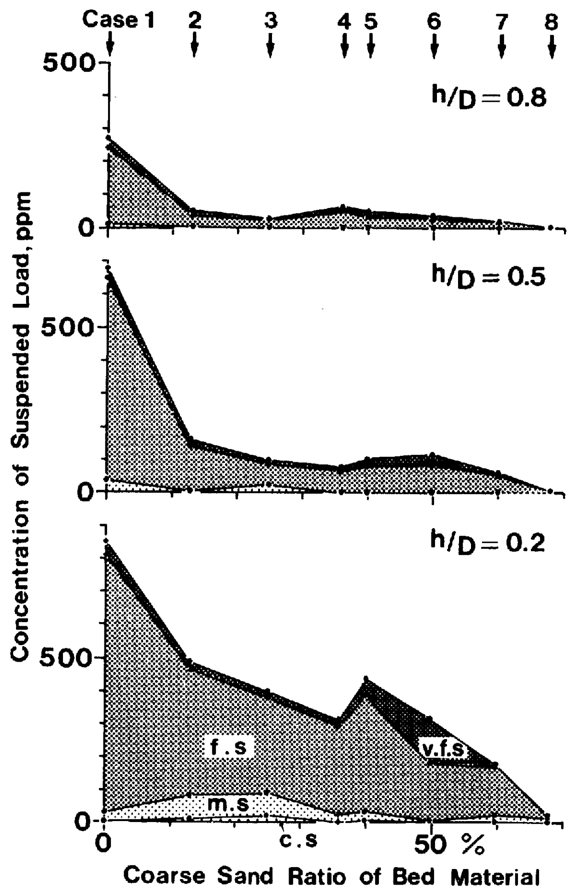


Fig. 5-7 Suspended sediment concentration and grain size composition as functions of coarse sand fraction of bed material. (*h*: height above the bed, *D*: flow depth, c.s: coarse sand (0.5-1 mm), m.s: medium sand (0.25-0.5 mm), f.s: fine sand (0.125-0.25 mm), v.f.s: very fine sand (0.063-0.125 mm)

5-3. Abrupt changes in the transport mode from suspension to traction with increasing coarse sand fraction in the bed material

Fig. 5-8 shows changes in concentration and grain size composition of bed material. Total load increased abruptly as the coarse sand fraction of the bed material exceeded the critical mixture ratio, that is 40% in this case. This rapid increase of total load was caused by an abrupt increase in traction load as the transport mode changed from suspension to traction. When the traction mode predominated, total load was composed mainly of coarse and medium sand.

Why did the traction load increase sharply as the critical mixture ratio was exceeded? The main reason was that more stream power became available for bedload transport when the bed state changed to plane bed and energy dissipation by the roughness decreased.

This experiment indicates how important the precise estimation or evaluation of effective shear stress or available stream power for bedload transport is.

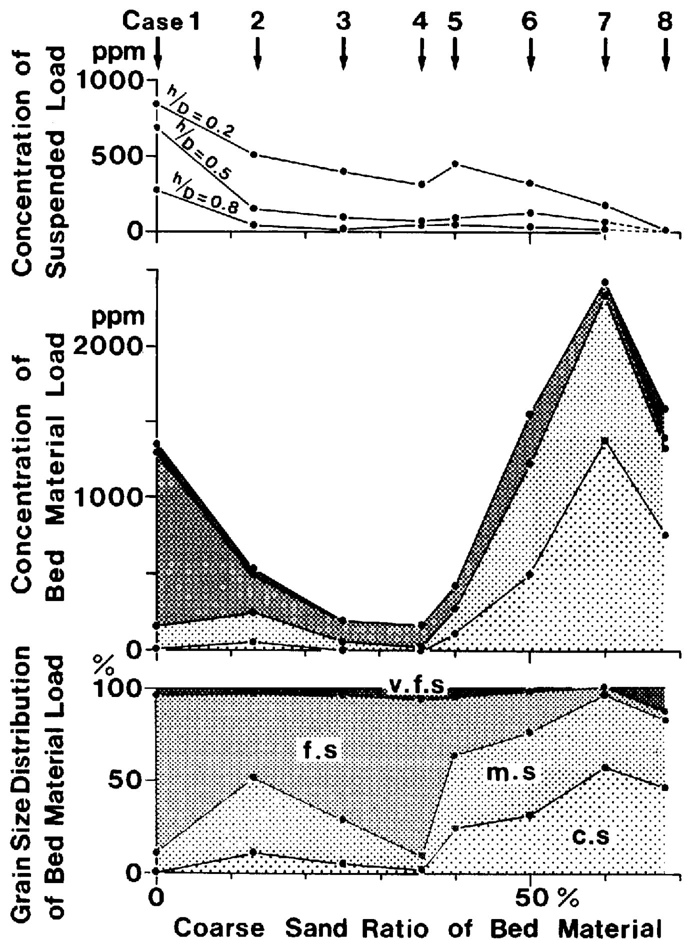


Fig. 5-8 Total load and its grain size composition as a function of coarse sand fraction of bed material under a flow of constant stream power. Legends are the same in Fig. 5-7.

CHAPTER VI

EFFECT OF SAND: GRAVEL RATIO ON BED STATES AND SEDIMENTARY STRUCTURES: A LARGE FLUME STUDY USING SAND AND GRAVEL MIXTURES

6-1. Experimental methods

The flume used for this study was a large steel flume 4 m wide, 2 m deep and 160 m long, at the Environmental Research Center in the University of Tsukuba. The maximum water discharge is 1.5 cumecs. This flume was selected to carry out experiments under conditions close to those involving actual bedforms in natural rivers. The flume can be operated with either a sediment recirculating or a feed system.

In the feed system, sediment that has deposited in the settling tank at the end of the flume is recovered, weighed, and transported to the sieving and mixing equipment by conveyor belts. Sediment can be sorted into three sizes and fed into the flume inlet at any desired size ratio. Two sizes of material were used in this study (Table 6-1). Water discharge and sediment feed rate were kept constant at about 860 ℓ/sec and 0.83 kg/sec respectively for all runs, and only the sand: gravel ratio were changed progressively (Table 6-2).

Table 6-1 Sediment characteristics

	d_{50}	d_{84}	d_{16}	σ/ρ
Gravel	6.4	8.5	4.8	2.7
Sand	0.45	1.8	0.25	2.7

(Sieve diameter, mm)

Table 6-2 Conditions and results of an experiment in the large flume

Run No.	1	2	3	4	5	6	7	8	9
Water discharge, m^3/sec	0.89	0.88	0.86	0.83	0.86	0.88	0.85	0.85	0.85
Water temperature, °C	14.5	13.5	11.6	10.0	11.0	15.0	16.5	16.9	18.0
Feed rate of gravel, kg/sec	0.45	0.56	0.36	0.63	0.17	0.99	0.0	0.19	0.82
Transport rate of gravel, kg/sec	0.38	0.48	0.37	0.53	0.22	0.69	0.0	0.07	0.58
Feed rate of sand, kg/sec	0.39	0.28	0.55	0.18	0.54	0.0	0.67	0.68	0.07
Transport rate of sand, kg/sec	0.28	0.18	0.27	0.13	0.53	0.0	0.31	0.29	0.02
Total feed rate, kg/sec	0.84	0.84	0.91	0.80	0.71	0.99	0.67	0.87	0.89
Total transport rate, kg/sec	0.66	0.66	0.64	0.65	0.74	0.69	0.31	0.35	0.60
Bed surface slope, %	0.33	0.37	0.21	0.36	0.38	0.52	-	0.21	0.46
Water surface slope, %	0.34	0.37	0.22	0.33	0.29	0.54	0.21	0.21	0.46
Mean depth, m	0.23	0.23	0.24	0.22	0.26	0.22	0.27	0.25	0.21
Surface flow velocity, m/sec	1.28	1.32	1.20	1.36	1.14	1.54	0.95	1.07	1.44

(Flume width: 4 m)

6-2. Abrupt changes in the mobility of sand and gravel mixtures

Fig. 6-1 shows the equilibrium slope capable of transporting all of the sediment supplied. The equilibrium slope is inversely proportional to the mobility of mixtures because the water discharge was kept constant for all runs. The greater is the mobility of sediment, the smaller is the equilibrium slope.

Slopes required to transport a fixed amount of sediment fed into the flume were 5% for gravel and 2% for sand. This means that the mobility of sand was 2.5 times that of gravel in this experiment. When the sand fraction was more than 60%, the mixture had nearly the same mobility as that of pure sand. However, when the proportion of gravel was more than 50%, the mobility of the mixture decreased sharply. Therefore, we could recognize an abrupt change in the mobility of mixtures not only in the small flume (Chapter 4), but also in the large flume experiment.

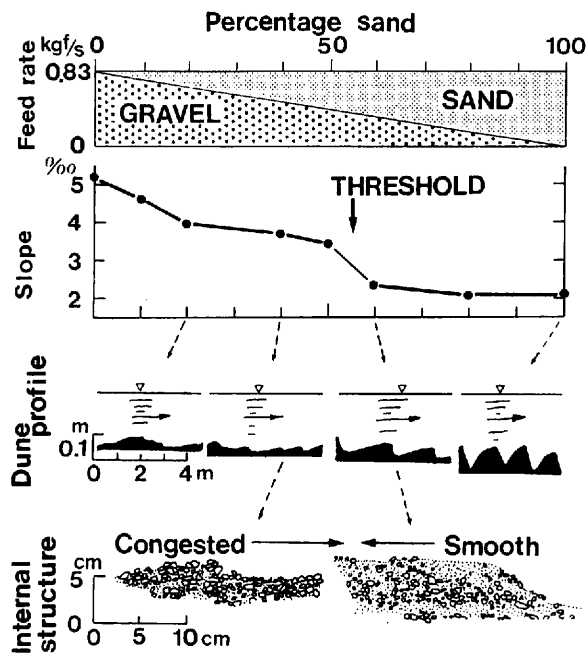


Fig. 6-1 Changes in mobility, dune profiles and sedimentary structures as functions of the sand: gravel ratio of bedload.

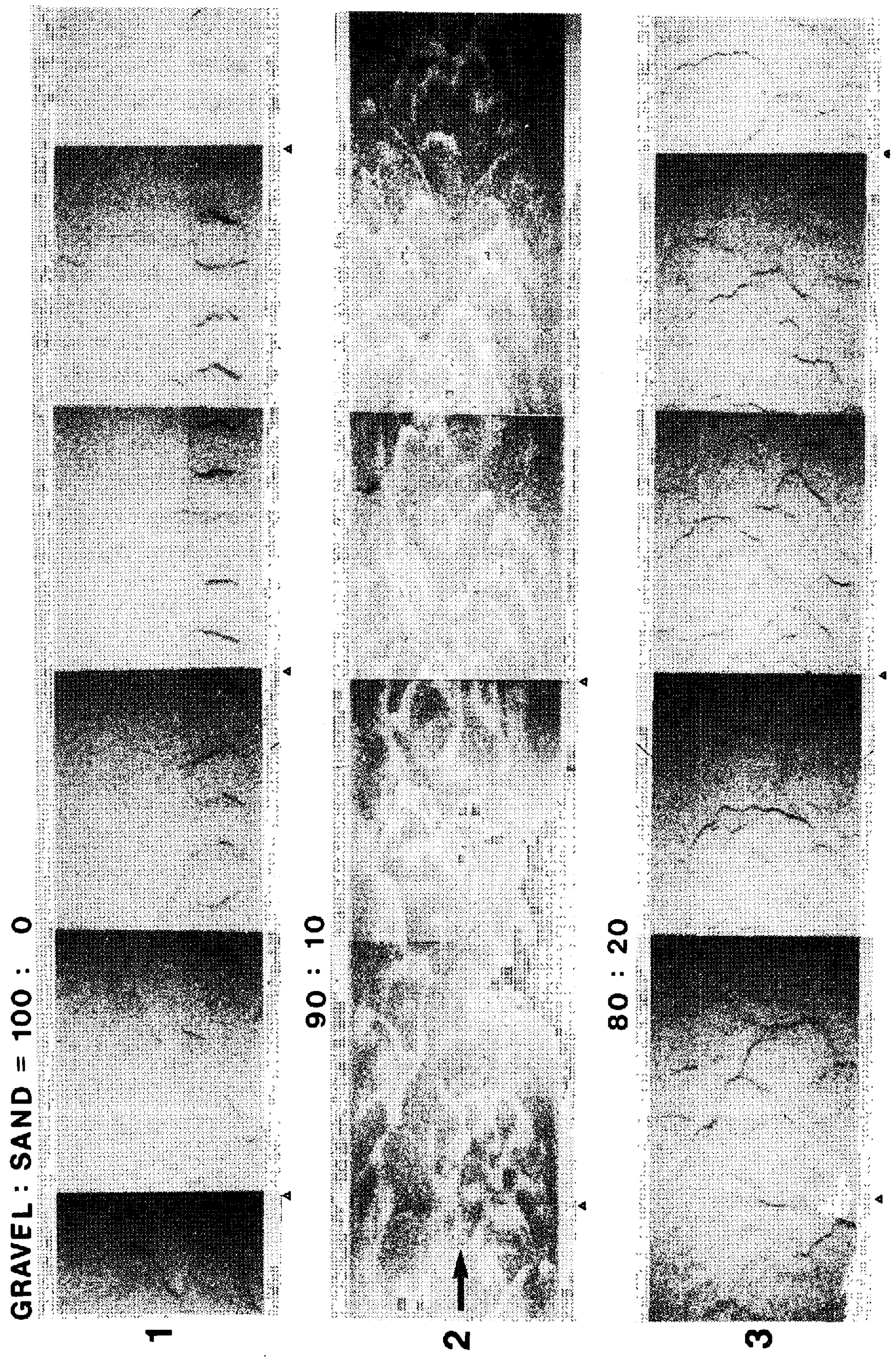
6.3 Vertical sorting process as a factor which affects the abrupt changes in the mobility of sediment mixtures

Fig. 6-2 shows the effect of sand: gravel ratio on the bed state. Fig. 6-3 can be used for a stereoscopic view of the bed. In a macroscopic sense, the state was a plane bed when the bed material was composed only of gravel (Fig. 6-2-1). Trains of standing waves were developed along the right side of the flume. Standing wave length and height were about 95 cm and 9 cm respectively.

A sand fraction of only 10% (Fig 6-2-2) had remarkable effects on the transport of mixtures. Low relief linguoid dunes were formed. Dune crests were composed of open-work gravel (Fig. 6-4). When the gravel fraction was higher than 50%, the bed state was essentially similar, that is, sand grains settled among interstices of gravel and the entire bed was covered by gravel.

However, when the sand fraction exceeded the gravel fraction, sharp continuous dune crests were formed(Figs. 6-2and6-3)and patches of sand developed(Fig. 6-3-3). Dune height increased as the sand content increased. Gravel grains accumulated in the troughs of dunes, and all gravel layers were matrix-filled (Fig. 6-4). Most of gravel grains were buried beneath the bed, which was composed mainly of sand.

The large flume experiment confirmed that a vertical sorting process may be a factor to create the abrupt change in the mobility of sediment mixtures. Seccessive changes in the moving layer on the dune surface in the large flume were almost the same as those on the plane bed surface in the small flume, seen in Figs. 3-6 and 4-2.


GRAVEL : SAND = 100 : 0
90 : 10
80 : 20
1
2
3

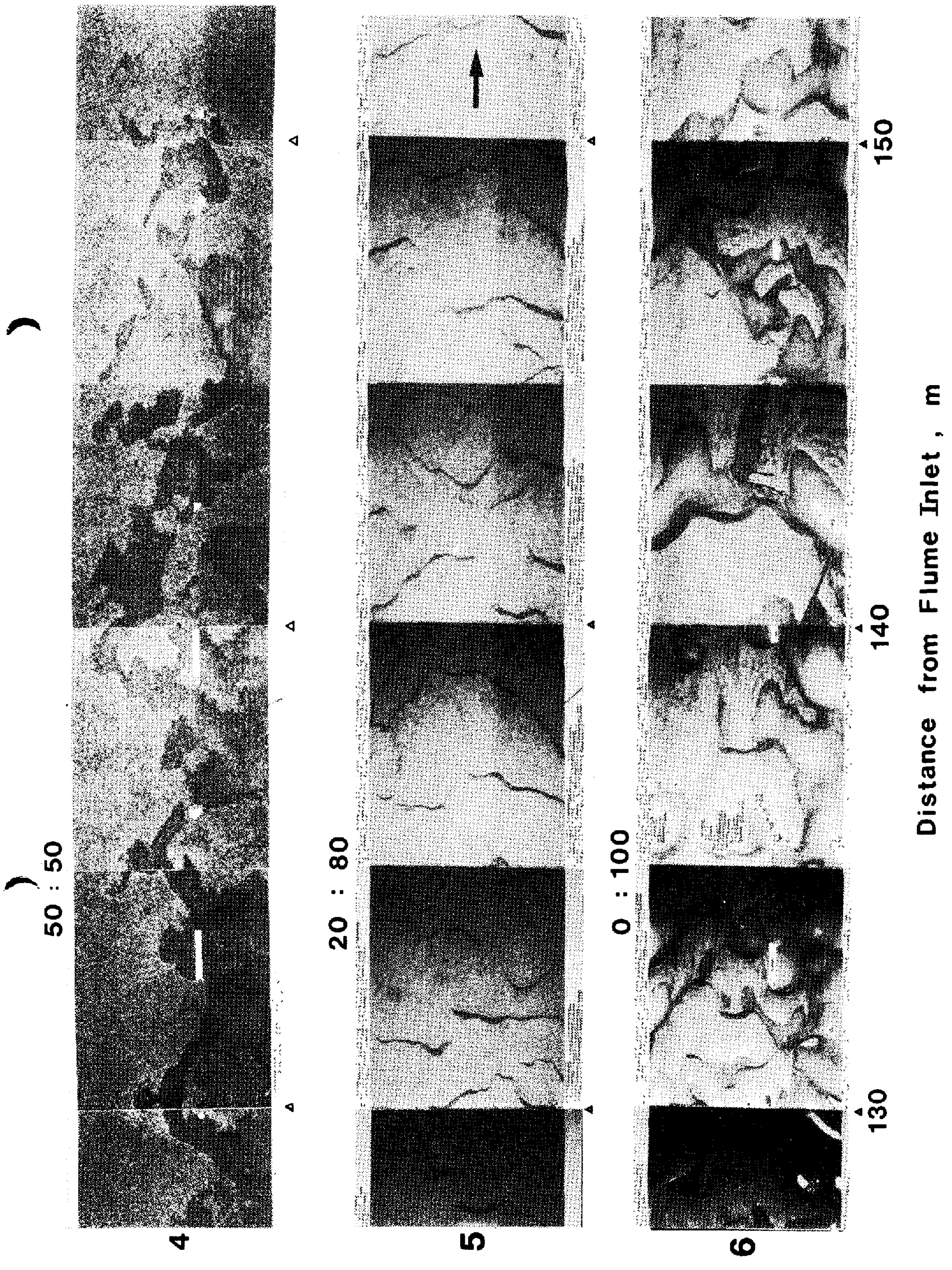


Fig. 6-2 Bed states in relation to the sand: gravel ratio of bedload.

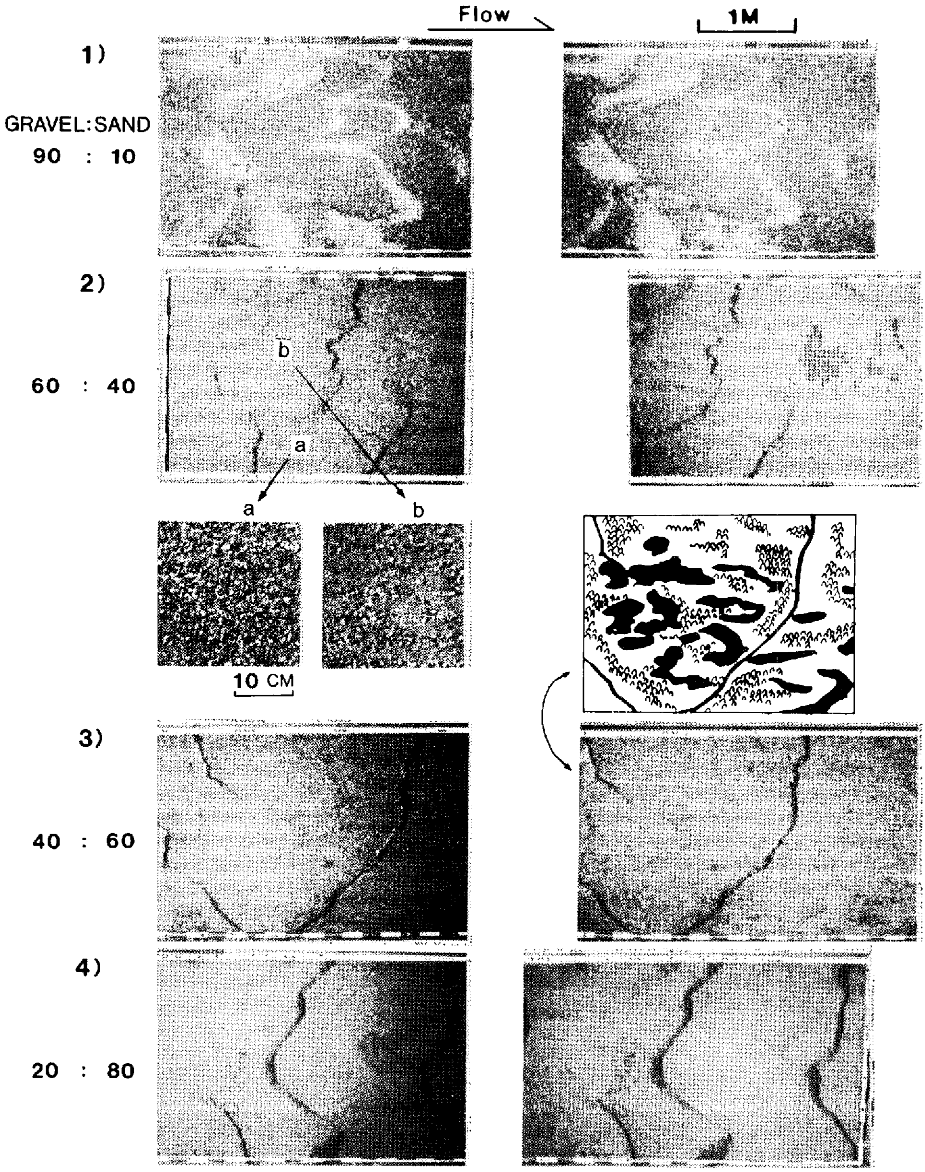


Fig. 6-3 Partial view of Fig. 6-2 showing the changes in bed states with increasing sand fraction.

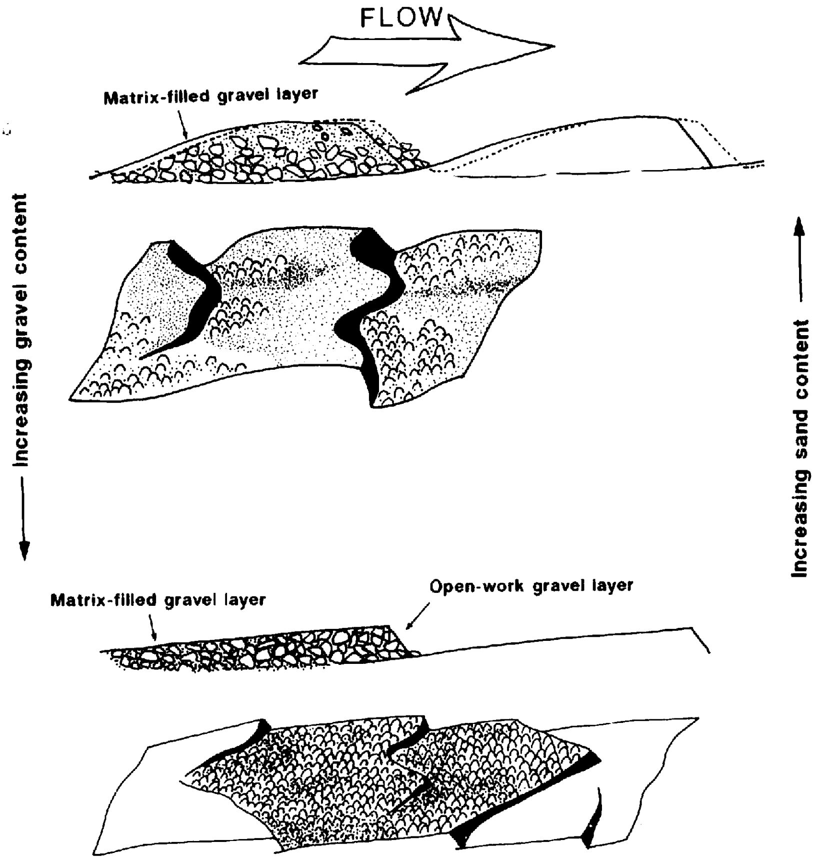


Fig. 6-4 Diagram showing two types of sedimentary structures of dunes in relation to the sand: gravel ratio of sediment

CHAPTER VII

A FEW REMARKS ON GEOMORPHOLOGICAL FEATURES ASSOCIATED WITH HETEROGENEOUS SEDIMENT TRANSPORT

7-1. Longitudinal slope discontinuity in alluvial rivers

An abrupt change in the mobility of mixed sediment as described in Chapter 4 will help in understanding the problem of longitudinal slope discontinuities in alluvial rivers. If the water discharge varies little in the downstream direction of a single reach, changes in sediment characteristics have the most significant effects. As the grain size of bed material declines downstream, the percentage of sand increases gradually. In that situation, the bed state must be strongly affected by the sand fraction at a critical point. In the upper reach, coarse particles strongly affect the mobility of the sediment mixture, and longitudinal slopes are determined by the mobility of the larger fractions. However, once the congested state is broken, transport phenomena are controlled by the smaller size fractions, and therefore gentle slopes will be established. Kodama and Inokuchi (1986) gave a detailed description of such bed state changes along the lower Watarase River.

7-2. Alternating repetition of scour and fill along a stream

Measurements of the bedload transport rate in gravel-bed rivers have clearly demonstrated complicated relationships between the bedload transport rate and hydraulic variables. For example, Emmett (1975) observed an unexpected fluctuation of transport rate at steady river discharge in the upper Salmon River, where bedforms did not perceptively migrate.

Reid *et al.* (1984; 1985) also observed rhythmic fluctuations characterized by a series of pulses, where identifiable bedforms were also absent.

In our flume experiments on the mobility of mixed sediment, longitudinal sediment sorting produced pulsations of transport rates and congested-smooth sequences of bed states (Fig. 7-1, Ikeda, 1984).

A special flume made of acryloyl plastics, 10 cm wide and 5 m long, was prepared for the supplementary experiment. A sediment feeder using a belt-conveyor was developed to keep the sediment feed rate constant.

It was found that scour and fill induced by congested-smooth sequences of the bed states alternate along a river channel, and that the progressive down-channel passage of different bed states also results in cycles of scour and fill at any given cross section. An alternating repetition of steep-slope and gentle-slope reaches can also be expected (Iseya and Ikeda, 1987).

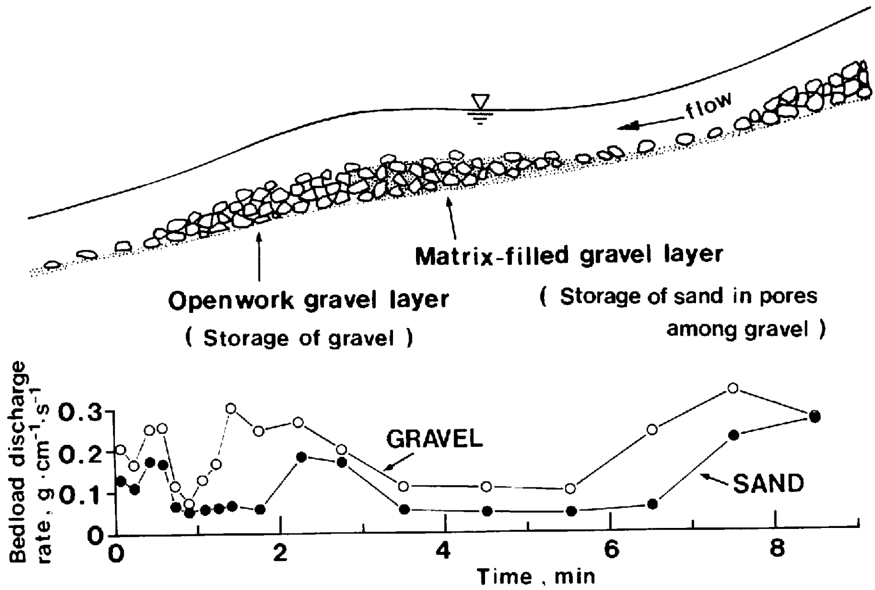


Fig. 7-1 An example of temporal change of bedload transport rates caused by sediment sorting (Run C-4 in Table 4-2)

7-3. Fan-head trenching

Entrenchment of the main stem channel on a fan is common. Some fan-head trenches appear to have been entrenched and backfilled one or more times before the present trenching. Fan-head entrenchment has been the subject of much discussion (Eckis, 1928; Beaty, 1963; Bull, 1964; Denny, 1965; Hooke, 1965; Lustig, 1965).

In our flume experiments on the transport of mixed sediment, a repetition of entreching and fill that is very similar to fan-head trenching and arroyo cutting was observed in a flume when the gravel was a majority of the mixture.

In such cases, most of fine fractions in the mixture were stored in the upper part of the fan and therefore, the character of the gravel governed the fan slope. However, when the stored sand was released by local scour of the fan-head a temporary high mobility of gravels resulted in fan-head trenching. Kodama and Iseya (1987) investigated in detail the mechanism of fan-head treanching in a small flume.

Only qualitative explanations have been presented in these works. Further experiments on the physical processes involved and necessary, as well as detailed investigation in the field.

Investigation of the origin of heterogeneous sediment in alluvial rivers also appears to be necessary to explain the size and shape of natural river channels.

ACKNOWLEDGEMENTS

We thank Dr. Tom Lisle, USDA Forest Service, Redwood Sciences Laboratory, Arcata, for his reading and valuable comments on a draft of this report. Dr. K. Yamamoto, Information Center on Rivers, gave us helpful suggestions on the transport of mixed sediments. Collegues at the Environmental Research Center assisted in various ways to complete the experiments. Among those, we would especially like to thank Mr. H. Kojima for making small flumes and useful equipments and Mr. H. Iijima for carrying out the experiments. We have been strongly encouraged by Prof. T. Kawamura, Directer of the Environmental Research Center, on the publication of this report. For all the persons and institutions, even those not mentioned here by name, who have helped in the completion of this work, we wish to express our sincere thanks.

REFERENCES

Ashida, K. and Michiue, M. (1972): Study on hydraulic resistance and bedload transport rate in alluvial streams. *Transactions of Japan Society of Civil Engineers*, **206**, 59-69. (in Japanese with English abstract)

Bagnold, R. A. (1973): The nature of saltation and of "bedload" transport in water. *Proceedings of the Loyal Society*, **332A**, 473-504.

Beaty, C. B. (1963): Origin of alluvial fans, White Mountains, California and Nevada, *Annals of the Association of American Geographers*, **53**, 516-535.

Bluck, B. J. (1987): Bed forms and clast size changes in gravel-bed rivers. in Richards K. (*ed.*) *River Channels–Environment and Process*, Blackwell, 391 p., 159-178.

Bull, W. B. (1964): History and causes of channel trenching in Western Fresno county, California. *American Journal of Science*, **262**, 249-258.

Denny, C. S. (1965): Alluvial fans in the Death Valley region, California and Nevada. *Professional Paper, United States Geological Survey*, **466**, 62 p.

Eckis, R. (1928): Alluvial fans in the Cucamonga district, southern California. *Journal of Geology*, **36**, 224-247.

Egiazaroff, I. V. (1965): Calculation of nonuniform sediment concentration. *Journal of the Hydraulic Division, American Society of Civil Engineers*, **91**, 225-247.

Einstein, H. A. (1950): The bedload function for sediment transportation in open channel flows. *Technical Bulletin, United States Department of Agriculture*, **1026**, 71 p.

Emmett, W. W. (1975): The channels and waters of the upper Salmon River area, Idaho. *Professional Paper, United States Geological Survey*. **870-A**, 113 p.

Fukami, T. (1978): Grading of gravel and sand in rivers. *Doboku-Gijutu-Siryo*, **20**, No. 1, 9-14. (in Japanese)

Gilbert, G. K. (1914): The transportation of debris by running water. *Professional Paper, United States Geological Survey*, **86**, 263 p.

Hooke, R. Le B. (1965): Processes on arid-region alluvial fans. *Journal of Geology*, **75**, 438-460.

Ikeda, H. (1970): On the longitudinal profiles of the Asake, Mitaki and Utsube Rivers, Mie Prefecture. *Geographical Review of Japan*, **43**, 148-159. (in Japanese with English abstract)

Ikeda, H., Ono, Y., Izumi, K. and Kawamata, R. (1978): The speeds of solid grains, rolling along a smooth bed, in turbulent flow. *Bulletin of the Environmental Research Center, University of Tsukuba*, **3**, 7-15. (in Japanese)

Ikeda, H. (1984a): Flume experiment on the transport of sand-gravel mixtures. *Bulletin of the Environmental Research Center, University of Tsukuba*, **8**, 1-15. (in Japanese)

Ikeda, H. (1984b): Flume experiments on the causes of superior mobility of sediment mixtures. *Annual Report of the Institute of Geoscience, University of Tsukuba*, **10**, 53-56.

Ikeda, H. and Iseya, F. (1985): Effect of fine sand on mobility of coarse sand. *Bulletin of the Environmental Research Center, University of Tsukuba*, **9**, 43-47. (in Japanese)

Ikeda, H. and Iseya, F. (1987): Thresholds in the moblity of sediment mixtures. in Gardiner, V. (*ed.*) *International Geomorphology 1986*, Part 1, Wiley, 561-570.

Ikeda, H. (1985): River-bed materials and longitudinal profiles of alluvial rivers. *Lecture Note, Hydraulic Engineering Lecture Series, Japan Society of Civil Engineer*, **85-A-3**, 1-13. (in Japanese)

Iseya, F. and Ikeda, H. (1986): A large flume experiment on the thresholds in the mobility of sand and gravel mixtures: a mechanism of the formation of breaks in the longitudinal slopes of rivers. *Bulletin of the Environmetal Research Center, University of Tsukuba*, **10**, 125-134. (in Japanese)

Iseya, F. and Ikeda, H. (1987): Pulsations in bedload transport rates induced by a longitudinal sediment sorting: a flume study using sand and gravel mixtures. *Geografiska Annaler,* **69(A)**, 15-27.

Kira, H. (1982): *Sedimentation in reservoirs and its prevention,* Morikita Shuppan, 392 p. (in Japanese)

Kodama, Y. and Inokuchi, M. (1986): Change in the sedimenatary fabric of surface deposits along the lower course of the River Watarase. *Bulletin of the Environmental Research Center, University of Tsukuba,* **10**, 67-79. (in Japanese)

Kodama, Y. and Iseya, F. (1987): An experimental study of fan-head trenching, using sand and gravel mixtures. *Bulletin of theEnvironmental Research Center, University of Tsukuba,* **11**,1-11. (in Japanese)

Leopold, L. B., Wolman, M. G. and Miller, J. P. (1964): *Fluvial Processes in Geomorphology*, Freeman, San Francisco, 522 p.

Lustig, L. K. (1965): Clastic sedimentation in Deep Springs Valley, California. *Professional Paper, United States Geological Survey,* **352-F**, 131-192.

Nakagawa, H. and Tsujimoto, T. (1977): Armoring process of alluvial bed composed of sediment mixtures. *Annual, Disaster Prevention Research Institute, Kyoto University,* **20-B**, 355-370.

Nakagawa, H., Tsujimoto, T. and Hosokawa, Y. (1979): Motion of a particle rolling along a bed and driving hydrodynamic forces. *Proceedings of 23rd Japanese Conference on Hydraulics,* 323-330. (in Japanese)

Nakayama, M. and Miura, T. (1964): Roundness of pebbles in the course of rivers in Japan. *Geographical Review of Japan,* **37**, 115-130. (in Japanese with English abstract)

Parker, G., Dhamotharan, S. and Stefan, H. (1982): Model experiments on mobile, paved gravel bed streams. *Water Resources Research,* **18**, 1395-1408.

Parker, G. and Klingeman, G. C. (1982): On why gravel bed streams are paved. *Water Resources Research,* **18**, 1409-1423.

Parsons, D. A. (1972): The speeds of sand grains in laminar flow over a smooth bed. in Shen, H. W. *(ed) Sedimention–Symposium to honor professor H. A. Einstein*, Fort Collins, Colorado, 1-25.

Pettijohn, F. J. (1957): *Sedimentary rocks* (2nd *ed.*), New York, Harper Bros, 718 p.

Plumley, W. J. (1948): Black Hills terrace gravels: a study in sediment transport. *Journal of Geology,* **58**, 526-578.

Reid, I., Brayshaw, W. C. and Frostick, L. E. (1984): An electromagnetic device for automatic detection of bedload motion and its field applications. *Sedimentology,* **31**, 269-276.

Reid, I., Frostick, L.E. and Layman, J. T. (1985): The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surface Processes and Landforms,* **10**, *33-44.*

Statham, I. (1977): *Earth surface sediment transport*, Oxford, 184 p.

Takashima, J., Iseya, F. and Ikeda, H. (1986): Flume experiment on the transportation of sand mixtures. *Bulletin of the Environmental Research Center, University of Tsukuba,* **10**, 95-103. (in Japanese)

West, E. A. (1978): *The equilibrium of natural streams,* Geo Abstracts Ltd., University of East Anglia, 205 p.

White, W. R. and Day, T. J. (1982): Transport of graded gravel bed material. in Hey, R. D. Bathurst, L. C. and Thorne, C. R. *(eds.) Gravel-bed rivers*, Wiley, 181-213.

Yamamoto, K. (1986): Study on the characteristics of alluvial river channels. *Report of the Public Works Research Institute, Ministry of Construction,* **168**, 66 p. (in Japanese)

Yatsu, E. (1955): On the longitudinal profiles of the graded river. *Transactions of the American Geophysical Union,* **36**, 655-663.

Environmental Research Center Papers

No. 1 (1982) Kenji KAI: Statistical characteristics of turbulence and the budget of turbulent energy in the surface boundary layer. 54p.

No. 2 (1983) Hiroshi IKEDA: Experiments on bedload transport, bed forms, and sedimentary structures using fine gravel in the 4-meter-wide flume. 78p.

No. 3 (1983) Yousay HAYASHI: Aerodynamical properties of an air layer affected by vegetation. 54p.

No. 4 (1984) Shinji NAKAGAWA: Study on evapotranspiration from pasture. 87p.

No. 5 (1984) Fujiko ISEYA: An experimental study of dune development and its effect on sediment suspension. 56p.

No. 6 (1985) Akihiko KONDHO: Study on the groundwater flow system by environmental tritium in Ichihara region, Chiba Prefecture. 59p.

No. 7 (1985) Chong Bum LEE: Modeling and climatological aspects of convective boundary layer. 63p.

No. 8 (1986) Kazuo KOTODA: Estimation of river basin evapotranspiration. 66p.

No. 9 (1986) Abdul Khabir ALIM: Experimental studies on transient behavior of capillary zone. 76p.

No.10 (1987) Michiaki SUGITA: Evaporation from a Pine forest. 61p.

No.11 (1987) Hye-Sock PARK: Variations in the urban heat island intensity affected by geographical environments. 79p.

No.12 (1988) Hiroshi IKEDA and Fujiko ISEYA: Experimental study of hetergeneous sediment transport. 50p.

発行　昭和63年3月26日

編集・発行者　筑波大学水理実験センター

〒305 つくば市天王台1－1－1

TEL 0298(53)2532

印刷　日青工業株式会社

東京都港区西新橋2－5－10