Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

Experimental investigations on the initiation of bed load transport in gravel rivers

S. CAVAZZA
Institute of Hydraulics, Faculty of Engineering, University of Pisa, Italy

ABSTRACT This report presents the results of research carried out on gravel river beds, composed of fractions of up to 350 mm, and the conditions of initial bed load transport. The method employed is applicable to rivers with short duration floods and significant periods of low water. It comprises the following elements: topographical survey of the geometry of the river bed; granulometric analysis of the bed material; selection of round pebble tracers, the measurement of orthogonal circumferences, weight and volume; colouring and numbering of tracers; placing of tracers along the section; water level observations; collection of tracers moved after every flood and, where possible, measurement of displacement. The report presents the results of experiments carried out on six marked sections. The data obtained have permitted the testing of theoretical formulae for bed load transport at these sites and the verification of the Shields curve in cases of extreme turbulence.

Recherches expérimentales sur le début du charriage de rivières a fond caillouteux

RESUME Ce rapport présente les résultats de recherches conduites sur des rivières a fond caillouteux, avec des éléments atteignant la taille de 350 mm, et concernant les conditions initiales du charriage de fond. La téchnique adoptée est applicable aux rivières ayant des crues de brève durée suivies de périodes ou le tirant d'eau est assez faible. Elle comporte les phases suivantes: rélevé topographique de la géometrie du lit; analyse granulométrique des matériaux de charriage de fond; sélection de galets sphéroïdiques, mesure des circonférences orthogonales, du poids et du volume. Marquage des galets par coloration et numérotage. Positionnement des cailloux marqués le long de la section; observation lymnimétrique; rélevé des cailloux marqués déplacés à la suite de chaque crue et, si possible, mesure de la distance de déplacement. Le rapport présente les résultats d'expériences conduites sur six sections marquées. Les données obtenues ont permis d'étalonner pour ces divers cas les formules théoriques du charriage de fond et de vérifier la courbe de Shields dans le domaine des fortes turbulences.

GENERAL INTRODUCTION

Present information on the phenomenon of bed load transport is based mainly on theoretical and laboratory experiments, but the results are also applied to natural water courses. The transfer of information gained from theoretical and laboratory research to more complex natural conditions obviously involves a series of schematizations which do not eliminate the complication of calculation and generally involve a degeneration in the quality of the results. This degeneration is principally due to the difficult and imprecise measurement of the variables under natural conditions and to the extreme variation in space and time of the natural conditions as opposed to those of the models with which they are compared. In addition, the theoretical or laboratory information currently available is, for certain natural conditions, extremely inadequate and ambiguous, often because of the difficulty in defining and resolving the conceptual problem and sometimes because of the complications which laboratory experiments involve.

When the conditions in a natural water course differ considerably from the theoretical methods and laboratory experiments, or when they are outside of the field of validity of these experiments, it would seem useful to carry out some simple tests on load transport in the natural water course in order to plot the values of variables which regulate at least some of the phases of the phenomenon. With these results, it is often possibly to apply the methods of calculation available for measuring the water flow and to obtain more reliable results.

The application of this type of procedure is described in this report for three rivers whose beds are composed of *c.* 10 cm diameter pebbles or stones contained in mobile river beds composed of material of the same size or smaller. In this case, the experiment on the water course aims to establish the hydraulic conditions under which some specially selected and marked pebbles start to move. Whenever possible the distance which the pebbles have been transported is measured.

The procedure which is described below can be applied to river channels where, at least for short periods, the water levels are sufficiently low as to allow the placing and observation of tracers on the bed. These conditions are frequently found in small streams with high gradients where the bed load transport is composed of pebbles and stones and the flows are low or non-existent for long periods during the dry season and greatly increase during floods.

The experiment consists, therefore, of placing a certain number of tracers along a channel section and of checking their position after every variation of flow and, in practice, after every flood.

SPECIFICATIONS OF THE EXPERIMENTAL SECTION

Selection and characterization of the section

The section chosen for the placing of the tracers must satisfy as exactly as possible the hydrological and morphological conditions for theoretical calculation. It is, therefore, preferable to choose a rectilinear section within a certain length of a river bed, with a longitudinal slope and sections as constant as possible, with a river bed with minimal transverse slope, but still symmetrical with the mid-stream axis of the channel, and with uniform roughness, at least along the bottom of the river bed. It is also necessary to ensure that the material comprising the river bed is virtually uniform throughout the section so that there are no areas of varying granulometry either longitudinally or laterally. Where such differences of this kind are evident, they should not be markedly asymmetrical to the axis of the channel. Obviously lithologically homogeneous bed materials with uniform dimensions allow a better interpretation of experimental results based on theories of bed load transport.

The chosen river bed section is then topographically surveyed in order to ascertain the geometrical characteristics, and to plot the longitudinal slope of the bed. A much more detailed survey may be carried out along the section to be prepared. This should be tied in to a water level gauge or to a level recorder installed in the section itself, or in the immediate vicinity, and possibly to other level gauges places along the river bed.

Information on the material comprising the river bed, on the banks, on the vegetation and on any other element that could affect the water current transporting sediment, boulders and large stones during periods of flood, such as holes in the river bed, or areas of varying granulometry, should be added to the topographical survey. Specimens large enough for granulometric analysis should be taken from the river bed in the immediate vicinity of the section.

Various writers have proposed formulae for measuring the size of the samples, where the importance of the volume of the sample is calculated according to the size of the largest of the pebbles of which it is composed. Furthermore, it must be recognized that, according to the phases and the duration of bed load transport and the characteristics of the water currents, either the superficial material alone, or also that of the underlying levels, will begin to move. Since the granulometry of the superficial level generally differs from that of the underlying levels, because of the changes which have taken place since their initial deposition, it is necessary to determine the granulometric curve of the material moved by each flood.

In order to estimate such curves by interpolation, when tests were carried out on the River Frigido, described later, samples of the superficial and the deeper materials were taken. The superficial samples were taken from an area of 4 m^2 and a depth equal to the largest size of the pebbles present. The deeper samples were taken from a cubic hole with 50 cm sides. The granulometric analysis was undertaken by measuring the diameters of single pebbles above $D = 8$ cm and plotting, for the smaller fractions, the weight of the material of each granulometric class, selected by hand with a sieve of $8 > D > 2$ cm and of

D < 2 cm.

Installation of instruments

During the experiment the water level and discharge in the channel must be assessed, especially during periods of flood. A gauging station should therefore be set up to measure the flow. If it is not possible to have a water level recorder, it is possible to collect useful experimental information by installing a simple maximum level gauge or a discolouration scale.

A very simple version of such an instrument was used for the tests carried out on the Oued M'Zi described below, as a result of the particular environmental conditions and the difficulties of access associated with setting up instruments in the chosen section.

The instrument consisted of a 5-10 cm metal tube firmly anchored in the river bed by means of steel rods, and of a height greater than the highest foreseeable flood level. A chain or rigid jointed index (Fig. 1(a)) was suspended from the inside of the screw-top cover of the tube, reaching to the bottom of the river bed and coloured with a substance easily soluble in water.

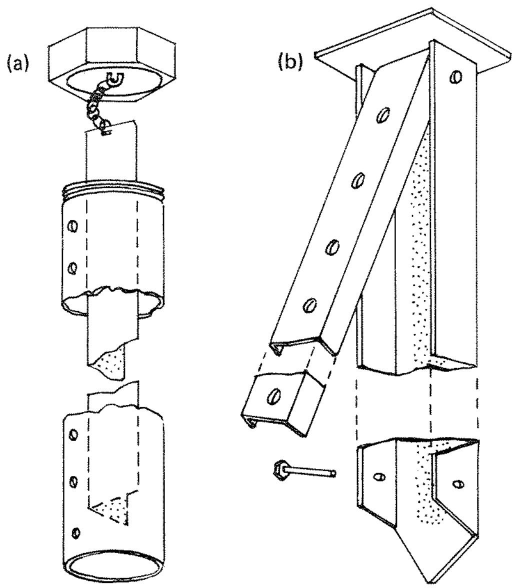

Fig. 1 The construction of the maximum water level gauges.

In a second version, used in the tests on the River Cornia, a maximum water level gauge was constructed from two U-shaped metal sections 6 and 10 cm wide respectively, hinged at the top and held opposite each other with a screw closure (Fig. 1(b)). In this version, the inside surfaces were entirely coloured in order to register a flood. After the flood the parts of the gauge still above the water level retained their colour, thus making it possible to deduce the highest water level during the flood.

The colour used for the maximum water level gauge must be easily soluble in water, and has a methylene blue base. Not only are these gauges easy to install and to use, but they also cost little, and their relative strength makes them substantially resistant to floods and vandalism. In addition to the water level recorder or discolouration scale, it is also useful to install in the experimental section of the river bed a second instrument which records the moving slope of the water in flood.

The installation of other maximum water level gauges along the river bed is advisable, firstly, in order not to lose data should any of them be destroyed during the floods; secondly, in order to record the moving slope; and thirdly, to register the inevitable differences in water level evidenced by flood marks left on the banks.

Tracing and placing of the pebbles

The pebbles used as tracers are preferably chosen from those found in the experimental reach in order not to alter its characteristics by the inclusion of extraneous material. They can be of any dimension, and there should be some small enough to ensure that they will be moved during the experiment and some large enough that they will not be moved even in extremely high waters. Since their movement is limited to periods of flood, they can simply be painted with a durable varnish, as the wear to which they will be subjected will be minimum. Their shape must be as rounded as possible in order to eliminate uncertainties when interpreting the course of their movement. The pebbles should be painted in bright colours and numbered on several sides. It is advisable to mark the greatest possible number of pebbles, so as to make it easier to find them after every flood, although not so as to cause any changes in the geometry and roughness of the section.

Each tracer is characterized by the size of its orthogonal circumference, or its relative diameter if this is easier, and its weight and volume. The latter can easily be measured by immersing the pebble in a receptacle of water, or, alternatively, when the water course is dry, it can be calculated from its diameter. Thus the specific weight can be evaluated, which can otherwise be calculated on the basis of the lithological nature of the pebble.

Once the pebbles have been marked and their characteristics recorded, they are placed along a profile, and the area indicated by two stakes on the banks so as to facilitate finding them and measuring the distance they have been transported. They can be placed at equal distances (0.5-2 m) or at varied distances, depending on the properties of the section. If they are placed in their original position, they must be isolated from mud which could cause them to stick to the bottom. So placed, these pebbles can be accurately levelled and their position established.

Characteristics of isolated rock masses

When considering performing an experiment of this type, it is worthwhile taking note of the position of the boulders and isolated rocks which may lie on the river bed, in case they should move during extremely heavy floods. The survey may be limited in this case simply to measuring the distances from fixed points or from photographs. If there are a lot of rocks, they should be numbered and their position recorded with photographs.

RECORDING OF EXPERIMENTAL DATA

In principle, experimental data should be collected at every change in the hydraulic conditions of the water course. If a series of short violent floods occurs, the survey should be repeated after every flood. If the survey only shows whether the pebbles have been moved or not, this information should refer to the conditions at the flood peak. If it is also possible to measure the distance they have been transported, these results should be referred to the complete flood hydrograph.

After every flood the following information should therefore be reported:

(a) The hydraulic characteristics of the flood: the level and moving slope at the peak of the flood as recorded from the maximum water level gauge; a hydrograph of the flood if a recorder is available.

(b) A survey of the tracers which have not moved and those which have. For this it is necessary to find the ones which have moved and measure the distance: an easy operation if the pebbles have moved only a little, but often fruitless if they have moved into depressions or been buried under other material.

In the first case the survey is done by hand, in the second a topographical survey may be preferable. When a survey is finished, and the experiment is not yet completed, the marked section should be reconstructed by replacing the moved pebbles, or by substituting new ones. After this the survey of the section is repeated as described above in readiness for the next flood.

EXPERIMENTAL TESTS

The experimental tests on which the above methods are based, were carried out on three rivers which provided six experimental sections.

The characteristics of these sections may be summarized as follows:

(a) Oued Fareg 1 km upstream of the confluence of the Oued M'Zi (Algeria): drainage area = 465 km^2

(b) Oued M'Zi at Seklafa (Algeria): drainage area = 726 km^2

(c) River Cornia at Frassine: drainage area = 97 km^2

(d) River Frigido at Canevara: drainage area = 46 km^2

(e) River Frigido at the Zecca: drainage area = 58 km^2

(f) River Frigido at the motorway bridge: drainage area = 101 km^2.

In each case pebbles with a diameter of more than 100 mm were transported by the river. In every case, with the single exception of the Oued M'Zi, the experiments covered several floods, with a maximum of seven floods observed during two successive wet seasons for the River Cornia.

The largest of the tracers was 35 cm. In general, however, the size varied between 6-8 cm and 20 cm. The maximum distance at which tracers were recovered was 235 m in the Oued Fareg (experiment a). With the exception of one or two other cases where tracers had covered a distance of 40-50 m, practically none of the tracers which had travelled further than 10 m could be found.

The criterion adopted for placing the tracers was appropriate to the characteristics of the section: in general, the pebbles were placed at intervals of 1 m (experiments b, c, d, e, f) and 0.5 m (experiments a, d, e) and only in one case at irregular intervals of 1 m (experiment f).

The marked sections were located, wherever possible, near to gauging stations equipped with water level recorders (experiments b, c, d). Where there was no station, a maximum water level gauge was installed in the marked section (experiment a). The calculation of the moving slope was based on discolouration scales established along the river bed (experiments a, b, c, d). In experiments e and f, the flood levels were recorded from the flood marks left along the banks. The results of the six experiments are shown in Table 1.

Table 1 Experimental data

Experimental section	Fareg 1 km from the M'Zi	M'Zi Seklafa	Cornia Frassine	Frigido Canevara	Frigido Zecca	Frigido motorway
Tracers:						
number	70	17	35	23 27	30	26 32
spacing (m)	0.5	1	1	1 0.5-1	0.5-1	1 variable
max. diam. (cm)	35.0	19.8	20.3	17.5 20.0	27	19.0 21.0
min. diam. (cm)	4.2	5.3	5.4	6.5 8.2	8.4	7.0 8.0
Level gauges:						
recorders (no.)	–	1	1	1	–	–
max. water level gauges (no.)	3	1	2	–	–	–
Hydaulic conditions of experiment:						
max. level (m)	1.96	1.48	1.34	2.60 1.74	1.60	1.81 1.41
max. tangential tension (kg m^{-2})	11.81	14.51	9.70	19.50 13.05	11.04	9.41 6.77

As an example of the experiments, the marked section of the Oued Fareg where experiment (a) took place is shown in Fig. 2(a). Figure 2(b) provides a schematic diagram from experiment (c), showing the pebbles which did not move during periods of flood, or were recovered in depressions, or were not found at all.

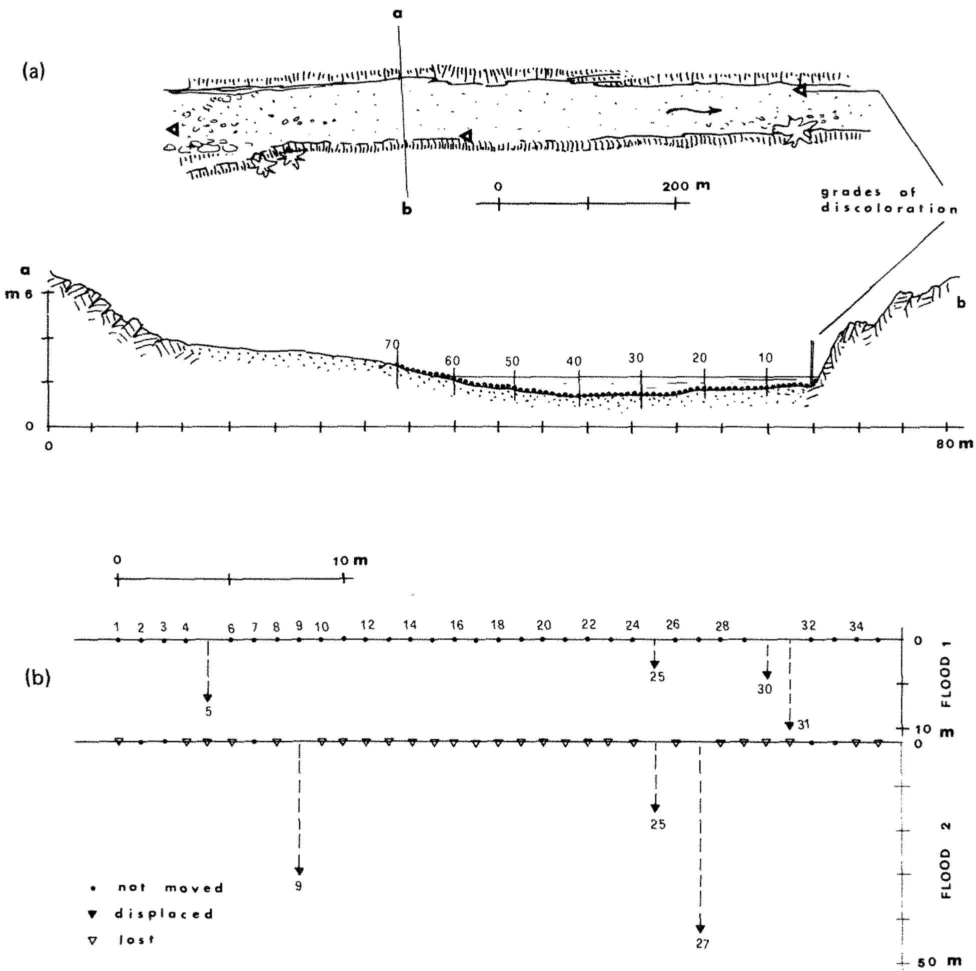

Fig. 2 Transverse sections used for positioning tracers. (a) Oued Fraeg 1 km upstream from the confluence with the Oued M'Zi (Algeria), showing numbering of the tracers and position of the discolouration scales. (b) River Cornia at Frassine (Tuscany, Italy): diagrammatic outline of the movements of the tracers.

ACHIEVABLE RESULTS

The data that have been collected by the experiments described are rather limited in relation to those which can be produced by particularly successful experiments. In spite of this, however, the few results obtained can be of fundamental value in the characterization of the transport of bed load material and are more valid than the simple application of theoretical formulae.

With the data collected it is possible, in fact, to ascertain with reasonable approximation, the essential sizes necessary to apply these theoretical formulae in specific cases, since the conditions of initial bed load movement are known.

Once this process has been defined, it is possible, by basing calculations on flood hydrographs and on the distances moved by the tracers, ultimately to improve on the estimate and to produce evaluation of the transport of bed load which occurred at that time.

One result of particular interest which emerged from the experiments described was the experimental verification of the Shields curve under conditions of extreme turbulence, for which available experimental data are few or non-existent. After each flood it has been possible to calculate, for each of the tracers, the pair of values:

$$T_o/(\rho_s-\rho)\ gd \qquad R_e^* = (T_o d/\rho\nu)^{\frac{1}{2}} = U^*d/\nu$$

The scatter of the points representing these values on the Shields curve, should be divided by the curve between those points representing the tracers which did not move, and those which did. Thus the value of T_o corresponding to a diameter between the largest of the tracers which did not move, and the smallest of those which did, assumes a critical T value.

Since the experiments described refer to river beds with varied granulometry and to flow velocities which are not easily identifiable in the vicinity of every single tracer, the results obtained do not always correlate with those theoretically expected, although taken as a whole they may be confirmed.

Figure 3 illustrates the points which represent, for each marked section, the experimental values of the critical T value: it can easily be observed how these values are arranged fairly close together around the Shields curve. They present the

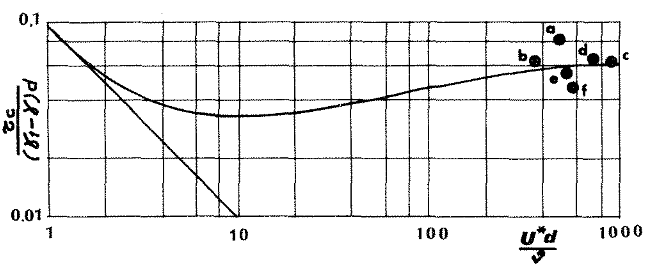

Fig. 3 Comparison of experimental values with the Shields function.

following two results: first, they bring together the conclusions drawn from the channels studied and established theories of bed load transport, and, secondly, they provide verification by investigations into natural channels of the branch of the Shields curve relating to excessive turbulence.

ACKNOWLEDGEMENT This work is being carried out with the support of the Italian National Research Council as part of the "Soil Conservation" project.