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Suspended sediment routing along a reservoir

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Abstract Results are given from some experimental research on the sediment movement along a reservoir. In the experiments, a variable slope flume was used to simulate the reservoir. 124 tests were performed using different water discharges, slopes, sediment concentrations, temperature profiles, suspended sediment and lengthwise sections. The sediment movement was observed by means of measurements of the running length, depths, concentrations and temperatures. The experimental data were analysed statistically and in terms of non-dimensional numbers. Finally, a theoretical approach is proposed for predicting the phenomena and a computational procedure is proposed.

Propagation de sédiments en suspension dans les retenues

Résumé Les résultats d'une recherche expérimentale sur le mouvement de sédiments dans une retenue sont ici présentés. Les expériences ont été menées dans un canal à pente variable qui simulait la retenue. 124 essais ont été réalisés en modifiant le débit, la pente, la concentration et le type de sédiments, les profils de température et les sections longitudinales. Le mouvement des sédiments a éte suivi par mesure des distances parcourues, des profondeurs, des concentrations ainsi que des températures. L'information expérimentale a éte analysée statistiquement et au moyen de nombres adimensionnels. Une approche théorique permettant de prédire le phénomène, et une méthode de calcul sont proposées.

INTRODUCTION

A revision of the most frequently used calculating procedures used to predict sediment location in a reservoir, shows that they are of empirical character (area-increment, area-reduction, trigonometric) and that they not always yield reliable results. Moreover, the analytic procedures are still in a developmental phase, especially those used to represent the behaviour of fine sediment. Whilst there are many studies of density currents, they are generally concerned with cases in which the differences in density are caused by differences in salinity or temperature, but not by the presence of water-borne material as in the case of suspended particles in a stream. It is also true that, while it is easy to reproduce the density currents in a laboratory, so that there are many studies on the subject (Anuchin *et al.*, 1972; Fukoka & Fukushima, 1980), in practice it is difficult to predict from the possible formation of the density currents up to their eventual arrival at the dam (Rooseboom & Annandale, 1982).

PLANNING AND EXECUTION OF TESTS

This paper can be applied to those cases where the bidimensionality assumption is acceptable. The principal variables to be analysed in an experimental study are the following: (a) inflow discharge, (b) concentration of suspended material that enters the reservoir, (c) bottom slope, (d) types of suspended sediment (grain size distribution), (e) thermal stratification in the water stored, and (f) horizontal bends in the channel.

124 tests were performed in which all the following parameters were combined. Slopes: 0.02, 0.04 and 0.06. Discharges: ¼, ½ and 1 l min^{-1}. Thermal stratification: 5–20, 5–12, 5–5 and 20–20°C. Concentrations: 10, 5, 2, 1 and ½ g l^{-1}.

Most of the tests were performed in a straight flume with a variable slope, 3 m long, 0.1 m wide and 0.3 m high. In addition, another flume was used with similar dimensions but with bends.

During the tests, the water-sediment mixture was fed by means of a Mariotte bottle, introducing 1 l volume with constant discharges. Temperatures were measured with thermocouples, concentrations at the entrance with a densimeter (Bouyocos), and the measurements inside the flume with a laser beam and using the turbidimeter principle. In order to register the movement of the sediments the tests were filmed with a video camera; the information was to be analysed later.

Three different sediments were used: kaolin (ϕ = 0.006 mm), ashes (ϕ = 0.018 mm) and a prototype solid material (the Balsas River, ϕ = 0.024 mm).

THE EXPERIMENTAL RESULTS

The general observed evolution of the phenomenon may be divided into three stages (Fig. 1). During the first, the water with the sediments enters into the reservoir; it can be seen there in a fast movement of the sediment which soon occupies all the cross section, then the movement begins to slow down until a density current appears. At this point the second stage starts: the current moves at an almost constant velocity while the discharge is constant. The third stage or recession stage begins when the inflow discharge stops; it is characterized by the current velocity diminishing gradually until it comes to a halt.

A multifactorial analysis showed that the most important factors are slope, discharge and their interaction. No important differences were observed regarding the use of the different types of sediments. The response surfaces gave an explanation of the evolution of the plunging zones, but a

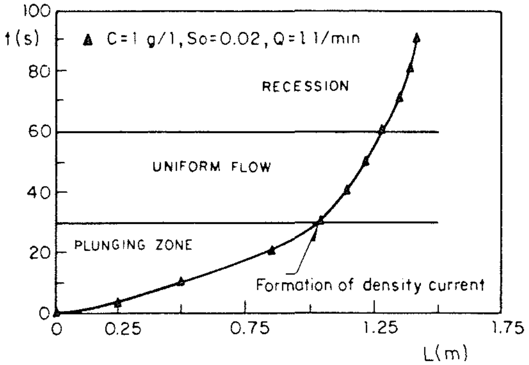

Fig. 1 Typical sediment routing through a reservoir.

generalization of results is not possible. Using non-dimensional numbers a good representation of the sediment behaviour for high slopes was obtained, but not for the smaller ones.

In the work of Gracia (1987) the results of the experiments and the details of the above-mentioned experimental procedure are developed more extensively, but were not included here because of space reasons.

THEORETICAL INTERPRETATION

As a function of the experimental results, the interpretation of the phenomenon is the following. As the incoming water enters with a concentration (C_o) and there is an intense mixing in the plunging zone, the sediment concentration (C) in that site is lower than at the entrance ($C < O_o$). As water continues to enter the reservoir, the sediment will occupy the complete cross section and will be moving forward. This process will take place until a critical value of the mixture is reached ($M = C/C_o$), which will also be related to the sediment advancing front (Y).

When this happens the current cannot travel occupying all the channel section, then a density current (bottom, or interflow or superficial) is produced.

From now on the plunging point remains practically fixed while the sediment keeps moving through the reservoir in the form of a density current.

The continuity equation for the water-sediment mixture is

$$\frac{\partial(AVC)}{\partial x} + \frac{\partial(yC)}{\partial t} = 0 \qquad (1)$$

where A is area of the cross section (m^2), V is mean velocity (m s^{-1}), T is width of the free surface (m), y is depth (m), x is horizontal coordinate (m), t is time (s), and C is sediment concentration (g l^{-1}).

In finite differences equation (1) may be expressed as

$$\{Q\ C_o \Delta t\}_{i+1} = \{C\ b\ y\ \Delta x\}_{i+1} \tag{2}$$

if $M = C/C_o$, and separating Δx_{i+1}, it is found that

$$\Delta x_{i+1} = \frac{(Q\ \Delta t)_{i+1}}{b\ y\ M_{i+1}} \tag{3}$$

Integrating this equation, and using $L_{i+1} = L_i + \Delta x$, we obtain

$$L = \surd\,[2Qt/(S_o bM)] \tag{4}$$

and, as $S_o = Y/L$, this equation may be written as

$$Y^2\, M^2 = (2QtS_o M)/b \tag{5}$$

The experimental analysis showed that the product MY was practically the same in all the tests when the density current appeared, and equal to $(MY)_c = 0.007$; therefore, equation (5) may be written as

$$t_c = (MY)^2 b/(2QS_o\, M) \tag{6}$$

where t_c refers to the instant when the density current appears.

The movement forward in stage 1 may be obtained by means of equation (4), and the plunging zone will be defined by the same equation when $t = t_c$. If the flood takes a time shorter than t_c, then the density current will not form.

Once the density current has formed, the computations can go on using equation (2), as follows:

$$C_{i+1} by \Delta x_{i+1} + C_{i+1} by\ \Sigma_0^i\ \Delta x_i = (Q\ C_o\ \Delta t)_{i+1} + C_i by\ \Sigma_0^i\ \Delta x_i \tag{7}$$

and taking out Δx_{i+1}

$$\Delta x_{i+1} = (QC_o \Delta t)_{i+1}/(byC_{i+1}) + [C_i/C_{i+1} - 1]\ \Sigma_0^i\ \Delta x_i \tag{8}$$

In steady flow and assuming that $y \approx$ constant (according to the tests), it can be established that the losses due to friction were $hf \approxeq S_o {}^*\Delta x$. If the Manning equation is applied to a densimetric flow, it can be established that

$$\Delta x_{i+1} = n^{-1} R^{2/3} [(W_2 - W) S_o / W_2]^{1/2}\ (t_{i+1} - t_i) \tag{9}$$

where n is the Manning roughness coefficient, R hydraulic radius (in this case the wet perimeter also includes the density current interface), W_2 specific weight of the mixture, and W specific weight of the stored water.

At this stage the mixture (M) of the incoming current does not change and it is equal to that produced in the plunging zone. Therefore, for a rectangular section and assuming that the difference in density is caused only by the presence of sediments, equation (9) may be written as

$$\Delta x_{i+1} = n^{-1}\,[by/(2b + 2y)]^{2/3}\,[\Delta W S_o/W_2]^{1/2}\,(t_{i+1} - t_i) \tag{10}$$

where $\Delta W = MC_o\,(1 - W/\gamma_s)$; with C_o and W in g l^{-1}; t in s; b, y in m; and γ_s the specific weight of the solid material in g l^{-1}.

With equations (8) and (10) the movement forward of the current in steady flow (stage 2), may be computed in the range $t_c < t < t_s$; t_s being the time at which the inflow discharge is stopped.

The recessive stage occurs once the inflow discharge stops. Gradually, the current will hold back its movement as concentration diminishes because of particle sedimentation and flow dilution. Due to the way in which the velocity decrement influences the deposit of sediments, it is proposed that during the recession stage, the concentration is modified by a factor *P*. This will allow for the decrement in concentration as a result of sedimentation. Using equation (8) to determine the current behaviour at this stage, $(C\,\Delta x)_{i+1}$ can be written

$$C_{i+1}\,\Delta x_{i+1} = [(Q\Delta t)_{i+1}\,C_o/by] + (PC_i - C_{i+1})\,\Sigma_0^i\,\Delta x_i \tag{11}$$

The value of *P* was obtained through experimental tests. In this case equation (10) may be written as

$$\Delta x_{i+1} \approx n^{-1}\,[by/(2b + 2y)]^{2/3}\,(\Delta W_i/W_2)^{1/2}\,S_o^{1/2}\,\Delta t \tag{12}$$

With equations (11) and (12), the movement forward of the density current during the recession stage may be computed.

COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

The laboratory tests were simulated according to the theory proposed in the preceding section. Figures 2, 3 and 4 show the results obtained, which are generally satisfactory.

A Manning coefficient of $n = 0.013$ was used in all the simulations, except in the case of the bending channel, where it was of 0.018.

The values of *P* for the recession stage with which the best representations were obtained were in the range of 1 ($S_o = 0.06$) to 0.8 ($S_o = 0.02$). However, for low concentration (<3 g l^{-1}) and temperature stratification, $P = 0.5$.

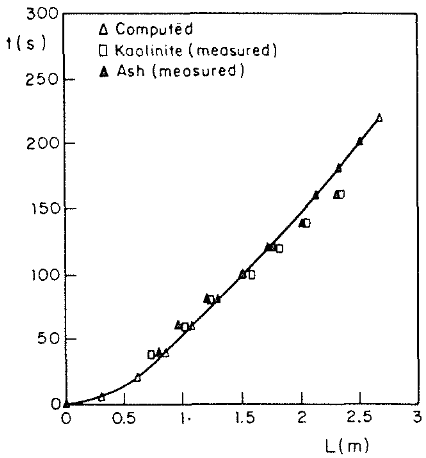

Fig. 2 Sediment routing for $S_o = 0.06$, *C = 10 g* l^{-1}, *Q =* 0.5 *l* min^{-1}.

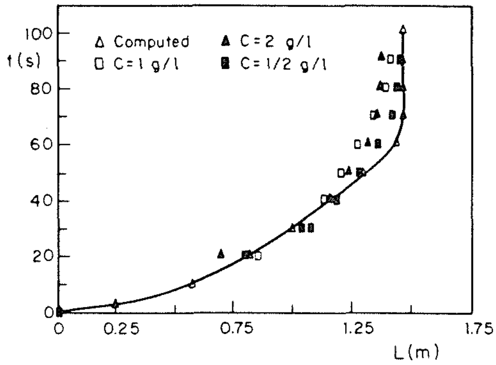

Fig. 3. Sediment routing for S = 0.02, Q = 1 l min^{-1} *with temperature stratification.*

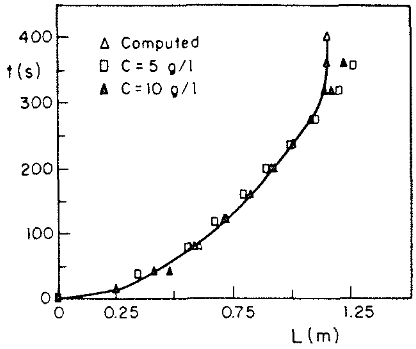

Fig. 4 Sediment routing for a bending channel (S = 0.02 and Q = 0.25 l min^{-1}.

APPLICATION TO REAL RESERVOIRS

The final object is to apply the results to real reservoirs. This is particularly important in this case because of the great scale differences.

An important comment refers to the fact that the tests provide an explanation of the phenomenon and the proposition of a theory, practically independent from the laboratory conditions. Only one parameter in the theoretical proposition is difficult to establish in a real problem and in this case it is necessary to base the information on the laboratory results: the critical condition (MY).

According with Cermak & Sethu (1977) the mean characteristics of stable stratified turbulent flows may be determined in big systems like the atmosphere, oceans and large reservoirs. To do this two conditions must be fulfilled: the equality of the Reynolds $(Re)_2$ and Froude $(F)_2$ densimetric numbers.

Applying the model theory based on these two numbers, it can be established that the critical condition for a prototype is

$$(MY)_{cp} = 0.75\, Q_p^{2/5} \tag{13}$$

where $(MY)_{cp}$ is the critical condition (m), and Q_p the average inflow ($m^3\ s^{-1}$), both for prototype.

Generally, smaller slopes than those in the experimental device must be used. In these cases the mixture may be determined as

$$M_p = 0.0108/S_p \tag{14}$$

Observe that the maximum value of M_p should not exceed unity; therefore, for $S_p < 0.0108$, $M_p = 1$. In other words, most probably $C = C_o$ in a prototype, what means that the concentration of the density current is quite similar to that at the inflow.

CONCLUSION

To simulate the behaviour of suspended sediment, a theory and an anlytic calculating procedure are proposed. This procedure was applied to the experimental data with good result.

The existence of a critical condition between the sediment concentration and the sediment advancing depth was proposed, in order that the density current may form. It was observed that sometimes the density currents do not form, only producing turbidity at the reservoir entrance.

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