Threshold of sediment deposition in medium stream power flow

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Abstract The latest results of a research programme on the beginning of sediment deposition in flowing water, and therefore about the maximum bed load capacity, confirm that stream power per unit of bed surface area is the best hydraulic variable to predict deposit formation, and that there are three types of bed load transport with different energy consumption laws. Two simple, equally reliable, criteria are proposed to identify the beginning of deposition, and a single expression for maximum bed load transport capacity is proposed, valid when solid loads and bed lining have the same grain size. These conclusions can be applied to flows in rough fixed bed canals transporting coarse sand with a Froude number ranging from 0.55 to 1.25, and maximum stream power of 0.3 kg m^{-1} s^{-1}.

NOTATION

d	mean diameter of sediment [L]
d_i	diameter of transported sediment [L]
d_f	diameter of bed material [L]
g	gravitational acceleration [L T^{-2}]
g_v	unit solid discharge in volume [L^2 T^{-1}]
k	ratio between weight of wet material gathered in the slot and the same after drying
N	number of grains deposited on bed
q	unit flow [L^2 T^{-1}]
C_u	uniformity coefficient of sands
F	Froude number
I	channel slope
V	mean flow velocity [L T^{-1}]
X	dimensionless solid load factor
Y	dimensionless flow factor
Z	dimensionless sediment factor
γ	specific weight of fluid [M L^{-2} T^{-2}]
η	rate of deposition
λ	length of deposition
μ	dynamic viscosity [M L^{-1} T^{-1}]
ν	kinematic viscosity [L^2 T^{-1}]

ρ specific mass of fluid [M L^{-3}]
τ bottom shear stress [M L^{-1} T^{-2}]
ϕ function

INTRODUCTION

In order to understand sediment routing in rivers and mountain streams, and, more generally, to establish sediment budgets in river basins, it is essential to know hydraulic conditions at which the sediment transported by free flow begins to deposit.

When these critical conditions are met, solid particles transported by a flow are deposited and rest on the river bed; this means maximum load capacity has been reached. Bed deposit formation is therefore a safe indication that the bed load transport capacity of flow has been exhausted.

From this standpoint the phenomenon of deposition is no longer seen as a by-product of transport, as is usually the case. It now appears as a distinct phenomenon whose study allows the solution of chronic uncertainties raised by the lack of precision of classic bed load formulae.

This communication presents the latest results of a research programme based on this concept of the phenomenon of deposition and the importance of using independent variables (especially power) in studying river mechanics phenomena (Bordas, 1973). The results were obtained in experiments performed in a rough fixed bed flume for subcritical and supercritical steady uniform flows ($0.55 < F < 1.25$) transporting coarse sand ($0.6 < d < 2$ mm) (Silvestrini, 1991).

BACKGROUND

The study of the effect of transport capacity on sediment deposition is a less traditional line of research, although it began in 1914 with the studies of Gilbert (1914). In sanitary engineering and hydro-transport this approach is frequently used, mainly because it identifies the conditions under which sediment deposition occurs in canals or pipes (Craven & Ambrose, 1953; Novak & Nalluri, 1978). Pedroli (1963) investigated deposition in smooth fixed bed canals in order to assess bed load transport at gauging stations built in mountain streams.

In 1974 the Institute of Hydraulic Research of the Federal University of Rio Grande do Sul (IPH/UFRGS) began research on this topic. Several series of experiments were carried out in fixed bed (Bordas *et al.*, 1988) and mobile bed (Borges, 1987) flumes. Sands with a mean grain size of 0.77, 1.22 and 1.98 mm were injected at variable rates (up to a maximum of 700 g min^{-1}) into flumes up to 1 m wide with slopes ranging from 0.004 to 0.010, which discharged up to 35 l s^{-1}. Priority was given to fixed bed experiments, especially since they eliminated one type of energy loss (erosion), thus allowing a better investigation of energy consumption distribution between the different sources. In all these studies the main difficulty encountered was to define the exact beginning of deposit formation.

These previous results showed that:

(a) the stream power per unit bottom surface is the most reliable hydraulic variable to predict the beginning of deposition and express maximum bed load capacity;

(b) there are at least three types of bed load transport (isolated grains, "bulk" and "mass" transport), with different energy dissipation laws (Fig. 1); and

(c) maximum flow transport capacity could be expressed in relatively simple terms (Bordas *et al.*, 1988).

However, conclusions (a) and (c) were only valid for low stream power values and small solid discharge, due to limitations in the facilities used for the studies. These limitations have been removed and new experiments were carried out at higher power rates (up to 0.3 kg m^{-1} s^{-1}). The results are presented here.

FUNDAMENTALS

If streamflow is defined by an independent variable as unit flow (q) we have:

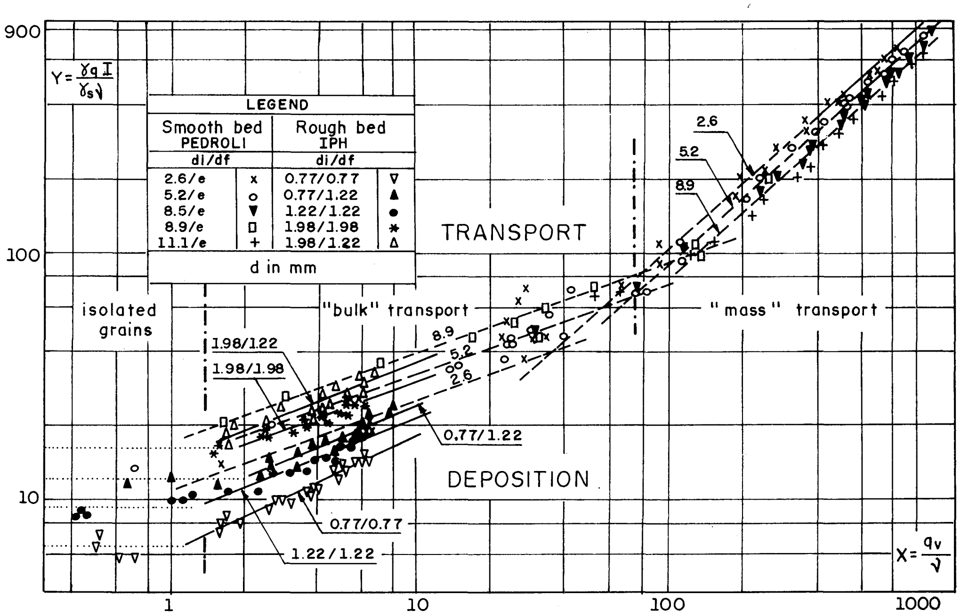

Fig. 1 Beginning of deposition for different types of bed load transport (after Medeiros, 1986).

$$g_v = \phi_1(q, g, I, \mu, \rho, \rho_s, d_i, d_f) \tag{1}$$

(symbols are as defined in the Notation) for the general case in which the diameter of the injected or transported sediment is different from the diameter of the sediment which constitutes the fixed bed of the stream.

According to normal procedures of dimensional analysis and gathering the three dimensionless terms $\beta = \rho^{-1} \cdot \rho_s$; I and $q\nu^{-1}$, so as to describe the power flow, the generic expression of transport is obtained:

$$\frac{g_v}{\nu} = \phi_2 \left[\frac{\gamma q I}{\gamma_s \nu}, \frac{d_i g^{1/3}}{\nu^{2/3}}, \frac{d_f g^{1/3}}{\nu^{2/3}} \right] \tag{2}$$

If streamflow is defined by dependent variables such as shear stress, mean velocity or unit power per unit weight, the above dimensionless flow factor will be substituted by

$$\frac{\tau g^{1/3}}{(\gamma_s \nu)^{2/3}}, \quad \frac{V}{(\nu g)^{2/3}}, \quad \text{or} \quad \frac{VI}{(\nu g)^{2/3}}$$

Simplifying the symbols,

$$X = \phi_2(Y, Z_i, Z_f) \tag{3}$$

In this new formula X is the dimensionless factor for solid discharge, Y the dimensionless factor for flow, Z_i the dimensionless factor which describes the transported sediment and Z_f expresses bottom roughness. In this communication the results will be presented with reference to the situation where $d_i = d_f$. Therefore the final relation must be of the following type:

$$X = \phi_3(Y, Z) \tag{4}$$

FACILITIES AND EXPERIMENTAL PROCEDURES

The experiments were performed in a flume 1 m wide and 26 m long, with maximum discharge of 35 l s^{-1}. The flume slope was moulded using levelled transverse profiles. Three slopes were used: 0.006, 0.008 and 0.010. The flume bed was lined with fine, carefully smoothed cement and painted. The sand used for the final lining was applied immediately after the bottom was painted in order to make the sand stick to it. Later, paint was applied lightly with a spray gun to consolidate the lining fixation and provide colour contrast which made it easier to identify the deposits.

The same sands with a density of 2.63 were used both for bottom lining and for the solid load: all of them had a uniform grain size (uniformity coefficient $C_u \cong 1.85$) with mean diameters of 0.77, 1.22 and 1.98 mm respectively. The particles were injected in the central part of the flume in a reach with uniform regimen by means of a device which provided an uniform supply to a 70 cm wide strip, at a rate ranging from 300 to 5000 g min^{-1}.

Sixty-five critical initial deposition events occurred in a total of 434 experiments performed, during which the Froude number varied from 0.58 to 1.24.

The methodology is basically the same as that used in previous studies. For a given solid discharge a liquid flow which will ensure transport of the injected material is initially discharged into the flume. This flow is then slowly reduced until a continuous deposition with the thickness of the injected sediment diameter is obtained. To help determine the deposit, the flume bed has a transverse retaining slot located a few metres downstream from the sediment injection section, which collects the particles that were not deposited during an experiment.

IDENTIFICATION OF THE DEPOSITION THRESHOLD

This task is the most demanding aspect of the research. Two criteria were used to identify the beginning of deposition. The first is basically experimental and attempts to determine the critical flow which generates continuous, uniform deposition with a thickness equal to the diameter of the injected sediment. This criterion is based mainly on the observation of the deposition process. Although this criterion had been easy to use in previous studies, it became a problem at higher powers due to greater irregularity of the deposits.

The second criterion is an effort to eliminate the degree of subjectiveness associated with the first. It is based on the concept of the rate of deposition originally developed by Costa (1974) and improved in this study. Considering the ratio between the area covered by sediment deposited with the thickness of a single grain and the total flume bottom area we have:

$$\eta = \frac{N\pi d^2}{4B\lambda} .100 \qquad (5)$$

The number of grains deposited during time Δt in the bottom reach with length λ of the injection section is given by:

$$N = \frac{(PMAS - kPMTM)/\gamma_s}{\pi d^3/6} \qquad (6)$$

In this expression, *PMAS* is the weight of material injected during period Δt, *PMTM* is the weight of wet material found downstream from the deposition zone during Δt and collected in the slot, and k is the wetness of the sediment collected to the slot, previously determined by weighing the material collected in the retention slot before and after drying. Transposing equation (6) to equation (5), the relationship:

$$\eta = \frac{2.143\,(PMAS - kPMTM)}{\gamma_s \lambda d} \tag{7}$$

is obtained, which allows the calculation of the deposition rate after measuring *PMTM*. The difference between equations (5) and (7) is that expression (7) can be applied to any predetermined value of λ and Δt chosen arbitrarily, thus limiting errors in assessing λ which result from irregular deposition. The procedure used to determine critical flow is simple: the curves $\eta = \phi(q)$ (see Fig. 2) are traced and the critical flow corresponding to $\eta = 1$ is determined. This value is used to calculate the power to be compared to that of the experiment in which deposit formation was observed. The pair of values thus obtained is plotted in Fig. 3.

The coincidence between the criteria is almost perfect although there is a slight tendency for the analytical criterion to indicate initial deposition flows higher than those found according to the visual criterion.

The similarity between results obtained using both criteria allowed the validation of those which were previously obtained using the visual criterion, and consequently increased the data base with the experiments performed by other authors (Almeida, 1980; Costa, 1974; Garcia, 1983).

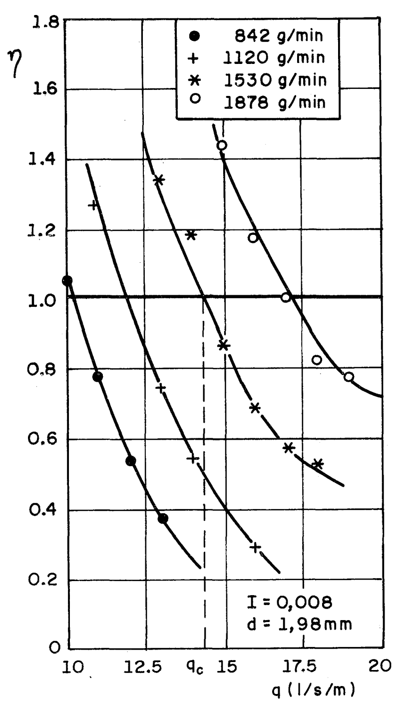

Fig. 2 Identification of the beginning of deposition with analytical criterion.

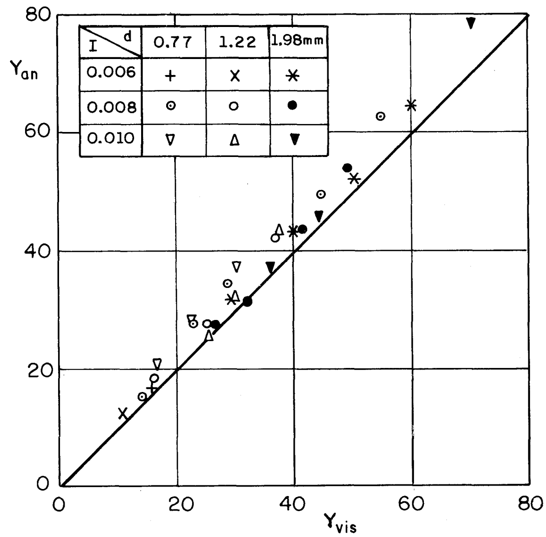

Fig. 3 Comparison of the analytical and visual criterion for the beginning of deposition.

RELIABILITY OF STREAM POWER TO EXPRESS DEPOSIT FORMATION

Experimental ratios were established linking the four dimensionless factors which include the main hydraulic variables

$$Y_1 = \frac{\gamma q I}{\gamma_s \nu}, \quad Y_2 = \frac{\tau g^{1/3}}{(\gamma_s \nu)^{2/3}}, \quad Y_3 = \frac{V}{(\nu g)^{2/3}}, \quad Y_4 = \frac{VI}{(\nu g)^{2/3}}$$

with a transport capacity expressed by $X = q_v . \nu^{-1}$.

The fitting of experimental points provided the following results:

(a) $d = 0.77$ mm $\quad Y_1 = 4.94 + 1.46\,X \quad (R^2 = 99.1\%)$ (8.1)

$Y_2 = 0.757 + 0.0391\,X \quad (R^2 = 96.6\%)$ (8.2)

$Y_3 = 13.4 + 0.386\,X \quad (R^2 = 93.4\%)$ (8.3)

$Y_4 = 0.106 + 0.00316\,X \quad (R^2 = 48.2\%)$ (8.4)

(b) $d = 1.22$ mm $\quad Y_1 = 7.14 + 1.57\,X \quad (R^2 = 95.4\%)$ (8.5)

$Y_2 = 0.914 + 0.039\,X \quad (R^2 = 94.9\%)$ (8.6)

$$Y_3 = 13.1 + 0.405\,X \qquad (R^2 = 93.1\%) \qquad (8.7)$$

$$Y_4 = 0.0985 + 0.0037\,X \qquad (R^2 = 53.0\%) \qquad (8.8)$$

(c) $d = 1.98$ mm

$$Y_1 = 15.9 + 1.89\,X \qquad (R^2 = 98.0\%) \qquad (8.9)$$

$$Y_2 = 1.18 + 0.0447\,X \qquad (R^2 = 96.6\%) \qquad (8.10)$$

$$Y_3 = 17.6 + 0.356\,X \qquad (R^2 = 93.8\%) \qquad (8.11)$$

$$Y_4 = 0.127 + 0.0038\,X \qquad (R^2 = 56.2\%) \qquad (8.12)$$

In all three cases it is seen that the hydraulic unit stream power per bottom surface unit gives the best fit and also the steepest slope of regression lines. In this way the best functional representation of the experimental points is obtained. These results confirm what was found in previous studies regarding the choice of unit stream power as the best parameter to represent the hydraulic variables and express deposit formation.

TYPES OF BED LOAD TRANSPORT

The data obtained in experiments with $d_i = d_f$ for values of $10 < X < 100$ were plotted in Fig. 1 to verify the different types of bed load transport indicated in previous studies. The result is seen in Fig. 4, which shows that:

(a) the results of present and previous experiments of Costa, Almeida and Garcia agree, proving that the experiments can be repeated, and validating the criteria used for beginning of deposition;

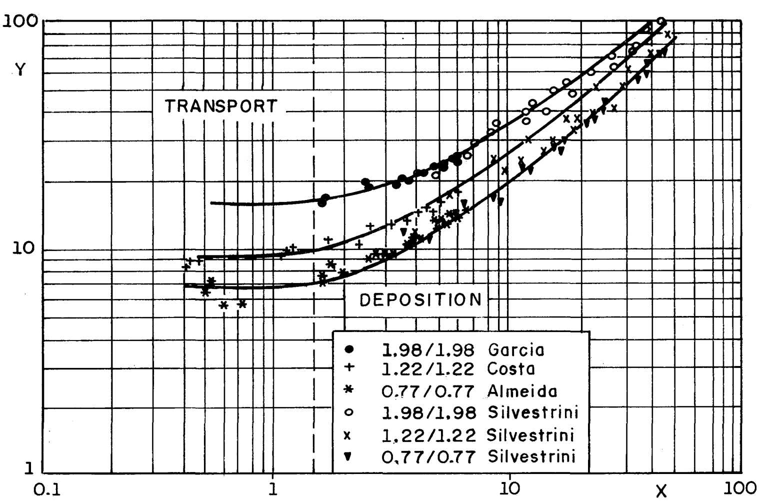

Fig. 4.

(b) as before, the power consumption due to transport presents three different behaviours, but these do not coincide fully with the previously identified types;

(c) for $X < 1.5$, unit stream power required for transport does not depend on the volume of transported sediment. In this zone, called isolated grain transport, the only variable which governs the phenomenon is particle size (or weight);

(d) for $1.5 < X < 10$, power demand increases with the volume of material to be transported. The fact that the three curves obtained are almost parallel implies that power demand growth is related mainly to the increased volume of material to be transported. In this zone, called "bulk transport", the main intervening factors are therefore the weight of each particle and the total weight of solid load. A preliminary attempt to express the phenomenon as a function of particle size showed that the power consumption law in this zone might take the form:

$$YZ^{-0.73} = \phi(X) \tag{9}$$

and the limits of X between which the equation might be applied vary according to grain size. The limit value 10 is merely indicative: actually, it varies between 5 and 10 according to grain size; and

(e) for $X > 10$ power demand growths are greater than those of the previous zone, but differ according to particle size. They are distinguished by the fact that demand increases faster for smaller grain sizes than for the larger ones. The three curves, therefore, tend to converge and obey the trend which could be perceived in Fig. 1 for flow over a smooth fixed bed (Pedroli, 1963). These facts suggest a new energy dissipation mechanism, probably related to collision among particles during transport, and that a fully established transition zone exists between the "bulk" and "mass" transport zones shown by the research performed by Pedroli.

MAXIMUM TRANSPORT CAPACITY

Figure 4 shows that the transition from one type of transport to another occurs more smoothly than expected from previous research. This fact, together with the obvious affinity between the three curves drawn in Fig. 4, makes it acceptable to look for a single expression of maximum transport capacity instead of several different ones, each one appropriate to one bed load type, as was attempted previously.

An attempt to find a single expression, valid when solid load and bottom lining have the same grain size ($d_i = d_f$), was made using the dimensionless term (X/Z) used previously (Bordas *et al.*, 1988). Little is known about it, so far, beyond the fact that it is related to the number of grains transported. The

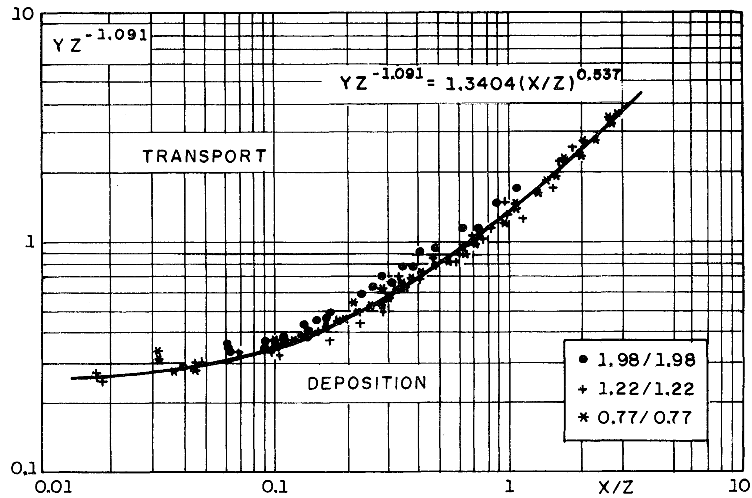

Fig. 5 Beginning of deposition on a rough fixed bed.

results are shown in Fig. 5: all experimental points surveyed are grouped on a single curve which obeys the equation below (valid for $XZ^{-1} < 3$):

$$YZ^{-1.091} = 1.3404\,(X/Z)^{0.537} \tag{10}$$

with $R^2 = 92.7\%$ which corresponds to the following expression of maximum bed load transport capacity:

$$X = 0.676\,Y^{1.862}Z^{-1.032} \tag{11}$$

CONCLUSION

The conclusions of previous studies on the relationship between the beginning of deposition and maximum transport capacity of a flow have been confirmed, broadened and improved. The stream power per unit bottom surface is the most appropriate hydraulic variable to predict the beginning of deposit formation. Three types of bed load transport exist, each with its own energy consumption law. The methodology used in determining the beginning of deposition has been improved. Two criteria, visual and analytical, have been defined and validated. Since they are equally reliable, new experiments can be carried out by a person who does not have much previous experience, which was not possible before, since it was difficult to know precisely when deposition would begin. Finally a relation has been established (equation (10)), which allows the calculation of either the minimum power required to transport a given solid load, or the maximum transport capacity of a given flow for a rough fixed bed and solid load with *X/Z* values below 3. One of the requirements to generalize these results would be to extend the research to flows with unit stream power greater than 0.3 kg m^{-1} s^{-1}.

Acknowledgements The authors thank the Brazilian National Council of Science and Technology (CNPq) and the Graduate Course in Water Resources and Sanitary Engineering of UFRGS for supporting this study.

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