Development of AYT gravel bed-load sampler and method for bed-load measurement

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Abstract The Bureau of Hydrology, Changjiang Water Resources Commission, China, has developed a new type of low pressure-difference gravel bed-load sampler based on basket-type and pressure-difference bed-load samplers. The new sampler is called the AYT bed-load sampler and it can be used to measure gravel bed load coarser than 2 mm. The main attributes of the sampler are its high stability, small resistance and acceptable resistance distribution, a thin base and a close fit between sampler and bed material. The sampler's hydraulic efficiency, K_v, is slightly larger than 1 and its sampling efficiency in a rough bed is close to 60%. The error of cross-sectional bed-load measurement is related to bed-load transport rate, sediment size, the number of verticals and the sampling duration. The influences of sampling duration and repeat times on measurement error, the number of sampling verticals and their placement, and the relationship between hydraulic factors and annual bed load have also been analysed.

INTRODUCTION

Bed-load measurement continues to be a significant problem in hydrological measurement in most countries. This is mainly due to fast flowing and fluctuating streamflow and the uneven distribution of the bed load over the cross-sectional width of the stream. The development of a bed-load sampler with high sampling efficiency is yet to be achieved. At present there are two main types of samplers widely used in the world, the basket-type and pressure-difference type. In China the basket-type is commonly used and is suitable for gravel bed load greater than 10 mm. However, it has large resistance to flow, low sampling efficiency and stability, and a hydraulic efficiency of approximately 0.9. The Helley-Smith pressure-difference bed-load sampler developed by the US Geological Survey is suitable for measuring bed load finer than 10 mm, with high hydraulic efficiency of 1.54 and high sampling efficiency. However, the sampling efficiency is unstable and varies with sediment size, and its rigid base makes the sampler difficult to fit to the riverbed. Two samplers have to be used at a hydrological station where bed load is coarser than 2 mm, that is, for bed load both coarser and finer than 10 mm. Therefore, a new bed-load sampler that is suitable for measuring all gravel coarser than 2 mm needed to be developed. After considerable efforts, the Changjiang Water Resources Commission (CWRC) and other organizations have developed a new type of low pressure-difference bed-load sampler—the AYT bed-load gravel sampler (Gao & Zheng, 1995). This paper introduces recent achievements in bed-load measurement and calculation, including measurement errors, the required number of sampling verticals and their placement and methods to determine bed load in a given period.

DEVELOPMENT OF THE AYT GRAVEL BED-LOAD SAMPLER

The AYT series bed-load samplers are low pressure-difference type and suitable for gravel bed load coarser than 2 mm (see Fig. 1 and Table 1).

When the bed-load sampler is placed on the riverbed, the flow field in front of sampler gate is different from the natural flow field due to disturbance by the sampler body and gate. The flow velocity is changed in both magnitude and direction (see Fig. 2). Under the changed flow field the volume and the size of the bed load entering the sampler are different from that under natural conditions. This raises the issues of sampling efficiency and sampler performance.

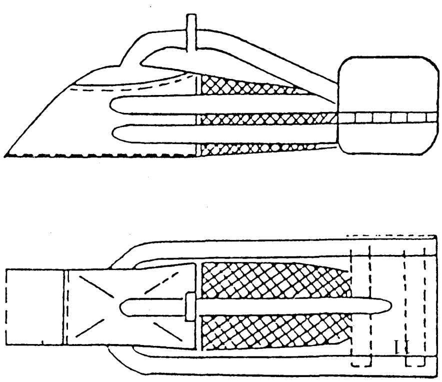

Fig. 1 AYT bed-load sampler.

Sampler performance

Stability The stability of the sampler relates to how and where it is placed on the riverbed, including how it is submerged into the flow. To achieve maximum stability the sampler gate should face the direction of flow and the sampler body should be kept in line with the direction of flow when placed on the riverbed.

Table 1 The AYT bed-load samplers.

	Size (mm): Gate Width	Gate Height	Total Length	Total Height	Volume (kg)	Weight (kg)	Available for: Particle size (mm)	Depth (m)	Velocity (m s^{-1})	Performance index: K_v	η (%)
1	120	96	760	176	10	40	2–100	40	4.0	1.02	$\eta=4.85G_A^{0.058}$
2	300	240	1900	438	60	320	2–250	40	4.5	1.02	"
3	450	360	2850	657	180	600	2–400	30	5.0	1.02	"

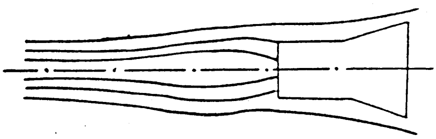

Fig. 2 Flow field in front of the sampler gate.

Resistance to flow The magnitude and distribution of the resistance are the main factors that induce the change of the flow field in front of sampler gate. To minimize resistance and provide a proportional resistance distribution, the sampler should have small gate area and small cross-sectional area and a streamlined body.

Hydraulic efficiency K_v K_v is defined as the ratio of the average velocity in front of sampler gate, V_f, to the natural average velocity at the point the sampler is located, V_n. In theory, K_v should be equal to 1. However, the particles entering the sampler gate have to rise at least the height of sampler base and overcome other resistance to enter the sampler, therefore K_v should be slightly larger than 1. It is obtained by:

$$\Delta K_v = K_v - 1 = \left(\frac{2g\Delta H}{V_n^2} \right)^{0.5} \qquad (1)$$

here, g is the acceleration due to gravity (9.81 m s^{-2}); ΔH is the thickness of the sampler base.

Base thickness A thin sampler base can closely fit the riverbed and thus increase the sampling efficiency.

Basic indices

Basic size The gate width is the dominant dimension of the sampler and should be slightly larger than the maximum expected particle size. Based on the gate width, other dimensions can be determined according to the structure and functions of the sampler. The gate height should be taken as 80% of the gate width.

Weight The sampler weight should be large enough to keep its deviation angle smaller than 45°. The weight should also be related to the flow depth and velocity.

Sampler body and main parts

Sampler body The main parts of the sampler are the gate, the control and widening reaches. The gate is skewed with a 45° angle. The length of the sampler is equal to its height and the base is 6 mm thick. The base is connected to the sampler by small steel plates and rings. The function of the control and widening reaches is to produce a proper negative pressure difference and an acceptable K_v.

Method of suspension A cantilever arm with one sliding point is the method of suspension.

Streamlined body The top and two sides are streamlined to reduce resistance and increase hydraulic efficiency K_v by about 1% and sampling efficiency η by about 3%.

Sample storage bag The storage bag is made of nylon mesh and is placed immediately after the widening reach. The diameter of nylon mesh is determined by the minimum particle size.

Influence of the widening reach on K_v and η

The sampler performance is affected by number of factors including K_v, the pressure difference produced by the widening reach, the resistance magnitude and distribution of the sampler body and the resistance of the inner body and the sample storage bag. Among them K_v is one of the key factors. A number of tests on the relationship between the widening ~ K_v ~ η have been conducted (Table 2). K_v and η are closely related to the ratio of intake area and end area and the length of the widening reach. The widening angle, α, is defined as:

$$\tan\alpha = \frac{R_2 - R_1}{L} \tag{2}$$

here, R_1 and R_2 are the hydraulic radii of the intake and end cross-section of the widening reach, respectively; L is the length of the widening reach. Through field and large flume tests, it can be seen that K_v and η are closely related to α (Fig. 3). The sampler length and α have been optimized, and α should be in the range of

Table 2 Tests on widening reach ~ K_v ~ η.

Group	No.	Gate size (mm): Width	Height	R_1	Length (mm): Control reach L_1	L	Widening Ratio of intake and end areas	α	K_v at: Intake of gate	Middle of gate	End of gate	η (%)
1	1	60	54	14.21	50	50	1.00	0		0.914		48.4
	2	60	54	14.21	50	50	1.20	1.52		0.938		49.8
	3	60	54	14.21	50	50	1.50	3.57		0.964		58.5
	4	60	54	14.21	50	50	2.00	6.53		0.976		47.6
2	1	120	102	27.55	100	120	1.50	2.89		1.015		40.7
	2	200	170	45.95	167	200	1.50	2.88		1.020		31.7
	3	120	102	27.55	100	120	2.50	4.61		1.025		30.1
3	1	150	120	33.33	130	200	1.30	1.37	1.009	1.010	1.136	52.5
	2	150	120	33.33	130	200	1.50	2.15	1.020	1.045	1.190	53.9
	3	150	120	33.33	130	200	1.84	3.43	1.032	1.054	1.208	58.2
	4	150	120	33.33	130	200	2.06	4.20	1.025	1.042	1.226	51.2
	5	150	120	33.33	65	200	1.44	1.95	1.022	1.036	1.180	48.0
Finally selected		150	120	33.33	130	200	1.64	2.70	1.03	1.05	1.20	55.4

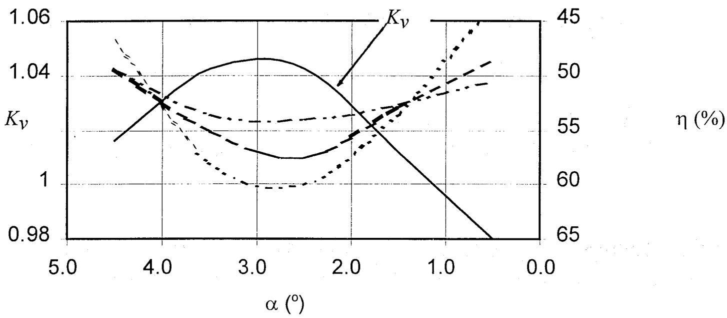

Fig. 3 Relationship between α, K_v and η.

2°~3°. Finally, the optimized AYT bed-load sampler performs well with high stability for K_v = 1.02 and η >50% on a rough bed. For a study of the upper reach channel of the Yangtze River (D_{max} = 250 mm), the main dimensions of the AYT sampler were: gate width = 300 mm; gate height = 240 mm; body length = 916 mm; total length = 1900 mm; total height = 438 mm; weight = 320 kg; K_v = 1.02, and η varied with the bed-load transport rate G_A measured by the AYT sampler as follows:

$$\eta = 48.5 G_A^{0.058} \quad (\%) \tag{3}$$

The average η value was 55.4% (for G_A = 0.5~500 kg s^{-1}). The comparison of size distribution measured by AYT and the pit hole method is shown in Fig. 4.

METHODS FOR BED LOAD MEASUREMENT

Methods for measurement of cross-sectional bed-load transport rate

Because of streamflow fluctuations and the uneven distribution of bed-load transport over the cross-section of flow, samples should be taken at a number of sampling verti-

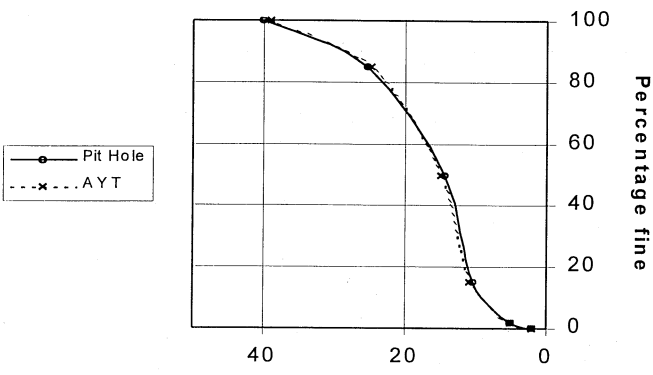

Fig. 4 Comparison of particle size by the AYT sampler and the pit hole method.

cals in a cross-section and sampling should be repeated several times at one vertical. The sampling duration and repeat times at a vertical and the number and placement of the verticals in a cross-section have been evaluated by CWRC with the aim of identifying an achievable and economic work load for a required measurement accuracy.

Sampling duration and repeat times at a vertical Considering firstly measurement error for bed-load transport rate per unit width. The temporal variation of bed-load transport rate per unit width follows the theory of the Poisson distribution. Its coefficient of standard deviation C_v for non-uniform particles (the case of general gravel bed) can be expressed as:

$$C_v = \left[\sum_{L=1}^{m} R_{bL} \left(\frac{R_{bL}}{R_{1L}} - 1 \right) + \frac{\pi \gamma_s D_0^3}{6btq} \right]^{0.5} \tag{4}$$

here, b is the gate width of sampler; t is the sampling duration; q is the temporal average bed-load transport rate, D_0 is the equivalent sediment size; γ_s is the sediment density; R_{bL} and R_{1L} are the weight percentages of sediment group L accounting for the total bed load and bed material, respectively; and, m is the number of sediment groups. From the equation it can be seen that the measurement error for bed-load transport rate increases with decreasing sampling duration and transport rate, and increasing sediment size.

Considering secondly the effect of sampling repeat times on error. If a sample is repeatedly taken n times, the coefficient of standard deviation for non-uniform sediment is:

$$C_v' = \left[\frac{1}{n} \sum_{L=1}^{m} R_{bL} \left(\frac{R_{bL}}{R_{1L}} - 1 \right) + \frac{\pi \gamma_s D_0^3}{6btq} \right]^{0.5} \tag{5}$$

It can be seen that if the sampling duration t is long enough, the second item in the above equation can be ignored. Increasing the number of sampling repetitions will result in smaller errors.

Considering thirdly field tests on sampling duration and repeat times. Tests have been conducted at the Cuntan, Wanxian, and Yichang stations on the Upper Yangtze River. Table 3 shows the coefficients of standard deviation for different sampling duration and repeat times. It indicates that C_v decreases with increasing bed-load transport rate and sampling repeat times which is in agreement with the with theoretical analysis.

Table 3 Coefficient of standard deviation of bed-load transport rate.

No.	Stations	Repeat times	Duration (minutes)	Average transport rate (g s^{-1} m^{-1})	C_v for repeat times of:					
					1	2	3	5	6	10
1	Cuntan	26	5	0.85	1.70					
2	Yichang	60	3	1.54	1.39		0.97	0.83		0.65
3	Wanxian	60	5	2.57	1.19	0.86	0.75		0.62	
4	Yichang	60	3	40.0	1.04		0.62	0.49		0.36

Numbers of vertical and placement *The number of verticals*—if m independent verticals are measured in a cross-section, C_v is:

$$C_v = \left\{ \sum_{j=1}^{m} \left[\left(\frac{b_j}{B} \frac{q_j}{q} \right)^2 (v_j - 1) + \frac{\pi \gamma_s D_{0j}^3}{6bt_j q_j} \right] \right\}^{0.5} \tag{6}$$

where, q_j and q are the vertical and cross-sectional bed-load transport rates per unit width, respectively; b_j is the representative width of q_j; D_{0j} is the representative bed-load size at vertical j; B is the width of bed-load transport band; the uneven coefficient of size distribution of bed material, v_j, is defined as:

$$\sum_{L=1}^{m} \frac{R_{bLj}}{R_{1Lj}} \tag{7}$$

When the sampling duration is long enough, the second item in equation (6) can be ignored. Assuming that the lateral distribution is even $q_j/q = 1$; and if the vertical intervals are equal, $b_j = b = B/m$, then equation (6) can be simplified as:

$$C_v = \left\{ \frac{v_j - 1}{m} \right\}^{0.5}$$

This indicates that C_v is in inverse proportion to the square of the number of verticals. If one wishes to reduce C_v by ¼, then the number of verticals should be 16.

Placement of verticals in a cross-section—from equation (6) it can be seen that if:

$$\frac{b_j}{B} \frac{q_j}{q} = 1$$

C_v reaches a minimum. Therefore, to minimize C_v all segments divided by verticals should have equal transport rate. But this is difficult to do in practice. Usually more verticals are placed in the band with a higher sediment transport rate.

Field tests on the number and placement of verticals—The test results for the Yangtze River are shown in Table 4. This shows that, in general, the error for verticals with equal interval is usually the greatest and that the error decreases with an increasing number of verticals.

Methods for measurement of bed load in a given period of time (e.g. a year)

One method is to programme the measurements necessary over the full period to

Table 4 Errors for different vertical placements.

Station	q (kg s^{-1})	Vertical placement	C_v (%) for verticals of				
			18	13	10	6	3
Zhutuo	25.5	With equal interval	3.2	1.1	6.4	8.3	39.3
		With equal transport rate	1.4	2.8	4.1	5.4	6.9
		More verticals for high transport band rate	0.2	0.3	0.9	4.5	12.5
Cuntan	4.75	With equal interval	2.4	0.1	9.1	7.0	22.0
		With equal transport rate	4.1	6.0	0.1	13.5	25.4
		More verticals for high transport band rate	1.3	3.6	7.0	20.1	24.1

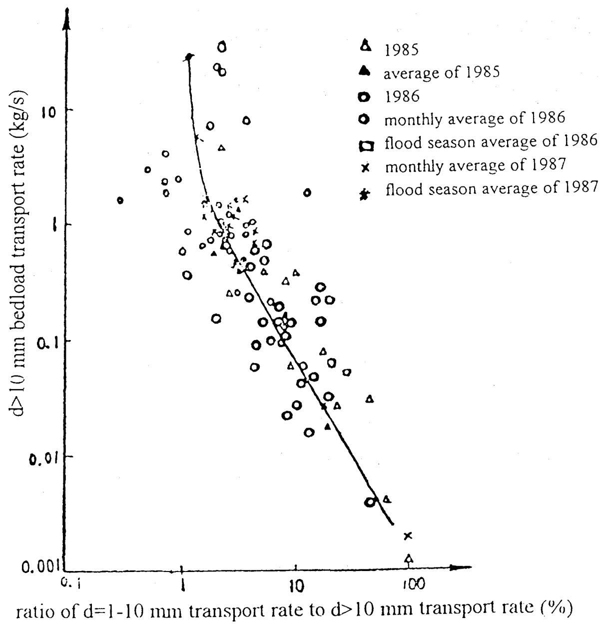

Fig. 5 Correlation of the bed-load transport rates at Cuntan station.

fully understand sediment transport processes in the river reach and calculate the bed load for the period. This method has high accuracy but requires a large amount of work and is therefore only used at a few specific stations (Gao, 1991). There are some simple methods available that require a reduced amount of work.

Relationship between velocity and bed-load transport rate There is strong correlation between bed-load transport rate and flow velocity, as follows:

$$q_s = a(V - V_0)^b \tag{8}$$

here, q_s is the cross-sectional bed-load transport rate; V and V_0 are flow velocity and threshold velocity for bed-load sediment, respectively; and, a and b are coefficients. q_s can be calculated from this equation.

Correlation between transport rates of different sediment sizes The data from Cuntan Station on the Yangtze River show that there is strong correlation between bed-load transport rates of sediment sizes in range of 1~10 mm and coarser than 10 mm as in Fig. 5. From this relationship the bed-load transport rate for sediment size in range of 1~10 mm can be obtained from that for sediment coarser than 10 mm.

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