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Application of sandwave measurements in calculating bed load discharge

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ABSTRACT Bed load transport in natural streams is a complicated phenomenon. Few types of samplers have been properly used in measuring bed load discharge up to now. One of the main reasons for the complexity is the fact that bed load movement usually takes the form of bed configurations such as dunes, or ripples. In this paper, a new method for measuring bed load transport rate by recording bed configuration in natural streams has been developed and a large number of field data have been collected to verify the validity of the method. The results of the study indicate that sandwave measurements can be conveniently applied to estimate the bed load discharge of rivers with few hydrological observations. Finally, an example of the application of the newly introduced method is presented and good agreement between the results obtained from sandwave measurements and a precisely designed sampler is obtained.

INTRODUCTION

In recent years, many analytical procedures and a variety of direct or indirect measurement techniques (Ackers et al., 1973) have been developed and used to determine bed load discharge which is a key problem in the design of hydraulic projects in streams with significant bed load transport. At present, most of the data on bed load transport rate are obtained through direct measurements in the field by using a certain type of samplers. However, attempts to verify these data, have shown that the results may vary over a large range and that considerable uncertainity exists. Bed load transport rates at the same discharge may be completely different along a stream. Among the reasons which explain the phenomenon are:

(a) As is well-known, bed load movement usually takes the form of bed configurations such as dunes, ripples, etc. Based on previous research on the properties of bed forms, it is known that bed load transport along a bed with sandwaves is completely different from that along a plane bed. Bed load transport rates vary greatly with time, as well as with location, and it is difficult to get average values of sediment transport.

(b) In natural streams, and especially in mountain rivers, the bed load discharge usually fluctuates. Because of the non-uniformity of the water flow and the bed load movement, it has been found that sediment transport rate at lower discharges may be grater than for the higher water discharges, a situation which is not in accordance with normal assumptions regarding bed load movement. This situation affects the apparent correctness of the data obtained using standard samplers.

(c) A sampler used for measuring bed load discharge in flowing water inevitably disturbs the flow structure, but observations of the bedforms can avoid such problems. Experimental research on these aspects has been conducted in the laboratory by Engel et al. (1980) but a lot of problems must be solved prior to practical application in natural streams. Based on this situation, a special field observation program was undertaken on a small river located in the middle part of China in order to study the practical application of the method.

THEORY

Along a moveable bed with sand forms, the continuity equation of sediment movement can be written as

$$\frac{\partial q_b}{\partial x} + v_b \cdot \frac{\partial Z}{\partial t} = 0 \tag{1}$$

where q_b is the bed load transport rate (kg s^{-1} m^{-1}), Z is the elevation of the stream bed (m), t is time (s), v_b is the dry weight of the bed load sample (kg m^{-3}), and x is the distance along the flow direction (m). Taking the bed form as a moving object, one can write the kinetic equation as follows:

$$\frac{\partial Z}{\partial t} + \omega_s \cdot \frac{\partial Z}{\partial x} = 0 \tag{2}$$

where ω_s is the celerity of the bed form (m s^{-1}). Substituting equation (2) into equation (1), the following equation can be obtained:

$$\frac{\partial q_b}{\partial x} - v_b \cdot \omega_s \cdot \frac{\partial Z}{\partial x} = 0 \tag{3}$$

Integrating equation (3) along the surface of the bedform with a known datum point as a reference, the transport rate at any section of the bed form is obtained:

$$q_b = v_b \cdot \omega_s \cdot (Z - Z_o) + q_o \tag{4}$$

where, q_0 is the bed load transport rate at the reference point Z_0. For a specified bed form, if a base level of zero sediment movement is selected in integration, equation (4) reduces to:

$$q_b = v_b \cdot \omega_s \cdot (Z - Z_o) \tag{5}$$

This expression is the same as that derived by Engel (1980). The average transport rate is obtained by integrating q_b over the whole length of the sandwave:

$$\bar{q}_b = \frac{1}{\lambda}\int_o^\lambda v_b \cdot \omega_s \cdot (Z - Z_o) \cdot dx \tag{6}$$

where λ = sandwave length.

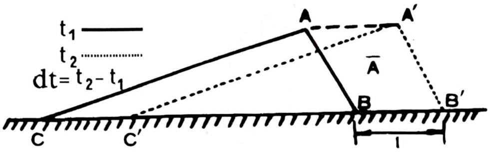

FIG. 1 Sketch of sandwave movement.

With the assumption of an idealized triangular bed form as shown in Fig. 1, the integration of equation (6) can be carried out:

$$\bar{q}_b = 0.5 \cdot v_b \cdot \omega_s \cdot \triangle \tag{7}$$

where Δ is the bed form height.

However, as previous researchers indicated, there are two reasons which make the coefficient not ½ but some other value:

(i) the assumption of an idealized triangle bed form is not accurate; and

(ii) the elevation of zero movement is not coincident with the elevation of the bed form trough.

In such a case, equation (7) becomes

$$\bar{q}_b = \alpha \cdot v_b \cdot \omega_s \cdot \triangle \tag{8}$$

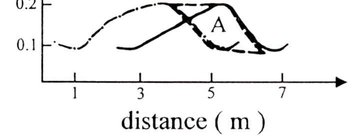

FIG. 2 Variation of bed form.

where α is the shape coefficient of a bed form. Equation (8) means that if ω_s and Δ of a bedform are determined, the average bed load transport rate can be calculated for a given value of α. However, previous experience has illustrated that it is very difficult to utilize equation (8) because of the difficulties in correctly measuring Δ, the height of a sandwave and ω_s, the celerity of its movement.

Figure 2 illustrates the profiles observed in a stream that indicate that sandwave movement in natural streams is unstable because of its three dimensional properties. It means, that, even in fully developed steady, two dimensional uniform flows, bedforms are still unstable. On the other hand, sandwave length, λ, varies over a great range from several centimetres to hundreds of metres. Sometimes, the length of a sandwave is so long that it is even impossible to obtain a complete observation of the badform. Based on such a situation, it is evident that som transformation of equation (8) is required to make it more suiteble for practical use. Referring to Fig. 2, which is a scheme of a sandwave movement, we can write:

$$\omega_s \cdot \triangle = \overline{A} / dt \tag{9}$$

where, $\overline{A}$ is the propagating area of the sandwave, and dt is the time interval between two measuring times t_1 and t_2. Substituting equation (9) into equation (8).

$$\bar{q}_b = \alpha \cdot v_b \cdot \overline{A} / dt \tag{10}$$

Equation (10) means that as long as the propagating area $\overline{A}$ and corresponding time interval dt between the two observations are known, the calculation of the bed load transport rate would be possible.

FIELD OBSERVATION

To test the validity of equation (10) in calculating bed load transport rates, a series of field observations were made in several small streams with substantial bed load transport. A typical example of these streams was the ShenShui River, a tributary of the Zijiang river, located in the middle part of China. Most of the observations were undertaken in the dry season when the suspended load was nearly zero and the water flow was so clear that the bed load movement could be viewed by the naked eye and a verification procedure could be readily employed by using a specially designed sampler. The selected stream reach was located near a hydrometric station where basic data on water flow such as water surface slope, water flow discharge, etc., were available. All the measurements were undertaken manually to avoid errors and uncertainties.

After the survey reach had been selected, a series of basic data were recorded. At the beginning of the measurement, two observation cross sections A and B at downstream

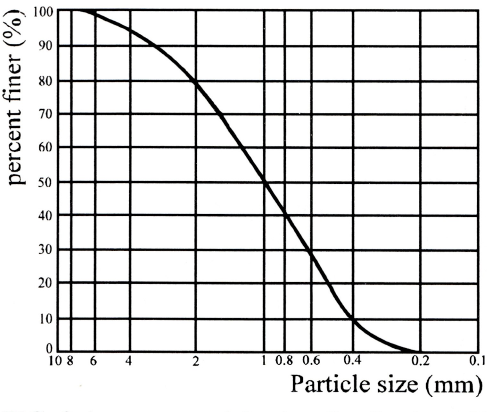

FIG. 3 Average particle size distribution of bed load.

and upstream unit of the study reach were fixed for controlling the measuring position. Along the surface of bed form a series of points were measured at time t_1, so that the profile of the bed form between the two fixed cross sections was obtained. After a predetermined time interval dt, which could be estimated by calculating the velocity of the sandwave movement a new profile at time t_2 was recorded at the same location between the cross sections. The two profiles were plotted on graph paper, and the propagating area A of the sandwave movement was measured. During the period of our experiments, little variation of the characteristics of the bed load sample was observed. The average particle size distribution is shown in Fig. 3. For verifying the measurement method suggested above, a typical hand-operated basket sampler suitable for the observation was designed. The basket sampler consisted of a rectangular frame and tail section, into which an open ended basket was fitted. The size of the sampler varied according to the dimensions of the bedform which was to be measured.

ANALYSIS OF THE OBSERVED DATA

(a) Value of the coefficient α

If the sandwave is in a stationary situation and the shape can be described by a standard triangle as shown in Fig. 1 (many previous researchers have made this assumption), it is

TABLE 1. Measured values of α in the present experiment.

River Name	No.	Δ	λ	A	α	No.	Δ	λ	A	α
Hunan Shen Shui River	1	0.900	1.60	0.059	0.410	8	0.120	1.80	0.122	0.565
	2	0.085	1.60	0.059	0.410	9	0.100	1.40	0.072	0.514
	3	0.055	1.50	0.075	0.550	10	0.025	0.70	0.008	0.486
	4	0.110	1.40	0.030	0.360	11	0.055	0.71	0.023	0.602
	5	0.100	1.30	0.073	0.474	12	0.045	0.91	0.018	0.452
	6	0.075	1.30	0.065	0.500	13	0.065	1.20	0.039	0.500
	7	0.081	1.52	0.052	0.533	14	0.091	1.62	0.078	0.529
Guang Dong Zenjang River	15	0.250	2.30	0.273	0.475	22	0.260	2.90	0.430	0.570
	16	0.220	2.20	0.295	0.610	23	0.250	2.10	0.295	0.558
	17	0.220	2.10	0.225	0.487	24	0.180	2.30	0.220	0.531
	18	0.100	1.60	0.090	0.563	25	0.090	1.40	0.075	0.595
	19	0.290	3.30	0.500	0.522	26	0.150	1.80	0.140	0.519
	20	0.100	1.20	0.050	0.521	27	0.130	1.70	0.115	0.520
	21	0.080	2.10	0.240	0.519	28	0.110	1.40	0.085	0.552
Guang Dong Dongjang River	29	0.060	2.10	0.090	0.714	33	0.120	2.30	0.165	0.598
	30	0.070	1.50	0.065	0.619	34	0.080	2.90	0.130	0.560
	31	0.060	1.90	0.050	0.439	35	0.070	2.50	0.100	0.571
	32	0.100	1.90	0.095	0.500	36	0.090	2.10	0.110	0.595

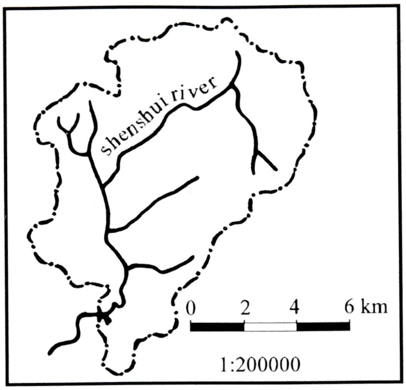

FIG. 4 Map of the experimental site.

evident that the value of α is 0.5. But unfortunately, as described in preceding section, sandwave movement in natural streams is neither stationary nor in a standard triangle shape but with an arbitrary shape. For using the simplified equation (10) in the calculation of bed load transport rate, the value of α must be correctly determined. For this special purpose, a series of observations were conducted in the present experiment. The experimental results listed in Table 1 show that α varies between 0.62 - 0.36, with an average value of α <0.53, which is also in fairly good agreement with the laboratory experimental results of Wang (1988). Further analysis of these data indicates that the case of α <0.5 corresponds to a declining stage of bed form and the case of α <0.5 corresponds to a developing stage. The scatter of the observed data implies that in natural streams many of the bed forms are in an unsteady state, with some decaying and others developing.

(b) Application of Equation (10)

The increasing construction of hydraulic engineering works on mountain rivers where hydropower is to be exploited in recent years has created a requirement for estimation of bed load transport rates. Lack of confidence in applying existing sediment transport theories to rivers without sufficient data prompts a direct method for measuring the bed load transport rate. The ShenShui River, is typical of such a situation. Fig. 4 shows the study location where a reservoir was to be built for the purpose of flood prevention and hydropower generation. Up to the time when the experiments were conducted, there were no data available for the calculation of the bed load transport rate in the study reach. Tests were conducted under different discharge conditions. The procedure of the test was similar to the usual water discharge observation. A summary of the measurements is provided in Table 2. According to these data, a relation between water flow conditions and bed load discharge can be established.

TABLE 2 Characteristic values from the measurements.

q	V	H	Δ	ν_b	ω_s	G_s
$m^3s^{-1}m^{-1}$	$m\ s^{-1}$	m	m	$kg\ m^{-3}$	$m\ s^{-1}$	$kg\ s^{-1}$
0.039~0.102	0.26~1.19	0.08~1.34	0.01~0.42	1.20~1.37	0.72~520.0	0.05~52.0

The most simple sediment transport law (Colby, 1964) can be expressed as:

$$G_s = a \cdot V^b \tag{11}$$

where G_s is the bed load transport rate; V is the mean flow velocity; and a and b are the coefficient and exponent, respectively. Data from the sandwave measurement are utilized to determine the values of a and b in equation (11). The G_s versus V curve is plotted on log-log paper (Fig. 5). The fact that the relatively small scatter of these data permitted fitting a straight line through them justified the form of equation (11). The best fit line drawn through these points by regression methods yielded values of a and b of 22.5 and 4.0, respectively. Equation (11) then becomes:

$$G_s = 25.5 \cdot V^{4.0} \tag{12}$$

Using equation (12), hydraulic engineers can easily estimate the volume of bed load transport in a certain time interval and the volume of deposition in the reservoir.

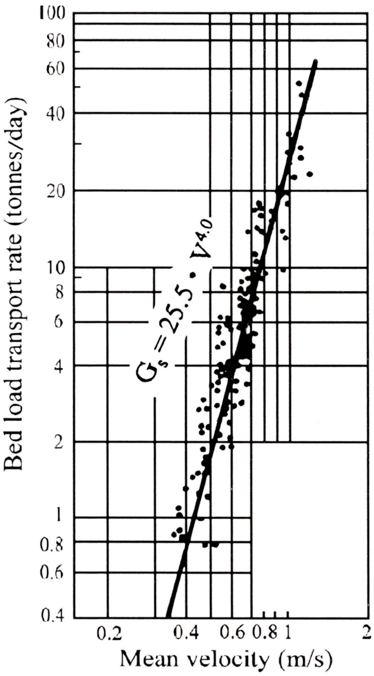

FIG.5 Relation between bed load transport rate G_s and mean flow velocity V

CONCLUSION

In natural streams with significant bed load movement, bed load discharge can be easily estimated with sufficient accuracy by measuring and recording bed configuration. Experiments illustrate that the method is not only suitable for a single profile along the direction of water flow but also appropriate for cross-sections in order to calculate the average bed load transport rate in a stream reach. The coefficient α varies between 0.36~0.62 with an average value of 0.53 which is in good agreement with the results of some laboratory research. Application of equation (10) in a small stream in Middle China indicates that the procedure of sandwave measurement can be used for practical engineering design.

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