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COMPUTATION OF BED LOAD USING BATHYMETRIC SURVEY DATA

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MANAGEMENT PERSPECTIVE

Measurement of the sediment transported by dune movement in large rivers cannot be obtained within reasonable engineering tolerances by conventional bottom sediment samplers.

This report describes a method in which successive echo sounding tracers may be analyzed to provide a reliable estimate of bed-load transport.

Laboratory studies, simulating conditions indicate that the procedure advocated, estimates the solid discharge to within ±20% of its true value which is a good improvement on other methods.

The procedure could be adapted for any dune type movement in rivers, or tidal coasts.

T. M. Dick, Chief
Hydraulics Research Division

PERSPECTIVE GESTION

La mesure des sédiments transportés par les dunes en mouvement dans de grands cours d'eau, ne peut être obtenue dans une marge de tolérance acceptable par des échantillonneurs classiques de sédiments de fond.

Ce rapport décrit une méthode permettant d'analyser les traceurs successifs de sondage par écho afin de fournir une estimation fiable du charriage de fond.

Les études en laboratoire c.-à-d. par simulation, indiquent que le procédeé préconisé donne une estimation de l'écoulement solide de + à - 20 p. 100 de sa valeur réelle, ce qui représente une bonne amélioration par rapport aux autres méthodes.

Ce procédé peut être adapté à tout genre de mouvement de dune dans les cours d'eau ou sur les côtes maritimes.

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KEY WORDS: Bathymetric survey; Bed form; Bed load; Sediment transport.

ABSTRACT: A method of calculating bed-load transport is presented. This method takes advantage of the rapid bathymetric surveys which can be made in large rivers. The proposed equation is based on sediment continuity and an assumption for the base level of zero transport. Experimental data were obtained in a series of flume tests and the measured transport rates are compared with the calculated transport rates using the proposed equation. Comparisons are also made with the Ackers-White Equation.

MOTS CLÉS: Levé bathymétrique; forme du lité charriage de fondé transport des sédiments

SOMMAIRE: On explique comment calculer le charriage de fond d'après les levés bathymétriques qu'on peut faire rapidement dans les grands cours d'eau. L'équation proposée repose sur la continuité des sédiments et sur une hypothèse du niveau de base de tranport nul. Les données expérimentales proviennent d'une série d'essais en canal sur appuis et les taux de transport mesurés sont comparés aux taux de transport calculé en utilisant l'équation proposée. On effectue également des comparaisons au moyen de l'équation d'Ackers et White.

COMPUTATION OF BED LOAD USING BATHYMETRIC SURVEY DATA

by Peter Engel[1] and Y. L. Lau[2]

INTRODUCTION

The total sediment load in a river is composed of suspended as well as bed-load transport. Whereas the suspended load can often be determined with sufficient accuracy by direct measurement, this is not the case for bed load. Present methods, such as the use of bed-load samplers (12) and tracer techniques (8) are, as yet, too imprecise, time consuming and costly for general application in large rivers. These limitations indicate that there is room for further development of measurement methods.

Hydrographic survey systems (5, 4) have been developed to conduct bathymetric surveys of reservoirs, estuaries and other bodies of water. These systems obtain bed profiles using echo sounders on a rapidly moving boat, the horizontal control of which is maintained with telemetric units on shore. Surveys can be made quickly and precisely and when applied at a suitable frequency over a given traverse, will provide both spatial and temporal data. In this paper a method is presented with which bed load can be computed using data obtained directly from surveys of river-bed profiles. Experimental data are used to test the proposed method.

THEORETICAL DEVELOPMENT

During the time in which two successive profile measurements are taken, there has been a transport of bed load through the downstream propagation of the bed forms. Various investigators (3, 11, 14) have attempted to relate bed-load transport to some bed-form height and speed. Cheong and Shen (2) assumed that alluvial bed forms can be represented by a Gaussian random process and showed that the downstream velocity of a point on the sand wave does not depend on its position on the wave. They concluded that although the shape of the individual bed forms may change as they progress downstream, there is a statistical constancy of form. This makes it possible to use average parameters describing the bed form migration to compute the bed load transport.

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With reference to Figure 1, it has been shown by Crickmore (3), that the volumetric bed load transport rate at a given point x can be given as

$$q_s = U_w (\eta - \eta_o) \tag{1}$$

in which q_s=volumetric transport rate at point x per unit width, including the voids, U_w=bed form speed, η=bed elevation at any given point and η_o=elevation of zero transport. The transport over a full bed form is obtained from

$$\bar{q}_s = U_w \frac{1}{\Lambda} \int_o^{\Lambda} (\eta - \eta_o)\, dx \tag{2}$$

in which $\bar{q}_s$ =average volumetric transport rate over a bed form, per unit width including the voids and Λ=length of one bed form. When considering a profile record with many bed forms, the average transport rate is obtained by averaging over the whole length of the record. Therefore one obtains

$$\bar{q}_{sa} = U_w \frac{1}{L} \int_o^{L} (\eta - \eta_o)\, dx = U_w (\overline{\eta - \eta_o}) \tag{3}$$

in which $\bar{q}_{sa}$=average volumetric transport rate over the whole length of record; L=length of profile record and $\overline{(\eta-\eta_o)}$ = average thickness of the sediment layer above a base level of zero movement.

The values of η can be obtained from the echo soundings and the value of U_w can also be calculated from the profile records, as will be shown later. However, the value of η_o is not normally known and a means of determining η_o must be found before Eq. 3 can be used.

It has been pointed out that the usual assumption that η_o is the same as the trough elevation η_o is not correct (7). For ripples and dunes, upstream movement of material can be observed to begin at the point of flow reattachment (Fig. 1) and the elevation of zero transport is in the immediate vicinity of the reattachment point. Jonys (6) measured the pressure distribution along moving bed forms and found that the maximum mean pressure occurred at the point of the separation stream-line reattachment on the upstream face of the bed forms. This was the same as found by Raudkivi (10). The measurements of Jonys for a large number of bed forms showed that the location of maximum pressure was relatively constant and could be taken to be above the trough elevation, η_t, by an amount equal to 0.17 times the bed-form height.

Using this value fo η_o, Eq. 3 can be written as

$$\bar{q}_{sa} = U_w \overline{(\eta - \eta_t - 0.17\Delta)} \tag{4}$$

in which η_t= elevation of the trough and Δ= bed-form height.

For the computation of bed load, it is often assumed that the bed forms are triangular in shape. Willis and Kennedy (15) have stated that the assumption of triangular bed forms is sufficiently accurate as far as computations of transport rates are concerned. For idealized triangular bed forms, as shown in Fig. 2

$$\overline{(\eta - \eta_t)} = \frac{\bar{\Delta}}{2} \tag{5}$$

Substituting Eq. 5 into Eq. 4, one gets

$$\bar{q}_{sa} = 0.33\ \bar{\Delta}\ U_w \tag{6}$$

Eq. 6 gives the average transport rate in terms of the bed-form speed and an average bed-form height. Crickmore (3) suggests that, in practice, it is more convenient to use a parameter ξ which is equal to the absolute value of the departure of bed elevation from the mean bed level $\bar{\eta}$, i.e.

$$\xi = \left| \eta - \bar{\eta} \right| \tag{7}$$

For triangular bed forms $\bar{\xi} = \bar{\Delta}/4$ and Eq. 6 can be written as

$$\bar{q}_{sa} = 1.32\ \bar{\xi}\ U_w \tag{8}$$

Converting to submerged weight, the bed load can be computed from

$$\bar{G}_s = 1.32\ \gamma_s (1 - p)\ \bar{\xi}\ U_w \tag{9}$$

in which $\bar{G}_s$=average submerged weight of sediment transport per unit width, γ_s=submerged unit weight of sediment and p=porosity of sediment.

It is interesting to note that the coefficient of 1.32 in Eq. 9 is the same as that used by Crickmore (3). However, Crickmore obtained the coefficient by considering characteristic bed-form shapes and not from experiments related to the measurement of η_o. Crickmore tested his equation using essentially only one experimental run and found very good agreement.

The accuracy of using Eq. 9 to compute bed load was tested with a series of experiments in the laboratory.

EXPERIMENTAL EQUIPMENT

The experimental runs for this study were made in a tilting flume, rectangular in cross section, two meters wide with glass side walls 3/4 meters high and having an overall length of about 22 meters (Figure 3). The flume could be tilted to slopes of ±1%.

Water was fed from a large constant head tank through a 16 in. (0.406 m) I.D. pipe which was terminated by a diffuser in the head box of the flume. In addition, baffles were placed in the head box to ensure a satisfactory velocity distribution through the cross section of the flow at the entrance of the flume. Sediment was introduced into the flow from a gravity feed hopper located above the entrance section of the flume. The feed rate could be very accurately controlled by using a rotating, grooved shaft installed at the bottom of the hopper which was driven by a variable speed motor. The channel floor was recessed 20 cm below the lip of the head box floor so that the sand bed could be made level with the floor of the head box at the exit.

The water level in the flume was controlled by a set of vertical louvres at the downstream end of the flume. The flow leaving the flume was split into three streams, each of which flowed into a separate sediment trap. The two outside traps were used to collect sediment before steady state conditions were achieved while the centre trap was kept closed by means of a pneumatically controlled gate. Once steady state was achieved, the centre trap was also opened to begin collection of sediment for weighing. With this procedure, only the sediment transport from the centre portion of the flume, where the flow was close to being two-dimensional, was collected. The effects of side walls could more or less be neglected.

The sediment flume is equipped with a self propelled instrument carriage, which can travel along the length of the flume on rails fastened to the laboratory floor. This carriage was used for making profile traverses of the mobile bed water surface as well as for levelling the sand bed prior to a new run.

To measure the profiles, an adjustable instrument rack was used which was mounted on the upstream face of the carriage. The bed level and water level probes were mounted on this instrument rack. The bed level probe was an electro-optical sensor which followed the sediment bed very closely and can pickup change in bed elevation down to about 1.5 mm. The water-level probe measured the depth by maintaining contact with the water surface using the water as a conductor and thus·completing a circuit.

Displacement along the length of the flume was measured by an aluminum wheel whose circumference was 1/10 of the overall length of the flume. It was attached to the instrument carriage and travelled on the same rails. The wheel provides a signal that activates the pen carriage on an XYY' recorder, making it possible to repeat bed profiles over exactly the same traverses, thus ensuring changes in elevations are always observed at the same fixed points.

A Honeywell XYY' Model 540 TM recorder was used to record the signals received from the measuring wheel and the two profile probes. It produces an XY (displacement vs water level elevation) and an XY' (displacement vs bed level elevation) plot on Cartesian Coordinates on 28 x 42 cm graph paper.

Elapsed time was measured using a precision scientific electric digital stop watch. It could be read to 1/10 of a second and was able to accumulate up to 10,000 seconds.

The river wash sand used for the experiments in this study was fairly uniform in size with a median sieve diameter of 1.10 mm (Figure 4). Transported sediment collected in the traps had virtually the same size distribution as the material remaining on the flume bed. Most of the grains were not particularly spherical and their edges were of intermediate roundness. The specific gravity of the sand was found to be 2.65 and its average porosity was 0.45.

EXPERIMENTAL PROCEDURE

The experiments were divided into runs and profiles. A run was a test for a specific flow condition and consisted of a series of profiles a specific length of time apart.

To begin a run the flume was set at a slope which was expected to be close to the final equilibrium slope. This often reduced the time required to reach steady state conditions. Water was then passed very slowly over the carefully levelled sand bed with tail louvres closed until a depth of 60 cm was reached. The louvres were then gradually opened, the flow increased and the sediment feed started. Adjustments in depth, flow and sediment feed were continued until the flow was close to the desired depth. The sediment feed was carefully watched to ensure that there would be minimal agrading or degrading of the overall mobile bed.

When the flow was at or close to the required depth after dunes had formed, test profiles of the water surface and the bed were made to see if any changes were occurring. Attempts were made to compare the slopes of the water surface and bed profile to see if they were parallel, but this turned out to be too impractical. The bed was too irregular due to the presence of dunes and as a result the slope obtained for the bed had a large variance. Consequently, only the water-surface slope was used as an indicator of steady-state conditions. If water-surface profiles taken from 1/2 to several hours apart showed no appreciable change in slope and if on the average the sediment bed looked uniform and there was no visual evidence of agrading or degrading, then the water-sediment system was considered to be in equilibrium and the flow taken as being uniform. It usually took about 24 hours of continuous running to achieve this steady-state condition. Once this condition was achieved, measurements were begun to obtain the necessary data.

The profiles were measured over a working section nine meters in length, the upstream end of which was located nine meters below the flume entrance. All profiles were initiated at the beginning of the working section (x=0 on XYY' RECORDER) and taken on the centreline of the flume. At the start of the first traverse the digital stop watch was started and kept running during the entire run thereby providing a continuous, cumulative time record. At the end of each profile, the time was noted while the carriage stopped automatically. The carriage was then returned to its starting position. At the start of the next traverse, the accumulated time was noted and the same procedure followed as before. The run was usually completed when 20 or more traverses had been taken.

The water surface and bed profiles recorded on the XYY' recorder were digitized and the data stored on electromagnetic tape. A computer program was written to make linear interpolations between successive digitized values to convert the profile records into discrete, elevation points a fixed distance apart. This made it possible to compare all elevations for different profiles at the same points along the length of the profiles. There were 9000 such points, 1 mm apart, for each profile record.

The water discharge was obtained by measuring the overflow from the constant head tank which supplies the flume, using a large volumetric tank.

The sediment transport was collected in the centre traps from the time at which steady state conditions were achieved to the end of the run which, on the average, was about 12 hours. The sediment was withdrawn from the trap and placed into a steel box suspended from a monorail hoist. The box was then submerged in water and the submerged sediment weight obtained with a dynamometer which was accurate within 0.5 kg. The total sediment discharge rate was computed by dividing the weighed sand by the total elapsed time in seconds.

The water depth was obtained by taking the differences in elevations between the water surface and the bed using the digitized record. The average depth for a traverse was then the arithmetic average of all the differences taken. The overall average for a run was simply the average depth for all the traverses in that run.

The digitized water surface profile data was fed into a computer program to compute the water surface slope by linear regression. This was repeated for each traverse in a given run. The slope for the run was then simply the arithmetic average of the slopes for the individual traverses.

Data for the experiments are given in Table 1.

RESULTS AND ANALYSIS

Bed-Form Speed. - A number of methods can be used to evaluate the speed of the bed forms from profile records (9). These include the determining of mean period and mean wavelength from the average time and average distance respectively between zero upcrossing; as well as the ratio between centroidal values of frequency and wave number from the spectra. In the present case, because of the large numbers of profiles available, the bed-form speed U_W was obtained from the cross-correlation of successive profiles. Cross-correlations were performed on two successive profiles for different values of longitudinal displacement ℓ. The value of ℓ which produced the maximum correlation was taken as the average distance travelled by the bed forms during the time t. The speed was then computed from the relationship $U_w = \ell/t$. The U_w values obtained for all the pairs of profiles in a run were then averaged to obtain U_w for that run. Values of U_w are listed in Table 1.

Computation of Bed Load. - Fifteen runs were made but, after inspecting the data, five of the runs were discarded because of unsteady conditions. Values of $\bar{G}_s$ were then computed for the remaining ten runs with Eq. 9 and these are given in Table 2. Values of $\bar{G}_s$ were plotted versus the measured bed load $\bar{G}_m$ in Figure 5. Except for the case with the highest transport rate, the plotted points are quite evenly distributed about the line of equal agreement. Relative errors were then computed and these are also given in Table 2. The errors varied from -29.4% to +18.6%. Out of ten runs, six runs gave an error of less than 15% and for three runs the estimated bed load was within 10%. The average error was 5.9% with a standard error of 16.7%. This meant that there is a 95% confidence that the bed load can be obtained with an error between -39% and +27%. This is better than results attainable with present sampling methods.

These results indicate that the assumptions that the bed forms are triangular and that the base elevation of zero transport is at a distance of 0.17Δ above the trough appear to be justified, at least for the present experimental conditions.

A method of predicting sediment transport rate has been proposed by Ackers and White (1) and has been found to be superior to the most commonly used transport equations, such as those of Einstein, Meyer-Peter and Muller, Bagnold, Toffeleti, Engelund and Hansen etc. (13). The Ackers-White equations are rather involved and will not be repeated here but the sediment transport rate is calculated from knowledge of sediment properties, mean-flow velocity, shear velocity, flow depth and fluid discharge. With the data from Table 1, the sediment transport rates were calculated for the ten runs using the Ackers-White method. The calculated transport rates are also listed in Table 2 and plotted against the measured rates in Fig. 5. Even though the Ackers-White method is supposed to predict the total sediment load, it can be seen from Fig. 5 that, in every case, it is underestimating even the bed load in the present experiments.

TABLE 1. - Experimental Data

Run No. (1)	Flow Depth in Meters (2)	Discharge in Cubic meters per second (3)	Slope (4)	U_w in meters per second (5)	Measured Bed Load $\bar{G}_m$ in Kilograms per second per meter (6)
1	.1606	.175	.00184	6.02	.0166
3	.1665	.175	.00237	6.25	.0134
4	.1498	.150	.00171	5.37	.0089
5	.1544	.171	.00227	6.52	.0177
6	.1644	.203	.00313	10.87	.0336
7	.1626	.164	.00103	4.20	.0107
8	.1417	.160	.00196	7.33	.0171
13	.1270	.121	.00206	6.75	.0128
14	.1287	.124	.00208	7.79	.0153
15	.1358	.138	.00231	9.09	.0174

TABLE 2. - Computed and Measured Bed-Load Transport

Run No.		Equation 9		Ackers-White Equations	
(1)	$\bar{G}_m$ in Kilograms per second per meter (2)	$\bar{G}_s$ in Kilograms per second per meter (3)	% Error (4)	$\bar{G}_s$ in Kilograms per second per meter (5)	% Error (6)
1	.0166	.0145	-12.7	.0102	-38.6
3	.0161	.0143	-11.2	.0093	-42.2
4	.0089	.0106	19.1	.0057	-36.0
5	.0177	.0137	-22.6	.0125	-15.3
6	.0336	.0237	-29.5	.0233	-30.7
7	.0107	.0083	-22.4	.0062	-42.1
8	.0171	.0182	6.4	.0133	-22.2
13	.0128	.0119	- 7.0	.0046	-64.1
14	.0153	.0167	9.2	.0050	-67.3
15	.0174	.0195	12.1	.0077	-92.8
		Average % error=15.2		Average % error=45.1	

The average error for the ten runs is 45.1%. Thus, even the best predictive equations can give large errors and a method such as Eq. 9, which can be used to determine sediment transport from bed-form profiles, is still needed.

Base Elevation of Zero Transport. Eq. 9 was derived using the assumption that the base elevation of zero transport was above the trough of the bed form by the amount 0.17 Δ. Although this value was found to be relatively constant, based on pressure distributions measured by Jonys (6), it is reasonable to expect some variations as flow and bed-form characteristics are changed. The elevation difference $(\eta_o - \eta_t)$ depends on the length of the separation zone downstream of the crest as well as the steepness of the bed form. For large Reynolds numbers, $(\eta_o-\eta_t)$ should depend on Δ, bed-form length Λ, flow depth h, flow velocity u and gravitational acceleration g. Therefore

$$\frac{(\eta_o - \eta_t)}{\Delta} = \Phi\left(\frac{\Delta}{\Lambda}, \frac{u}{\sqrt{g\Delta}}, \frac{h}{\Delta}\right) \tag{10}$$

If the flow depth is large relative to the bed-form height, the variable h/Δ should not have much effect. Some simple experiments may be sufficient to determine the range of variation of $(\eta_o-\eta_t)/\Delta$ for dunes and ripples.

SUMMARY

A method of computing bed-load transport using bathymetric survey data has been presented. The final form of the equation given is based on the elevation of zero transport inferred from measurements of pressure distribution on bed forms made by Jonys (6) and also on the assumption that bed-form shapes may be represented by triangles. The computed bed-load discharges were in reasonable agreement with the measured discharges, with an error of -39% to +27% at the 95% confidence level. This is much better than results attainable with present-day sampling methods. The validity of the proposed equation can be tested by experiments on the elevation of zero transport using different bed-form geometries and flow velocities.

APPENDIX I - REFERENCES

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APPENDIX II - NOTATIONS

The following symbols are used in this paper:

g = gravitational acceleration;

$\bar{G}_m$ = measured average submerged weight of sediment transport per unit width;

$\bar{G}_s$ = average submerged weight of sediment transport per unit width;

h = depth of flow;

ℓ = longitudinal displacement of profile records;

L = length of profile record;

p = porosity of sediment;

q_s = volumetric transport rate per unit width;

$\bar{q}_{sa}$ = average volumetric transport rate;

t = time interval between successive profile measurements;

u = flow velocity;

U_w = speed of bed forms;

x = distance in downstream direction;

Δ = bed-form height;

η = bed elevation;

η_o = elevation of zero transport;

η_t = elevation of trough;

ξ = absolute value of departure of bed elevation from mean;

γ_s = submerged unit weight of sediment;

Φ = a function.

CAPTIONS

Fig. 1	Dune profile Definition Sketch
Fig. 2	Idealized Triangular Bed Form
Fig. 3	Sediment Flume and Instrument Carriage
Fig. 4.	Grain-Size Distribution of Test Sand
Fig. 5	Comparison of Measured and Computed Bed Load

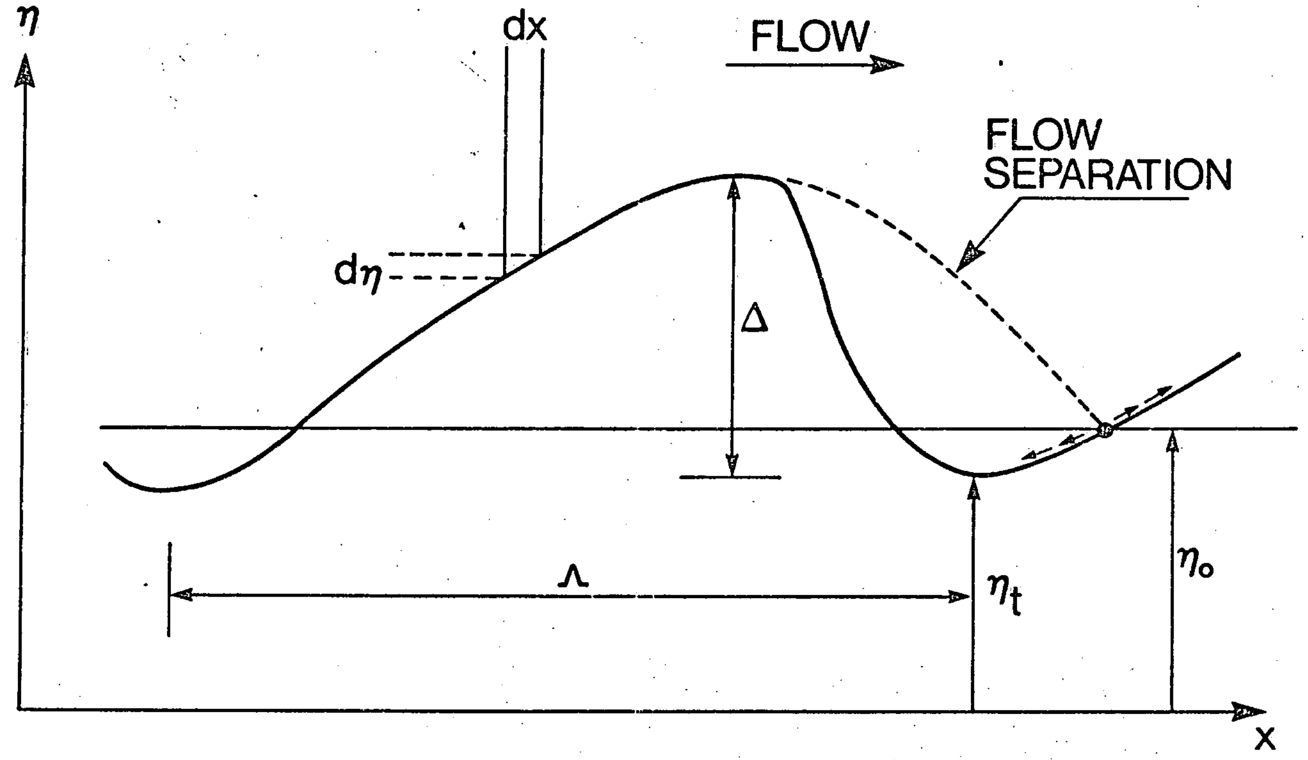

FIGURE 1. DUNE PROFILE DEFINITION SKETCH

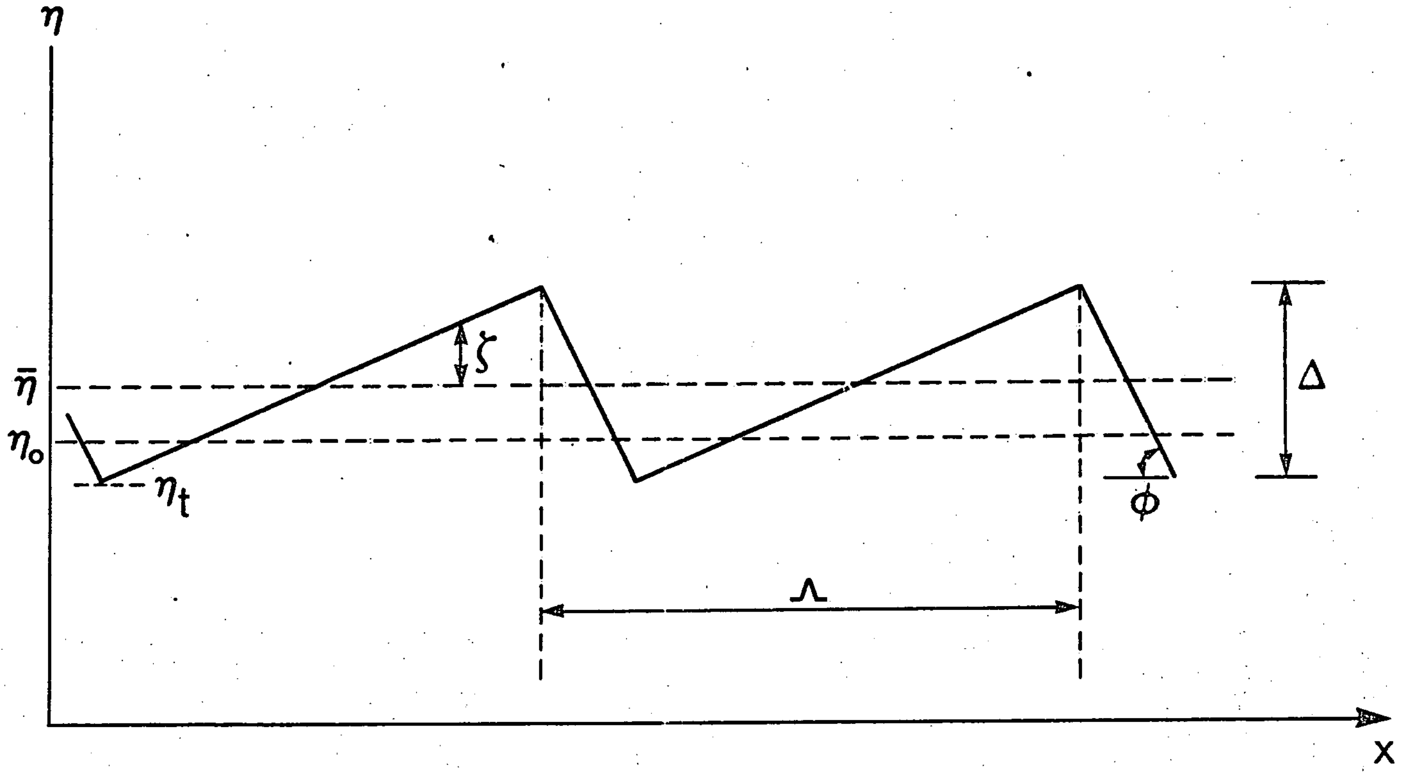

FIGURE 2. IDEALIZED TRIANGULAR BED FORM

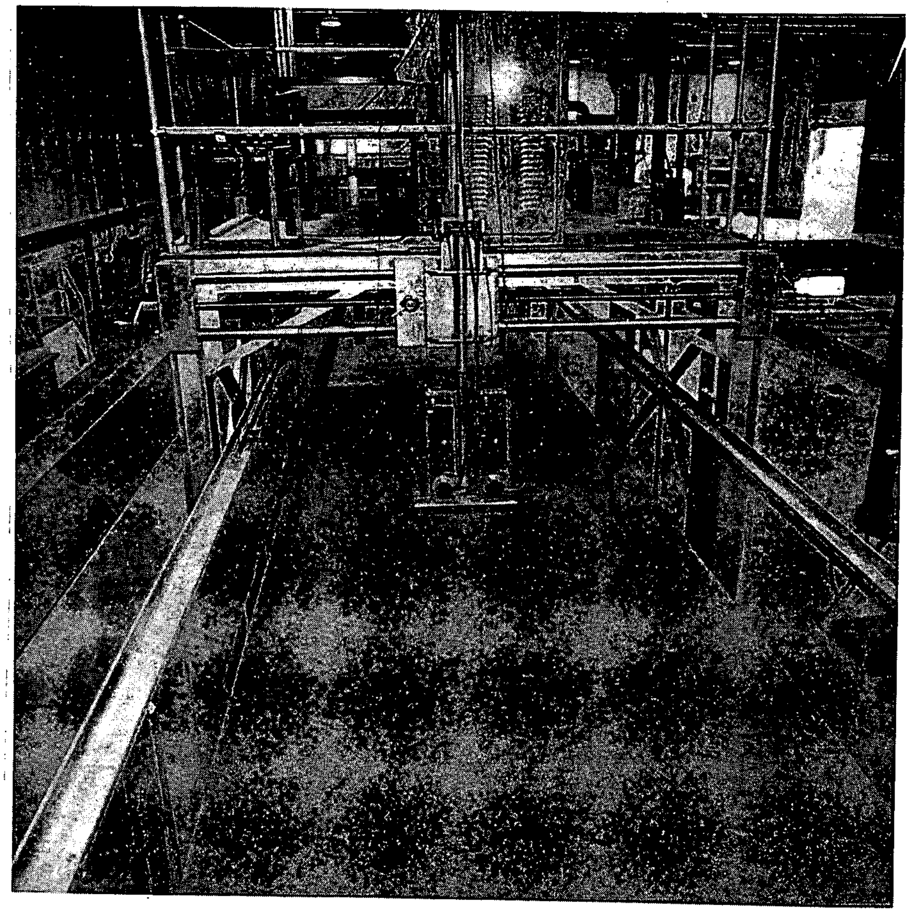

FIGURE 3. SEDIMENT FLUME AND INSTRUMENT CARRIAGE

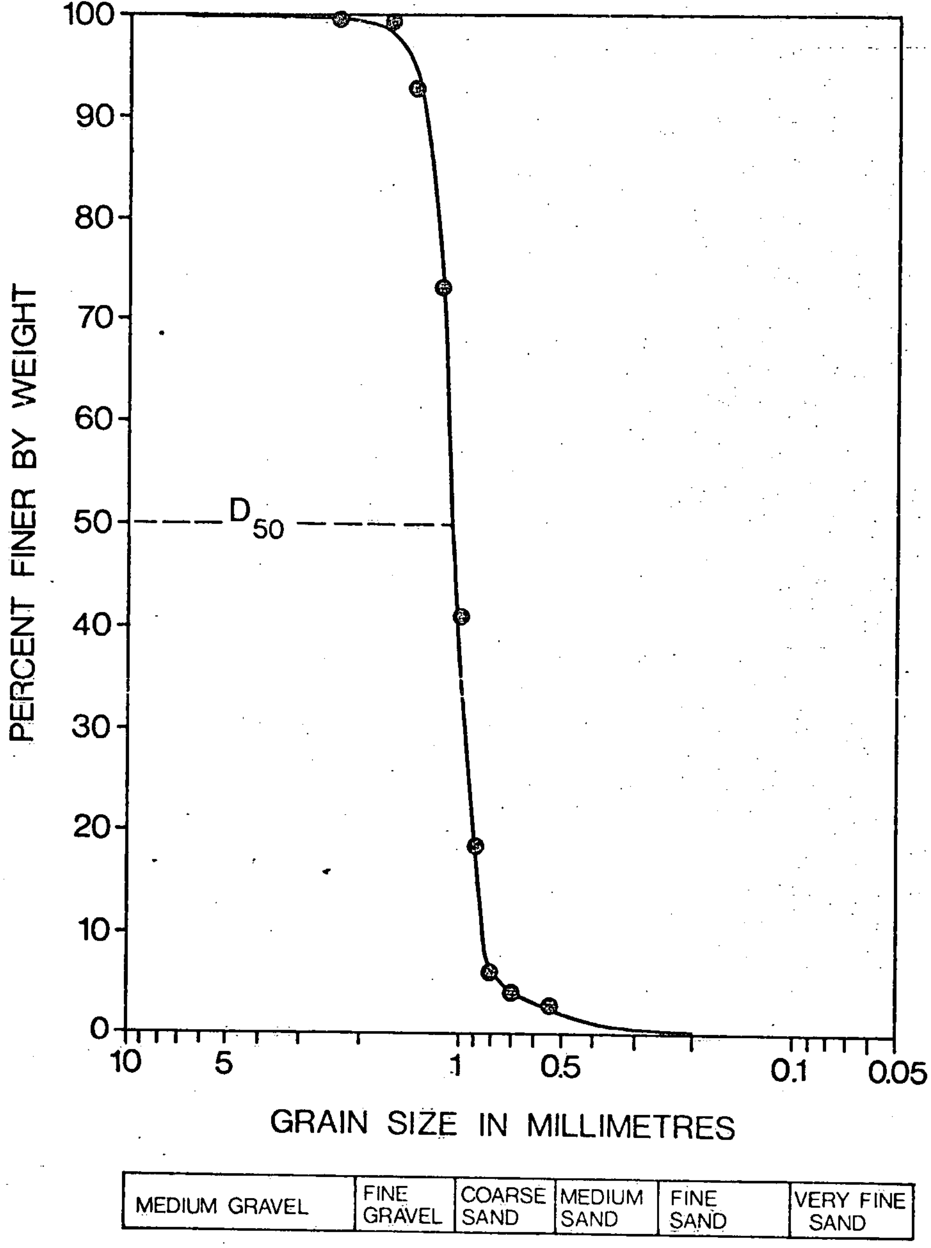

FIGURE 4 GRAINSIZE DISTRIBUTION OF TEST SAND

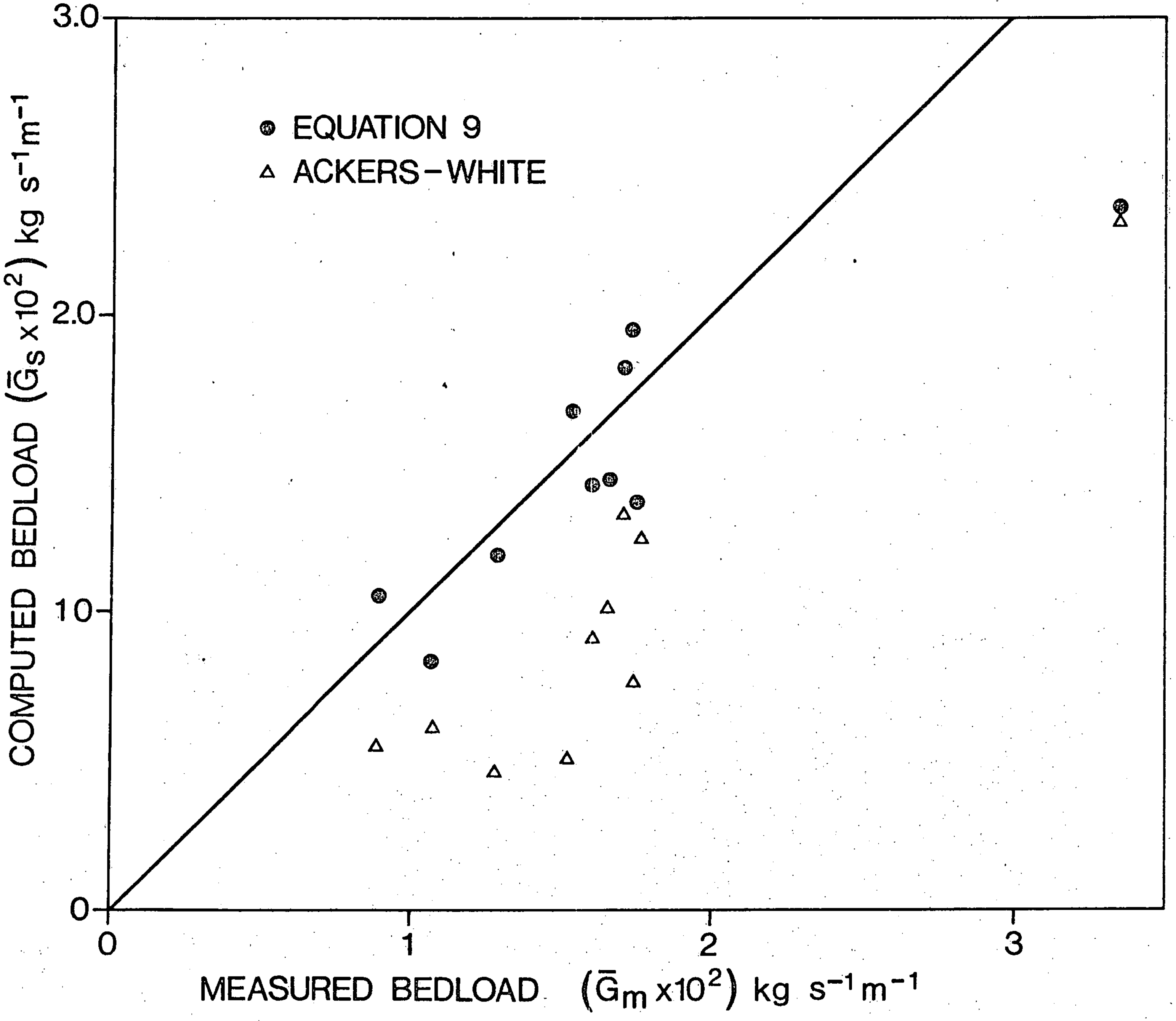

FIGURE 5. COMPARISON OF COMPUTED AND MEASURED BEDLOAD