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ROLE OF HETEROGENEOUS PROPERTY OF BED MATERIALS IN THE FORMATION OF STEP-POOL SYSTEMS IN MOUNTAIN STREAMS

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SYNOPSIS

Recently, studies on step-pool systems in mountain streams have been increasing because of concern for environmental conservation. However, no studies can be found which elucidate the role of heterogeneous property (grain size distributions) of bed materials in the formation of step-pool systems. This paper shows : 1)the grain size distribution of bed surface materials sampled in the upper Ibi River is of the Talbot type, which is known to provide the closest packing; 2) stable and well-developed step-pool systems were formed with heterogeneous bed materials with a Talbot-type distribution but no step-pool systems were found when the bed materials had a non-Talbot-type distribution on movable bed experiments; and 3) the formulas proposed here for estimating a wave length and a wave height of a step-pool system are adequate, based on the assumption that when the Shields stress acting on the gravel of d_{84} is below critical, the step-pool systems are formed.

INTRODUCTION

In mountain streams, step-pool systems are frequently found. In this system, a step, which is formed through the accumulation mainly of boulders and cobbles, and a pool, a bed of which consists mainly of materials of a relatively small grain size, are connected alternately. Clarification of the structure and properties of such systems unique to mountain streams is not only of great interest from a viewpoint of sediment hydraulics, but also leads to their application to technological development for conservation, restoration and creation of mountain rivers. Ashida, Egashira and others(1) made detailed analyses of causes and conditions for the formation of step-pool systems through experiments with heterogeneous materials. They proved that the formation of such system was ascribable to active transfer of heterogeneous materials accompanied by sorting, formation of sand waves in antidunes, and stoppage of cobbles near the crest of an antidune. Hasegawa and Kambayashi(2), Kambayashi and Hasegawa(3), and Hasegawa(4) classified this bed topography into a rib, in which the materials constituting the step are aligned in a straight line transverse to flow direction and the pool is scoured relatively shallow, and a step-pool, in which the materials forming the step are placed in an arch horizontally, and waterfalls with a small plunge pool are created. They showed, through experiments and linear stability analyses, that a step-pool (the latter type) is formed by synchronization of the length of forced wave on surface caused by the antidune on the bed, and the wave length of a stationary surface diagonal wave in the chute flow.

No considerations have, however, been given to heterogeneous property of materials, which is regarded as a key factor in the formation of step-pool systems. Experiments have only confirmed that no such beds are formed when the grain size is uniform(1). In this connection, the authors reviewed grain size distributions of materials sampled in the bed of a real mountain stream , and conducted movable bed experiments with heterogeneous materials, and studied the relationship between the heterogeneous property of bed materials and the factors for the formation of step-pool systems, the stability of a step-pool system, characteristic of its shape.

GRAIN SIZE DISTRIBUTION OF BED MATERIALS AND TALBOT'S CURVE

As an example, the distributions of bed material grain sizes in percent by weight is studied in the catchment of the Shiratani (catchment area: approximately 21 km^2, river length: approximately 12 km, river slope: 0.03 to 0.10), a tributary of the Ibi River in the Kiso River system(5). The survey was conducted in 1971 by the Etumi Mountain Sediment Control Branch Work Office, Central Japan Regional Construction Bureau of the Ministry of Construction of Japan. The objective of the survey was the collection of basic data on debris flows in the catchment. Grain-size analyses, unit weight tests and specific gravity tests were carried out on samples of the bed material collected near the two points on the right and left banks in nine cross-sections between the junction with the Ibi River and the upstream point. Size of the samples was 0.5 m x 0.5 m x 0.5 m. Fig.1 shows grain size distributions obtained through the sieve analyses of 12 samples collected in the upper three cross-sections. All of the samples have distributions with downward crests on the semilog paper. Fig.2 shows the distributions normalized by maximum size of each material. The thick lines in the figure represent the Talbot's distribution(6),(7) expressed by the following equation.

$$P=(d/d_{max})^n \tag{1}$$

where d = a given grain size of the material, d_{max} = the maximum grain size of the material and P = ratio of materials by weight passing a sieve of a size of d. This equation was proposed by Talbot based on experimental results to represent an ideal grain size distribution which facilitates packing or provides the maximum density for heterogeneous materials such as fine and coarse aggregate. It is known that grain can be packed well when the exponent n is 1/2 to 1/4. Fig.2 indicates that distributions of d/d_{max} demonstrate lines almost like the Talbot curve with an exponent n of 1/2 to 1/3, and thus the bed of the Shiratani River had a grain size distribution which could easily pack grains, at the time of the survey.

The above results agree with the conventional general understanding that bed surface materials in mountain streams are closely packed. Talbot's curve represented by equation (1) can, therefore, satisfactorily explain general properties of grain size distributions in mountain stream beds. Properties of grain size distributions are essential to the study of roughness coefficient, velocity distribution, sediment discharge, formation and stability of step-pool systems and armoring. This study focused on the role of heterogeneous property of bed materials in the formation of step-pool systems in mountain streams, based on the information on the distribution properties.

MOVABLE BED EXPERIMENT WITH HETEROGENEOUS MATERIALS

Three types of materials were used in the experiment as shown in Fig.3 and Table.1. Materials which had a Talbot-type grain size distribution, A (n=1/2) and B (n=1/4), and material the distribution of which has an upward crest on the semilog scale, C were used, where d_m = initial value of mean grain size of each material, the mean grain size d_m was 1.7, 1.0 and 0.74 cm for materials A, B and C, respectively. And the maximum grain size d_{max} was 5.0 cm (sieve-passing grain size) for all materials. Slope-adjustable equipment with a flume 11 m long, 30 cm wide and 40 cm deep made of plates with one side covered with acrylic resin was used in the experiment as shown in Photo.1. At the upper end of the flume, a tank for circulating water and a baffle plate were installed. Flow discharge was measured by electromagnetic flowmeters attached to two systems of water supply pipes with diameters of 50 mm and 200 mm. In the experiment, well blended experimental materials were spread 15 cm high all over the bottom surface of the flume, and hydraulic filling was applied to flatten the bed surface. Then water was supplied without any sand, and the bed transformation was investigated during the water run. The surface bed materials were sampled at the several points to measure the grain size distribution after stoppage of flow and bed shape was observed. Table.2 lists experimental conditions, where I = initial bed slope and Q = discharge of water into the flume. Each run consists of three rounds, each of which lasts four minutes.

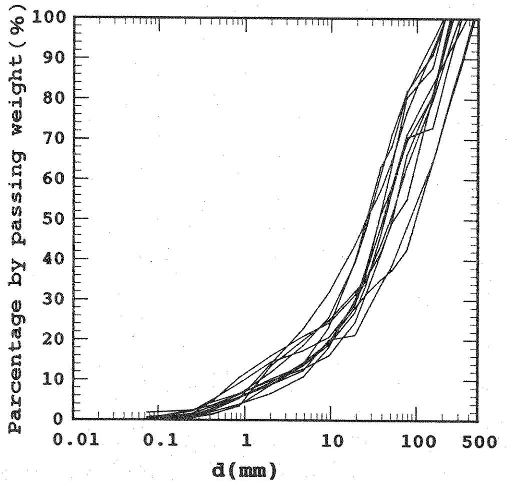

Fig.1 An examples of bed materials grain size distribution of the SHIRATANI.

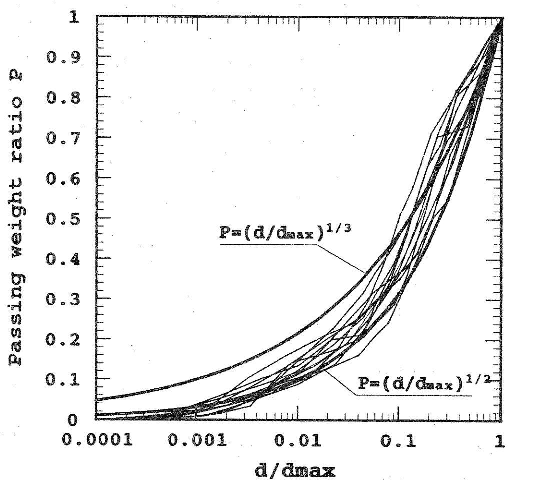

Fig.2 A comparison between bed materials grain size distributions and Talbot's curve.

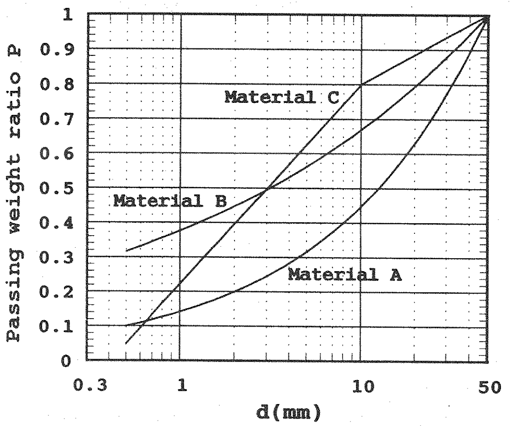

Fig.3 Grain size distributions of experimental materials.

Table.1 Mix proportion by weight of experimental material

d	Material A	Material B	Material C
～0.5mm	0.1	0.316	0.05
0.5mm～ 1mm	0.041	0.06	0.174
1mm～ 2mm	0.059	0.071	0.173
2mm～ 5mm	0.116	0.115	0.229
5mm～ 10mm	0.131	0.106	0.174
10mm～ 20mm	0.185	0.127	0.086
20mm～ 30mm	0.142	0.085	0.051
30mm～ 50mm	0.225	0.12	0.063
dm	17mm	10mm	7.4mm
dmax	50mm	50mm	50mm

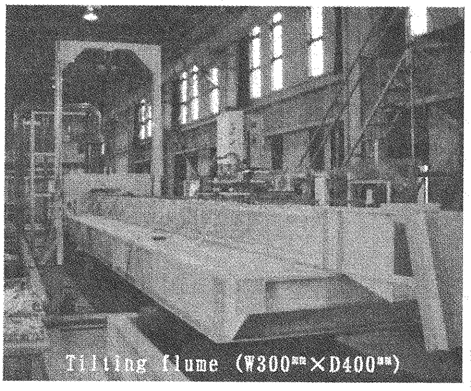

Photo.1 Experimental equipment.

Table.2 Experimental conditions.

Run No.	Material	Initial bed slope I	Discharge of flow Q(cm^2/s)
A-1	A	0.025	36000
A-2	A	0.05	15000
A-3	A	0.1	6000
B-1	B	0.025	24000
B-2	B	0.05	10000
B-3	B	0.1	4000
C-1	C	0.025	17000
C-2	C	0.05	7000
C-3	C	0.1	3000

RESULTS OF EXPERIMENTS

Process of Bed Transformation

Figs.4 show vertical height of the bed along the central line measured at the end of each of three rounds for the experimental cases listed in Table.1. The horizontal axis shows the position in the direction of flow, and the vertical axis represents the height of bed after each round relative to the initial bed level. In areas where ribs are explicitly recognized, the vertical height of bed is measured alternately at the mean height point in the step and the lowest point in the pool. In other areas, bed height is measured at a spacing of approximately dozens of centimeters.

In Run-A and Run-B series with a Talbot-type initial grain size distribution in the bed, clear ribs are formed following the rib formation mechanism described by Ashida and others(1). A comparison of the results of Run-A and Run-B series, where the formation of ribs is recognized, shows that in Run-A series the bed degrades by 2 to 3 cm and clear ribs are formed all over the flume in the first round. On the other hand, in Run-B series, ribs are formed gradually from upstream to downstream in the second round. Ribs are fully developed only after the third round when the bed degrades by 6 cm or more. Photo.2 shows the bed surface viewed from downstream after the third round in Run A-2. Two steps with clear ribs are recognized near the end of flume.

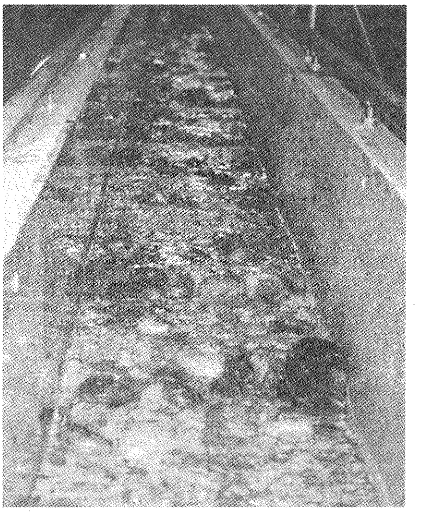

Photo.2 The bed surface at the end of the third round in Run A-2.

In Run-C series, neither clear rib or step-pool formation is recognized except vague ribs in the upstream area at the end of third round in Run C-1. In this series, antidunes are formed with active transfer of the bed materials. The antidunes are, however, formed intermittently. Thus, it seems that the antidunes cannot stop the movement of gravel. Even at the end of runs, gravel are distributed randomly on the flat bed, where no regularity is observed.

In Runs B-3 and C-3, substantial meandering of stream is recognized in the first or second round. Therefore, the bed height is measured along the both side walls of the flume at the end of third round in Run B-3, and at the end of each rounds in Run C-3, as shown in Figs.4(a)～(d). The figures show that the meandering lengths are approximately 2 to 3m, which are 7 to 10 times larger than the channel width of 30 cm. The meandering wave length of stream can also be confirmed by the bed heights measured along the central line after the third round in Run B-3.

Grain Size Distribution

Figs.5 show grain size distributions of surface layers approximately 5 cm thick of the bed at the end of three rounds of water conveyance. In Run-A series, where ribs are recognized in the first round, coarse grains are slightly increased as compared with the initial grain size distribution $\{P=(d/d_{max})^{1/2}\}$. In Run-B series, where formation of ribs is recognized at the end of second or third round, the distribution ended up with $\{P=(d/d_{max})^{1/2}\}$ though the initial distribution was $\{P=(d/d_{max})^{1/4}\}$. In Run-C series, where the formation of ribs is hardly recognized, distributions are almost linear on the semilog scale.

Comment

As a result of the above, it is found that the characteristics of grain size distribution in the bed have a close relation with the formation of step-pool systems, and that clear step-pool systems are formed on the bed with a Talbot-type distribution

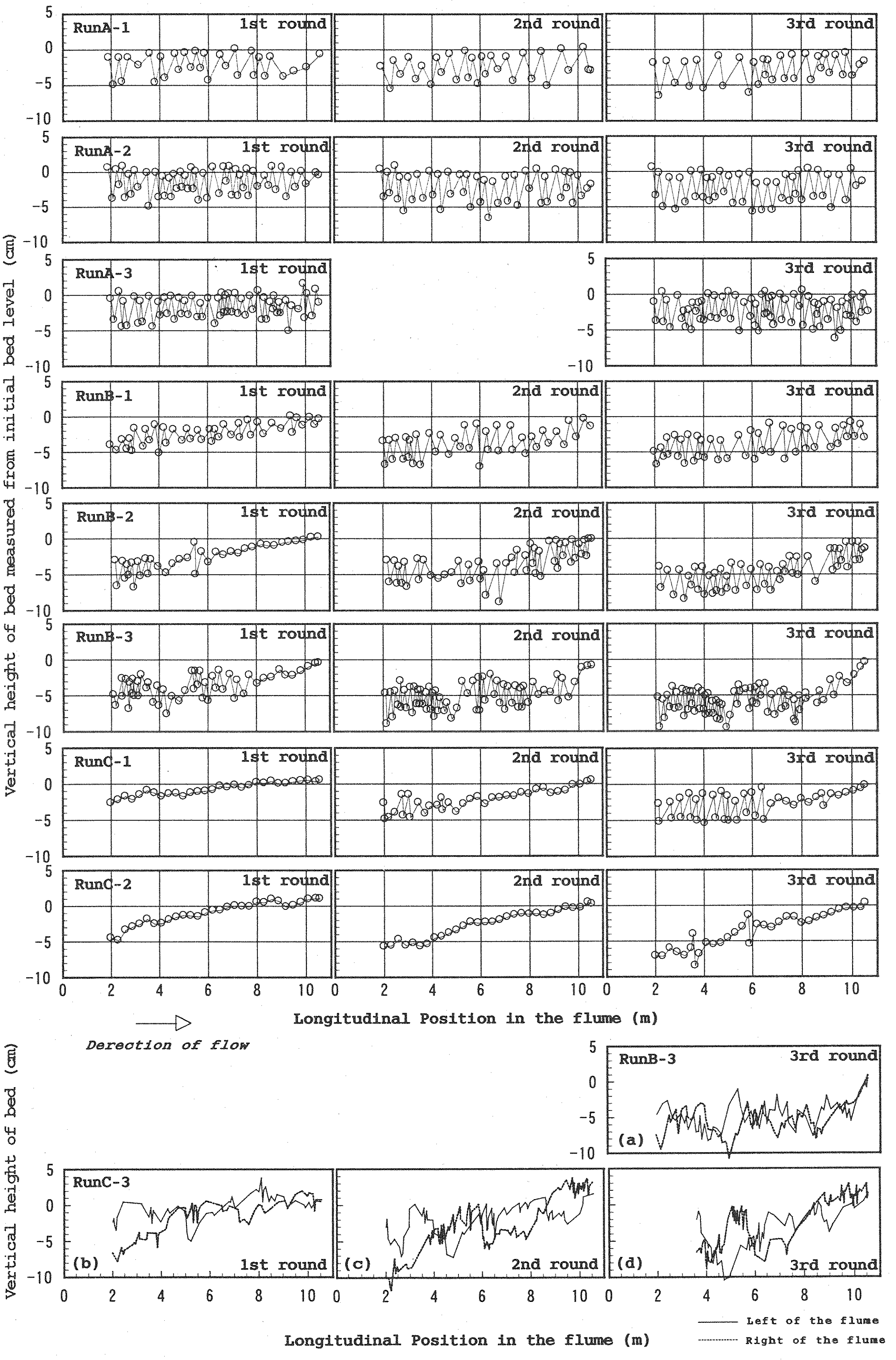

Fig.4 longitudinal profiles of the steps and pools.

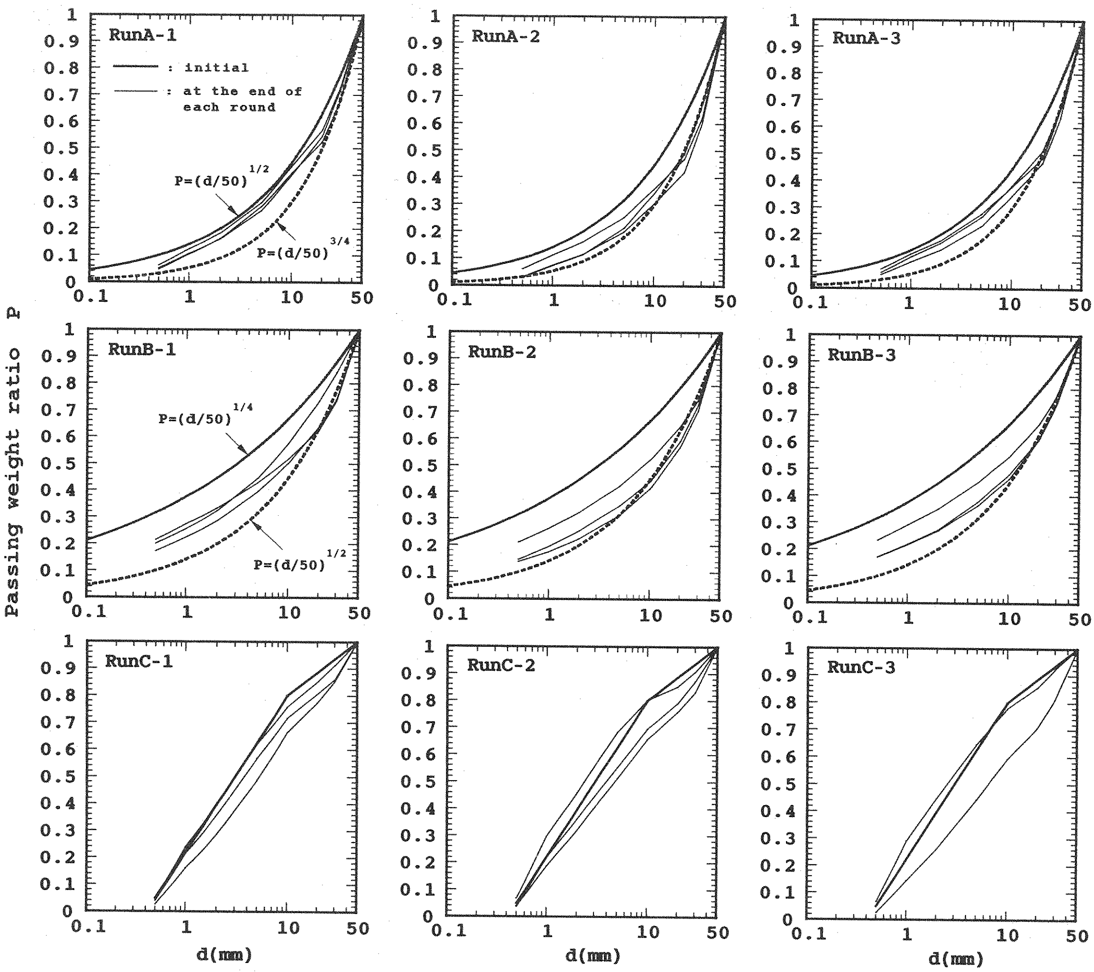

Fig.5 Grain size distribution of bed surface materials at the end of three rounds of water conveyance.

with the exponent n=1/2 to 3/4, under the condition in which approximately maximum-size grain among heterogeneous materials are acted by the critical shear stress. Vertical transformation of the bed due to meandering of stream with a wave length 7 to 10 times larger than the channel width may be ascribable to medium-scale bed topography which was confirmed in field investigations(4).

ANALYSIS OF WAVE HEIGHT AND WAVE LENGTH OF STEP-POOL SYSTEMS

Derivation of Formulas

Formulas for estimating a wave height and a wave length of a step-pool system are derived, based on the assumption of critical dimensionless shear stress τ_{*co} of 0.05, by using the following Hey-equation, a law of resistance of flow.

$$\frac{u}{u_*} = 5.75\log\left(\frac{ah}{3.5d_{84}}\right) \quad , \ a=11.16 \tag{2}$$

The wave height Δ can be expressed by the following equation in view of many field measurements and experiments.

$$\Delta \approx d_{84} \tag{3}$$

On assumption that when the Shields stress acting on the gravel of d_{84} is below critical, the step-pool systems are formed, the following equation is obtained from equation(3).

$$\Delta \approx d_{84} = \frac{hI}{s\tau_{*co}} \qquad (4)$$

If the following equation which is an approximation of Hey-equation(2) corresponding to mountain streams is adopted,

$$\frac{u}{u_*} = 6.5\left(\frac{h}{3.5d_{84}}\right)^{1/4} \qquad (5)$$

water depth is estimated by the following equation.

$$h = \left(\frac{d_{84}{}^{1/4}Q}{6.5B\sqrt{gI}}\right)^{4/7} \qquad (6)$$

where, h = depth of flow, I = mean bed slope, g = gravity acceleration, s = underwater specific gravity of grain(1.65), u = mean velocity, u_* = shear velocity, B = width of the flume and Q = discharge.

When equation(6) is substituted into equation(4), the equation(7) is obtained, there hc = critical depth of flow expressed by the equation(8).

$$\Delta = 3.5^{1/6}\,6.5^{-2/3}\left(s\tau_{*co}\right)^{-7/6}I^{5/6}\,hc \quad = 6.43\,I^{5/6}\,hc \qquad (7)$$

$$hc = \sqrt[3]{\frac{Q^2}{gB^2}} \qquad (8)$$

Then wave length λ can be estimated as shown below by using an approximated form of the equation for antidunes proposed by Hayashi(8).

$$\lambda = 2\pi h\sqrt{F_r{}^2 - \frac{1}{3}} \qquad (9)$$

where F_r = Froude number. With the use of equation(4),(5) and (7), equation(9) can be reduced to the following equation.

$$\lambda = 3.5^{1/6}\;2\pi(6.5)^{-2/3}\left(s\tau_{*co}I\right)^{-1/6}\sqrt{6.5^2\sqrt{\frac{s\tau_{*co}I}{3.5}} - \frac{1}{3}}\;hc$$
$$= 3.36\sqrt{6.48\sqrt{I} - \frac{1}{3}}\;I^{-1/6}\,hc \qquad (10)$$

Comparison with Experimental Results

Figs.6(a)~(d) show histograms of the wave heights and the wave lengths of ribs observed in Runs A-1 to A-3 and Runs B-1 to B-3, horizontal axis of which represent the frequency of Δ and λ normalized by critical depth of flow, hc. The thick solid lines in the figures indicate the relations between Δ/hc , λ/hc and bed slope I, which were obtained from the equations (7) and (10), respectively. As shown in the figures, estimated values almost agreed with mode values of experimental data.

CONCLUSIONS

The following results have been obtained as to the relation between the formation of step-pool systems and the heterogeneous property of bed materials.

1. It was found that the grain size distributions (percentage by weight) of bed surface materials of the Shiratani are represented by a curve similar to Talbot's curve with the exponent n= 1/3 to 1/2, which is conventionally known as an ideal grain size distribution and gives the closest packing of heterogeneous materials.
2. Movable-bed experiments with two types of heterogeneous bed materials with Talbot-type grain size distributions, which are represented by a downward crest on the semilog paper, and another type with a non-Talbot-type distribution confirmed that the difference in the heterogeneous property of materials has a strong effect upon whether step-pool systems are formed or not and upon how they are formed. In those experiments, though typical step-pool systems were formed on the bed with Talbot-type grain size distributions, no step-pools were formed on the bed with grain size

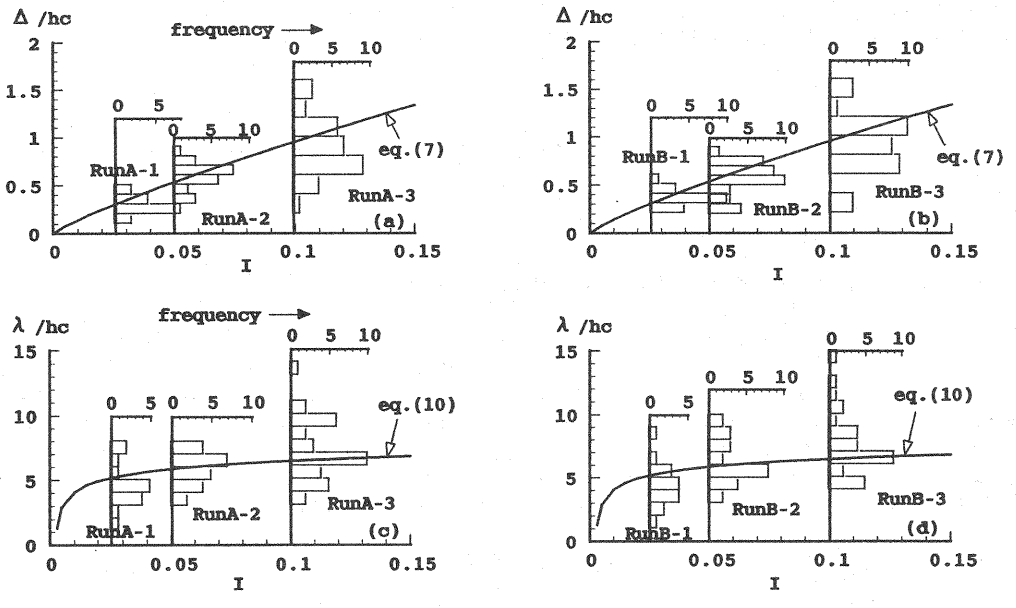

Fig.6 Histograms of the wave heights and the wave lengths of ribs observed in Runs A-1 to A-3 and Runs B-1 to B-3.

distributions which have an upward crest on the semilog paper. It was also found that the section, where stable and well developed step-pools were observed, had a grain size distribution smilar to a Talbot-type distribution with the exponent n of 1/2 to 3/4. In view of the above results, Talbot-type distributions are highly important to the formation and stabilization of step-pool systems.

3. Formulas for a wave height and a wave length of a step-pool were proposed. They agreed with the experimental data fairly well.

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APPENDIX - NOTATION

The following symbols are used in this paper:

a = a coefficient of Hey-equation;
B = width of channel;
d = grain size of the bed material;
d_{max} = maximum grain size of bed material;
d_{84} = grain size of 84 percentile passing by weight;
F_r = Froude number
g = acceleration of gravity;
h = depth of flow;
hc = critical depth of flow;
I = initial bed slope;
n = an index of Talbot's curve(distribution);
P = ratio by weight of materials passing a sieve of a size of d;
Q = flow discharge;
s = underwater specific gravity of grain;
u = mean velocity;
u_* = shear velocity;
Δ = a wave height of a step-pool system(rib or step-pool);
λ = a wave length of a step-pool system(rib or step-pool); and
τ_{*co} = critical dimensionless shear stress (=0.05).

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