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NEW TRACER TECHNIQUES FOR PARTICLES IN GRAVEL BED RIVERS

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Mots-clés: méthodes de traçage, charge de fond, cailloux.

Résumé

Les processus de transport des matériaux grossiers de façonnement des lits graveleux des rivières, de même que les interactions entre les matériaux transportés et le lit des cours d'eau sont le plus efficacement étudiés quand les déplacements de quelques éléments peuvent être suivis grâce à des traceurs. Le choix de la technique de traçage, eu égard à la recherche poursuivie et au site étudié, dépend non seulement du coût mais aussi de la disponibilité d'une instrumentation technique (électronique) adéquate et du savoir-faire des chercheurs. C'est dans cette perspective que les auteurs présentent ici une sélection de plusieurs méthodes récentes de traçage, en montrant leurs caractéristiques et ce qu'elles peuvent apporter dans l'analyse des processus actifs dans les lits graveleux des rivières.

Key-words: pebblles, bedload, tracer techniques.

Abstract

Processes of river morphology, coarse material bedload transport and particle/bed interaction can be investigated more effectively when the behavior of (some of) the particles concerned is visualized by a tracer. Choosing the appropriate tracer technique for the question of research and nature of the site is not only dependent on pecuniary matters but on the availability of technical/electronical instrumentation and know-how. Therefore, a selection of several new tracer techniques, their features and possibilities for the analysis of the processes in gravel bed rivers is described.

I. INTRODUCTION

Measuring coarse material bedload transport is still a difficult task and many different methods have been tried to obtain more information on transport mechanisms. In natural streams it is usually not possible to observe what an individual pebble or a bulk of gravel does during transport. Therefore, the material transported or representative parts of it have to be made "visuable". This "visualization" can be achieved by the use of tracers or markers which are detectable with sensors. These tracers bear valuable information on the conditions of erosion, mechanisms of transport and places of deposition. A quantification of the amount of bedload transported and bedload transport rates is possible. Even the path, the velocity and the motion of a particle can be detected. Needless to say, the information gained increases with the grade of sophistication applied to the method used.

In the following, several sets of relatively new tracer techniques, their detection devices and their applications are described.

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II. METHODS OF TRACING AND DETECTION

Tracing bedload material and especially the coarser fraction of it can be done by several different methods:

- *individual natural* pebbles are traced by
  - iron cores,
  - magnetic cores,
  - self emitting radio systems;
- *individual artificially manufactured* pebbles are traced by
  - adding fine particles of tracers to a matrix of concrete or resin,
  - implanting traceable of self-emitting items (radios) into the clasts;
- a bulk sample of *natural gravels* is *artificially* traced by
  - magnetic enhancement;
- *natural gravels* are *naturally* traced by
  - high magnetic content,
  - high iron content.

Individual particles as well as bulk gravels can be traced by radioactive marking. This method, however, shall be excluded from further description as it implies dealing with very hazardous material which might endanger not only the researchers dealing with this substance but become an unforeseen source of hazard to the environment in general.

The various *detection* devices available can determine

- the position of the pebble or the gravels after a flood event,
- the passage of pebbles or gravels through the cross-section during a flood event,
- the path, the velocity and motion of a pebble during the flood event.

Finding the right combination of tracers and detection devices is a matter of the research question involved, the natural conditions, and the technical practicabilities of the project.

III. TRACING INDIVIDUAL PEBBLES AND DETECTING THEM AFTER THE FLOOD

The information gained by these kinds of experiments can be listed as follows:

- influence of *hydraulic parameters* on transport length and position of deposition,
- influence of *actual and relative grain size and shape* on transport length and position of deposition,
- influence of *relative position* on transport length and position of deposition:
  - *position within a cluster*
    - shock,
    - wake,
    - obstacle;
  - *position outside a cluster*
    - upon plane bed,
    - imbedded in the armour layer;
  - *relative protrusion*
    - grade of exposure;
  - *position within the river morphology*
    - riffle,
    - pool,
    - thalweg,
    - lateral position,
    - bars.

The preparatory steps for tracing individual pebbles are to gather a collection of pebbles varying in size and shape according to the research questions being investigated. Drilling holes into the pebbles with a drill stand and a special drill bit may be troublesome depending on the petrology and the size of the pebbles. A collection of spare pebbles should be available. The tracer is inserted and secured with epoxy. A paint cover helps to visually identify the traced pebbles among the others on the river bottom.

For the experiments the pebbles are placed into the river bottom before a flood, preferably during low flow. After the flood a person will walk across the channel trying to search every square meter of the channel bottom with the hand held detector. The pebbles exposed on the river bottom are easy to find; those which are buried in the river sediment or which are swept far out of reach are very time consuming to relocate and yield a small recovery rate.

A. Iron core tracers

Iron core traced pebbles may be used to find answers to the following questions:

> What are the conditions for erosion, what are the transport lengths and positions of deposition for pebbles of various actual and relative size and shape implanted into various sites in the river bed during different hydraulic conditions ?

The method is cheap and easy to use and has been effectively applied by several researchers. Nevertheless, one of the biggest disadvantages in using iron core traced pebbles is the low recovery rate: when trying to find the pebbles with a metal detector, everything else containing metal makes a signal, too. (It is a very tedious job to dig in the river bottom when the detector beeps, and after a while come up with a piece of wire or a bottle cap). Another source of frustration is not finding the carefully prepared and positioned pebbles at all. The vertical reach of the metal detector into the river bottom is limited to a depth of some tenths of a meter. In order to increase the recovery rate the signal made by the metal detector should be as large as possible. Besides successful tuning, this is achieved (especially when using iron cores as a tracer) by inserting as big a piece of metal as possible. The factor limiting the size of the implanted iron core is the density of the pebble which should not be changed too much. Spare space beside the iron core can compensate for an increase in weight. The recovery rate of the traced pebbles is also limited by the enormously varying transport lengths of even similar pebbles during one flood event. While some pebbles are not transported at all others are swept far out of the reach and one would have to search miles of river bottom to find the pebble transported farthest.

B. Magnetic Tracers

Though, in general, the preparation and use of *artificially implanted magnetic tracers* is the same as that of iron core tracers, the magnetic tracer technique is a real improvement compared to iron cores. The biggest advantage of using magnetically traced pebbles is a higher recovery rate, not only because much less scrap in the rivers is magnetic, but besides that, the recovery rate is increased by an extension of the maximum distance allowed between pebble (magnet) and detector (magnetometer). Signals made by magnets can be more easily amplified because usually there are no other magnetic objects around which would create a "noise". That expands the reach of detection and even allows the worker to find pebbles which have been buried deeply. Another success of magnetic tracers is that the method allows the differentiation between several kinds of magnetic intensities, thus offering a variety of tracers. This helps to gain more information during one experiment.

The magnetic tracer technique was developed by ERGENZINGER & CONRADY (1982) and has been successfully applied by HASSAN, SCHICK & LARONNE (1984). The recovery rate of their pebbles tagged with ceramic magnets was as high as 93 %, though 53 % of all the pebbles retrieved were discovered below the river surface. Owing to their powerful tracers they even managed to relocate pebbles which had been buried as deep as 60 cm. This high recovery rate gives a reliable record of the three-dimensional distribution of fluvial transport populations (SHICK, LEKACH & HASSAN, 1987).

IV. ARTIFICIAL MAGNETIC ENHANCEMENT OF PEBBLES-DETECTION AFTER THE FLOOD

Whereas drilling holes into pebbles to insert magnets always implies a limitation to the number of pebbles traced, this limitation can be partially overcome by using a strong heat source to magnetize pebbles. OLDFIELD, THOMPSON & DICKSON (1981) used a heat treatment (900°C) to alter the mineralogy of the material and to produce a magnetization. This artificial magnetic enhancement works for bedload of different petrology, so the method is widely applicable.

ARKELL, LEEKS, NEWSON & OLDFIELD (1983) employed OLDFIELD *et al.*'s (1981) method to estimate sediment yields and determine features of supply and transport in an upland catchment in Wales. They achieved a maximum possible enhancement of the magnetic susceptibility for large amounts of all sizes of material. After floods they traced the magnetic material in the stream using a search coil and compared results with bedload material caught in a trap. As they were confronted with a poor correlation between bedload transport rates and discharge they had to take into consideration that bedload transport is not solely a function of current hydraulic conditions but also of the channel history which determines the conditions of supply of bedload material and its availability to transport. In order to distinguish between supply and transport mechanisms the magnetic tracer technique provides a means of tracing the site of erosion and the site of deposition.

Though the technical applicability has been much improved, the geomorphological or hydrological applicability of the artificial magnetic enhancement method has not increased very much compared to the methods described above: after a flood the magnetized material is detected with a search coil. Transport lengths and the positions of deposition can be registered and attributed to various parameters measured before or during the flood. What happened to bedload particles during the flood events remains unknown.

The advantage of the artificial magnetic enhancement method is that a bulk sample containing all grain sizes present in the stream can be artificially magnetized, thus being representative for all the material sizes. By comparing the percentage of traced material in the original sample with the sample taken after the transport event the amount of material transported can be quantified.

V. ARTIFICIAL ELECTROMAGNETIC DEVICE FOR AUTOMATIC DETECTION DURING THE FLOOD

REID, BRAYSHAW & FROSTICK (1984) were interested in the question of mutual interference of neighboring bed particles upon initial motion and transport rates. They used 100 artificial particles labelled with ferrugineous material. The particle size responded to the D_{90} of the gravel bed mixture. The particles were seeded within certain positions of the river bed to compare the influence of open plane bed positions and cluster positions as well as the shock of particle cluster with hydraulic conditions of erosion. The motion of the previously seeded particles during a flood was registered by their passage over a sensor which distorts the magnetic field causing a change in the inductance of the coils installed across the river bed. After the flood the particles were sought with a metal detector.

The advantage of this system is undoubtedly the automatic detection of the passage of traced pebbles. Compared with the methods above it combines the possibilities of working with individual pebbles (allowing, for example, certain positions of erosion or deposition to be traced), with the possibilities offered by automatic detection of the movement, i.e. attributing motion to dynamics or conditions during the flow. The disadvantages are the financial restriction to a relatively small number of traced pebbles. Such a detection device is expensive, too and, once installed, of limited mobility.

VI. NATURAL MAGNETIC TRACERS AND THEIR AUTOMATIC DETECTION DURING THE FLOOD

A different kind of information is gained by this tracer technique which makes use of the natural magnetic content of the pebbles. They originate from volcanic rocks which are globally widespread. The method is the following:
According to the Faraday Inductive Principle a voltage peak is induced when a magnet passes over a coil (copper windings on an iron core). Several sets of coils are inserted into a detector block which is installed into the bottom of the river reaching from one bank to the other. The signals induced by the magnetic pebbles passing over the detector block are amplified, filtered and recorded with special electronic devices. This measuring device works automatically and produces a continuous, spatially and temporally high-resolution record. The analysis of these raw data give new insight into the processes influencing coarse material bedload transport (e.g. supply dependency, time series analysis of the bedload pulses).

Though this method is expensive and implies considerable electronic skill, an interesting analysis can be obtained by the *in situ* observation of an unlimited number of real bedload particles, which have never been disturbed by any action of tracing or seeding. This system can be applied to big rivers as there is no need to look for traced pebbles during periods of low flow. The disadvantage of this method (as well as of the methods described above) is the difficulty in calibrating the signals. As the size of the signal is a function of many parameters (e.g. magnetic content, velocity, magnetic orientation and height above the detector) the calibration of the number of signals registered can only be done by statistical means or by comparison with bedload samples taken simultaneously. Other difficulties are the tuning of the electronics and the "noise"-reduction.

This method was invented by ERGENZINGER & CONRADY (1982) who still used artificially implanted magnets which of course limited the number of pebbles observed. The first continuous in situ observation of the passage of naturally magnetic coarse material bedload transport was done by ERGENZINGER & CUSTER (1982, 1983) in a high energy mountain river in Montana, USA. The measurements were carried out during several spring snowmelt seasons with their typical diurnal fluctuations of flow. In a statistical calibration they attributed the rate of impulses to a bedload transport rate and found that the total load comprised of 66 % of bedload. They had set up a means to study the spatial and temporal variation of bedload transport.

CUSTER, ERGENZINGER, BUGOSH & ANDERSON (1987) show that this method by its high real time record of the passage of pebbles is a powerful tool to detect various incidences of coarse material bedload transport. Often, bedload transport occurs in "bursts", a sudden set in of transport, which may stop as abruptly as it had started. During intermediate high-flows those "bursts" of transport are confined to the upper falling limbs of the daily highflows.

BUNTE, CUSTER, ERGENZINGER & SPIEKER (1987) have improved this method. Especially the signal-noise distance was greatly enlarged allowing the detection of pebbles as small as 3 cm (provided the magnetic content is high enough). The extreme temporal variation of bedload transport thus recorded does not correspond with variations in discharge. The gaps in bedload transport shortly after high flow were interpreted as the results of a limited supply which does not allow bedload to continue at a more steady rate.

In a further analysis of the data obtained BUNTE & ERGENZINGER (1987) showed different modes of transport by enlarging the time scale. The fluctuations in transport were differentiated into high flow induced "major waves" on the one hand and "minor waves" on the other hand which tend to occur during waning flow and "random transport" which is not confined to any particular part of the flow at all.

SPIEKER & ERGENZINGER (1989) show that by a sophisticated system of demodulation and electronic data processing even the grain size of the transported material can be determined within a certain probability range.

VII. THE PEBBLE TRANSMITTER SYSTEM (PETS)

The pebble transmitter system, also called *radio pebble*, allows the detection of conditions of entrainment, manner of transport, travel length, velocity and the position of deposition of an individual pebble. The radio pebble is an active system in which a transmitter emits a signal (2m wavelength). One or several antennas detect the signal and conduct it to the receiver. Data thus obtained are stored in a data logger for further data processing by a computer.

In accordance with some of the methods described above, a hole is drilled into a cobble. A waterproof capsule containing a transmitter and a battery and a mercury switch is inserted. As the batteries only last for three months the hole is just plugged, so the system can be easily removed. The mercury switch changes the signal whenever the radio pebble is turned over. A rotational movement of the radio pebble during transport can be detected by this way. The size of the capsule, still 55 mm x 20 mm, will be reduced to fit smaller pebbles as well.

The actual position of the radio cobble thus prepared is located by antennas which according to the research requirements have three modifications:

- *-stationary antennas:* these antennas, 2 m long each, are installed on the river bank 5 m apart from each other to trace the precise path of the cobble on its way downstream.
- *-a mobile antenna:* is carried along the river bank in order to keep contact with the emitting pebble, the position of which can be traced within a range of 1 m.
- *-a search antenna:* is used after the flood to find exactly the position of deposition which has been narrowed down by the use of the mobile antenna to a 1 m range. Thus, even deeply buried pebbles are easily retrieved.

Among the individually traced pebbles the radio pebbles are a highly sophisticated system. Apart from all the information that can also be gained by the other tracers described above, this system is an *improvement* with special regard to the following aspects of *pebble behavior:*

Velocity: the path of the pebble can be detected during the flood.
Path per time reveals the actual velocity of the pebble during motion or the duration of rest.
As bedload transport is the result of the behavior of the bed particles influenced by flow, and as transport consists of the process of erosion, traveltime, deposition and resting time, EINSTEIN (1942, 1950, in GRAF, 1971) defined the rate of transport by the average time between two steps and expressed the beginning and the end of particle motion with the concept of probability which relates instantaneous hydraulic lift forces to the particle's weight. Owing to the measurements which have become available by the radio pebble tracer technique, resting and travel times of a pebble under natural conditions can be registered and compared with EINSTEIN's concept.

Rotation: by recording how often the pebble rotates per time and combining this with velocity the manner of motion can be deduced (rolling, sliding, saltation). A first analysis of the data from the measuring site in Bavaria revealed that motion started with a gliding movement and then turned into rolling, owing to the impact of waves and coarse bottom roughness. Once the cobble was set into rolling motion spin and momentum caused in increase in travel length.

Relocation: the relocation of the pebble after the flood was easy and precise (recovery rate 100 %). Even when buried under a layer of sediment more than 60 cm deep the pebbles could be retrieved.

Position of deposition: coarse material was mainly deposited behind big boulders, in pools, on bars or at the banks.

With the Pebble Transmitter System the exact moments of erosion, movement and deposition can be measured. By simultaneously measuring conditions of flow a closer relation between the behavior of the individual pebbles and the hydraulic conditions prevalent at that time can be established. The system is easy to handle. Unfortunately, the number of radio pebbles is limited by costs.

VIII. CONCLUSION

Several new tracer techniques were described and it was shown how tracers have been successfully applied to obtain deeper insight into the processes of particles in flow in gravel bed rivers. Though the grade of sophistication increases with the development of newer tracers this should not discourage researchers from using them as a powerful tool for their research.

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