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Some problems related to sediment transport measurement in steep mountain streams

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ABSTRACT The measurement of sediment transport in steep mountain streams presents particular problems. Very high sediment concentrations as well as unsteady phenomena in the bed erosion process are to be expected. The simplest method consists of trapping the whole sediment load by tranquillizing the flow. Uncertainty about the expected amount of sediment load, as well as important variations in the load carried by different flood events have important consequences in relation to the precision of this method. The paper describes a "sediment-scale" which may be used to record continuously the variation of a sediment load with time. The scale measures the forces exerted by the water-sediment mixture on a steel slab inserted in the flume bottom. Knowing the weight of the mixture, worked out from calibrated extensiometers supporting the slab, the height of the water table over the flume bottom and the mean velocity of the sediment, the instantaneous sediment transport rate can be found. The first laboratory tests are described and a preliminary assessment of the precision of the device and the practicality of its future use in the field given.

<u>Problèmes liés à la mesure du transport de sédiments dans des rivières de montagne à forte pente</u>
RESUME La mesure du transport de sédiments dans des rivières de montagne à forte pente présente quelques problèmes particuliers. On doit prévoir des concentrations élevées et des phénomènes hautement instationnaires concernant l'érosion du lit. La méthode la plus simple est de retenir toute la masse de sédiments en tranquillisant l'écoulement. L'incertitude sur la quantité attendue de sédiments charriés, de même que les fortes variations de cette quantité ont de grandes répercussions sur la précision de cette méthode. On espère enregistrer les variations du transport solide par une sorte de "balance à sédiments". On mesure les forces exercées sur une dalle du fond par des extensiomètres calibrés. Connaissant le poids du mélange, la hauteur du plan d'eau et une vitesse représentative du sédiment, le débit solide instantané peut être retrouvé. On décrit les premiers essais en laboratoire qui devront permettre une estimation de la précision et la possibilité

d'application sur le terrain.

NOTATION

B	width of sediment-scale (m)
d	grain size (m)
d_m	mean grain size (m)
G	instantaneous weight recorded on the sediment-scale (N)
G_S	sediment component of the instantaneous weight recorded by the sediment-scale (N)
$G_{S_{TOT}}$	total weight of the introduced sediment load (N)
G_W	water component of the instantaneous weight recorded by the sediment-scale (N)
g	acceleration due to gravity (m s^{-2})
h_d	height of deposition (m)
h_G	flow depth of mixture over the sediment-scale (m)
h_W	flow depth over sediment-scale without sediment input (m)
J_S	bed slope
J_W	water surface slope
k	number of profiles
L	length of sediment-scale (m)
m_G	average error of the weight recorded by the sediment-scale (N)
m_{h_G}	average error of recorded flow depth of mixture (m)
m_V	average error of deposition volume (m^3)
m_{ρ_R}	average error of density of mixture (kg dm^{-3})
n	number of points levelled in a profile
Q_S	sediment discharge (m^3 s^{-1})
Q_W	water discharge (m^3 s^{-1})
t	time (s)
V_S	volume of sediment on the scale (m^3)
$V_{S_{TOT}}$	total volume of sediment introduced in the flume (m^3)
v_G	representative velocity of sediment (m s^{-1})
Δl	distance between profiles (m)
ρ_R	density of water-sediment mixture (kg dm^{-3})
ρ_S	density of sediment (kg dm^{-3})
ρ_W	density of water (kg dm^{-3})

INTRODUCTION

The mechanism of sediment transport in steep mountain streams is even more complex than that in rivers with gentle slopes. Sediment concentration can become extremely high, moving particles can be of boulder as well as clay sizes and because of structuring and restructuring of the bed, the transport rate is expected to vary widely in time.

It is obvious that the movement of sediment in a steep stream will exert a high stress on any structure set up to record sediment transport. Therefore, some techniques used under calmer conditions might not be suitable, e.g. collecting baskets, or under-water cameras.

REVIEW AND DISCUSSION OF POSSIBLE METHODS

Sampling of transported material

In comparatively small mountain streams sediment transport rate has been recorded (Ashida *et al.*, 1976) by sampling part of the flow for short time intervals. By repeating the operation regularly over a flood period, the variation in sediment transport rate can be easily obtained. Klingeman & Milhous (1970) and Hayward (1980) used special structures which diverted the whole bed load with a part of the flow. Suspended load had to be sampled separately.

Good results are being obtained with these methods. However, until now they are only applicable in small streams; and they are dependent on operating staff, which makes the recording of sudden events difficult.

Sediment traps

The simplest method of measuring transport rate is to trap the sediment yield in a large basin. Very often it is difficult to design such a trap because the design size, to hold the maximum sediment yield, is not known and is supposed to be measured by means of the planned structure. This question is especially important if space is limited.

It must also be borne in mind that part of what was suspended load in the stream will settle in the basin and part of it will be washed out of the structure. It is necessary to determine the grain size distribution of the trapped sediment and to check, by separate sampling, which fractions have only been partially deposited.

The uncertainty about the expected sediment yield per flood event affects the methods for detecting this value from the deposited body of sediment. The simplest method would be to evacuate all the material after each event. This is usually not possible for financial reasons. The alternative consists of recording the surface of the material deposited in the basin by levellings will give the sediment yield for the corresponding time period.
period.

This value can vary considerably from one event to another. It appears, from a simple precision analysis, that a small sediment volume spread over a previous deposition is nearly impossible to evaluate. The same problem occurs if, at the entrance of the basin, there is no distinct separation structure. Some of the deposition will occur upstream on the natural bed, with a small deposition depth spread over a large area.

The relative error of a deposition volume is given by:

$$m_V/V = (1/h_d)(2/nk)^{\frac{1}{2}}[d_m{}^2 + (\Delta l^2/10^4)]^{\frac{1}{2}} \qquad (1)$$

It is assumed that the average error in recording one point of the surface is equal to the mean grain size of the material, d_m. With the second square root term it is considered that, with the choice of profiles, some of the irregularities of the topography might be lost.

Figure 1 shows a possible succession of depositions, some easy to record and some which present problems. The last deposition extended over the entrance sill, with a consequent loss of precision.

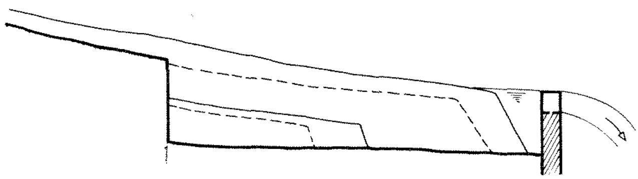

Fig. 1 Possible succession of depositions in a sediment trap (continuous line: recording will be imprecise).

Such arguments had to be considered when planning the sediment trap in the "Rietholzbach" experimental catchment 40 km east of Zurich. The basin has now been excavated and a sill is being constructed at the upstream end. According to the first results, a sluicing system will eventually have to be added, in order to record the yield of different events precisely.

Recently it has been shown that continuous measurement is possible in a trap, with the aid of a pressure recording system (Reid *et al.*, 1980). The precision of this method is, however, dependent on the same parameters as the method discussed below, which does not trap the sediment.

PILOT STUDY FOR CONTINUOUS MEASUREMENT OF SEDIMENT TRANSPORT RATE IN STEEP MOUNTAIN STREAMS

In a torrent in the Swiss pre-Alps a project is underway for collecting hydrological, hydraulic and sediment transport data. A flume with a 15% slope will be set up as a discharge recording station. Because of the high sediment concentrations expected, the flow depth will be substantially dependent on the sediment load. A device is therefore needed to record the sediment transport rate continuously.

The principle of the method is the continuous weighing of the water-sediment mixture flowing over a scale inserted in the channel bottom. By recording the elevation of the water surface over the scale, the volume of the mixture is known and sediment concentrations can be worked out. If a representative velocity of the sediment can be determined, solid discharge follows immediately.

The scope of the pilot study described here is to check the behaviour of the device and to estimate the resulting precision to assess whether an application in the field is possible. As the study is only in its initial phase, the presented results do not yet have a general character. More variations of the different parameters are needed to indicate the possibilities and limitations of the presented method.

Experimental set up

The first tests were performed in a rectangular tilting flume of

0.15 m width with a smooth bed, discharge being recorded with a V-notch weir. The sediment transport rate was always smaller than transport capacity.

The slab introduced in the flume floor to record the weight of the water-sediment mixture was 0.5 m long and 0.11 m wide. It was suspended on four calibrated extensiometers which produced an electric signal proportional to their deformation, e.g. the active stress. In addition, a hydrophone was inserted in the flume floor to record the passage of sediment. A fine rubber membrane covering the "scale" sealed the system (Fig. 2).

The elevation of the water surface over the slab was recorded by means of a pair of copper electrodes fixed to each side wall

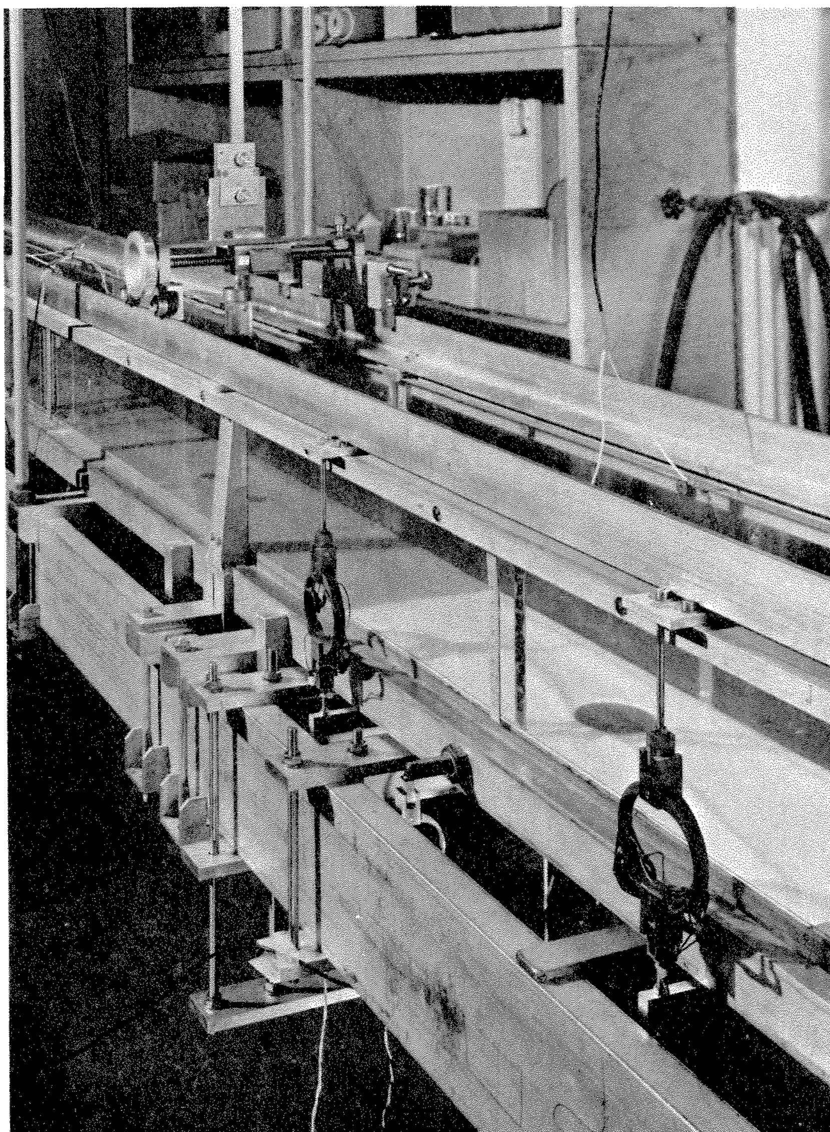

Fig. 2 General view of the "sediment-scale" with two extensiometers at the front and the hydrophone in the centre of the slab.

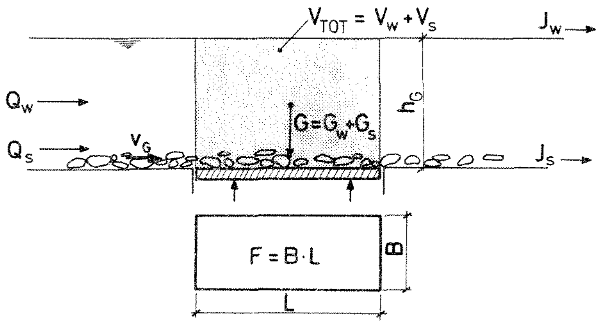

Fig. 3 Parameters used in the analysis.

at the centre of the slab, to measure the variation in conductivity. In a similar way the velocity of the transported material was obtained from the time lag between the signals given by two pairs of lateral electrodes which were 55 mm apart.

All the information was collected on a chart recorder and evaluated later.

Determination of instantaneous sediment discharge

Figure 3 shows all the parameters needed for determination of the solid discharge.

The first tests reported here were made using a slope of J = 2% and the influence of slope can therefore not be detected. The measured values for h_G in the centre of the slab were taken to be representative of the mean value over the scale. Knowing the values of G, h_G and v_G by direct measurement, one gets:

$$V_{TOT} = V_W + V_s = B\ L\ h_G \tag{2}$$

$$G = \rho_R\ g\ V_{TOT} = \rho_R\ g\ B\ L\ h_G \tag{3}$$

$$G = G_W + G_s = \rho_W\ g\ V_W + \rho_s\ g\ V_s \tag{4}$$

From (2), (3) and (4) results:

$$\rho_R\ g\ V_{TOT} = \rho_W\ g\ (V_{TOT} - V_s) + \rho_s\ g\ V_s \tag{5}$$

The volume of sediment on the scale is then:

$$V_s = V_{TOT}\ \frac{\rho_R - \rho_W}{\rho_s - \rho_W} = B\ L\ h_G\ \frac{(G/(B\ L\ h_G\ g)) - \rho_W}{\rho_s - \rho_W} \tag{6}$$

Introducing the mean velocity of the sediment v_G the solid discharge is obtained:

$$Q_s = \frac{V_s}{L}\ v_G = B\ h_G\ \frac{(G/(B\ L\ h_G\ g)) - \rho_W}{\rho_s - \rho_W}\ v_G \tag{7}$$

The total volume of material was checked against the integrated transport rate:

$$V_{s_{TOT}} = \frac{G_{s_{TOT}}}{\rho_s\ g} = \int Q_s\ dt \tag{8}$$

A first estimation of the precision to be expected for the density ρ_R, which indicates the sediment concentration, can be made according to the theory of error propagation.

For $\rho_R = G/(B\ L\ h_G\ g)$, the relative average error becomes:

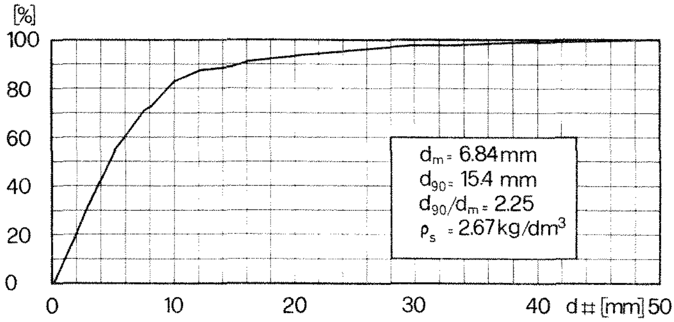

Fig. 4 Grain size distribution curve of the material used in the first tests.

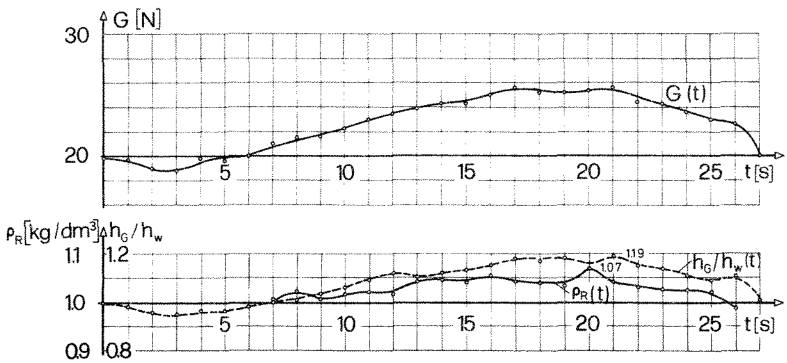

Fig. 5 Results of the test with a 4 kg total mass of sediment introduced: (a) value G(t) registered on the scale; (b) curves h_G/h_W, resp. ρ_R, as a function of t.

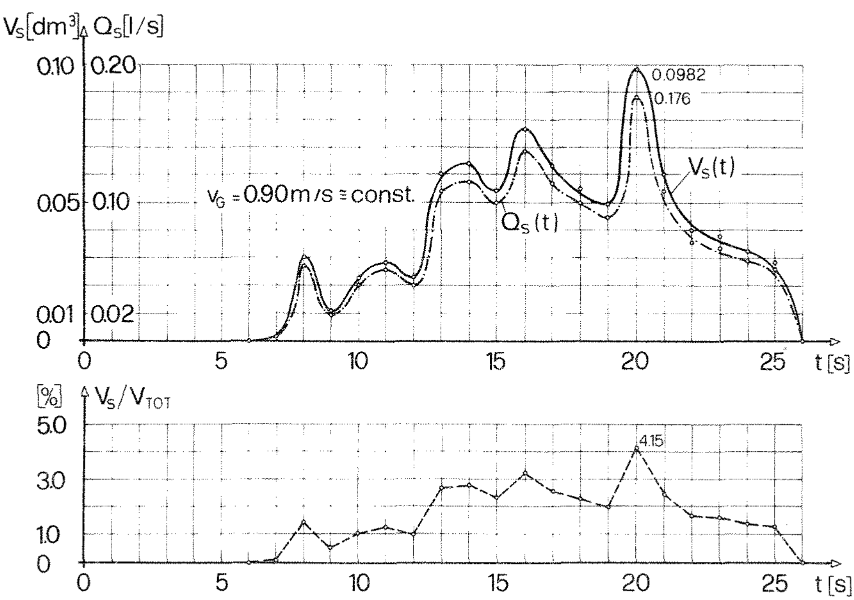

Fig. 6 Results of the test with a 4 kg total mass of sediment introduced: (a) volume V_s of sediment registered by the scale (Q_s(t) = instantaneous solid discharge); (b) concentration V_s/V_{TOT} as a function of t.

$$m_{\rho_R}/\rho_R = \left[(m_G^2/G^2) + (m_{h_G}^2/h_G^2) \right]^{\frac{1}{2}} \tag{9}$$

The measurement of G should be possible with an accuracy of 1% and h_G with 5%. The latter value was estimated for future field application with a 15% slope where air entrainment might make measurement difficult. In this situation the influence of an error in h_G was about 25 times higher than the error in G in equation (9). The relative error in ρ_R then becomes 5%. The precise determination of registered water levels is therefore important.

First results

Two preliminary tests were undertaken with a flow discharge of $Q_W = 7.4$ l s^{-1} and a slope of 2%. Masses of 2 and 4 kg of widely graded sediment (see Fig. 4) were introduced by hand at the upstream end of the flume. An unsteady, short period flow of water-sediment mixture resulted. The results of the test with a total mass of 4 kg are shown in Figs 5 and 6. As observed in a study of sediment transport in a steep flume (Haenger, 1979), the ratio h_G/h_W, where h_W is the flow depth with no sediment input, increases with increasing sediment concentration.

Introducing sediment disturbed the flow as illustrated in Fig. 5 by causing the water surface level to fall for the first 5 s. The sediment reached the scale only after 6 s; the curves have therefore been evaluated from that moment on. It was observed that the velocity v_G was almost constant throughout the passage of sediment, i.e. did not change significantly with sediment concentration. It resulted in a similar shape for the $V_S(t)$ and $Q_S(t)$ curves. Further tests are planned to obtain more precise information on v_G.

As a check, integration of the curves $Q_S(t)$ in Fig. 6 (equation (7)) gave with 1% accuracy, the original mass of 4 kg of introduced material. In the second test with 2 kg total mass, an error of 4.5% was found.

CONCLUSIONS

The possibility of the continuous measurement of sediment transport, by recording the force on the channel bottom, has been put forward. First tests to check the method have given encouraging results. More variation of the parameters is however needed before an application in the field can be recommended. The precision will depend mainly on the recording of the water surface level over the sediment-scale. Another difficulty arises with the estimation of the mean velocity of the sediment, required to transform sediment concentration into solid discharge. If this system were operational, it would have many advantages over other methods such as sampling part or total flow, or trapping the sediment, because the system should work without operating staff and without the need to excavate the sediment yield.

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