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INCIPIENT MOTION OF A BIMODAL MIXTURE OF GRAVEL AND SILT: A LABORATORY EXPERIMENTAL STUDY

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ABSTRACT

Water management requires a good understanding of sediment transport and associated river morphodynamics. In mountain and piedmont hydro-systems, gravel-bed rivers often transport large amounts of fine (silt-sized) sediment. The bed material can be regarded as a mixture of coarse (gravels) and fine particles (silt, clay, very fine sand). Whether they are transported separately or not cannot be answered simply, because complex interactions between these two classes of sediment exist. As a consequence, the riverbed is usually made of heterogeneous layers of gravel particles clogged by fine sediment infiltrated in the pores of the matrix. The hydraulic conditions for the deposition and erosion of such sediment mixtures are poorly known, although they are highly related to ecological (affection of river's habitat) and socio-economic issues (dam management).

In this paper, new laboratory experiments are presented to characterize the influence of fine particles on sediment transport. These experiments are conducted in the HHLab of Irstea in Lyon-Villeurbanne (France). Transport of fine (silt, 10 to 30 μm in diameter) and coarse (gravels, 5 to 12 mm in diameter) particles are studied in this controlled environment under conditions close to the incipient motion. Both gravel and silt are moderately sorted.

The incipient motion conditions are quite difficult to measure. Several methods for determining the critical shear stress are proposed, but most of them suffer from uncertainty or incomplete descriptions of the experimental parameters. In this paper, we show that according to the chosen methods the value of the critical discharge for incipient motion can vary significantly (23 %).

Three kinds of experiment have been achieved: one with a loose gravel bed, one with a well-settled bed, and one with a loose gravel bed clogged with silt-sized sediment. The critical discharge for incipient motion of the bed material was observed to be larger for the gravel-silt mixture. The initial arrangement of the bed appeared to be a crucial parameter, affecting directly the critical discharge

Keywords: sediment mixture, gravels, incipient motion, flume experiments, shear stress

1. INTRODUCTION

Numerous studies have been undertaken to understand the mechanisms of sediment transport and to characterize the incipient motion of particles. Few of them have been dedicated to the study of beds constituted with bimodal mixture, in particular with gravel-silt mixtures. The associated mechanisms are complex and remain not well known although they are highly connected to ecological and socio-economic issues, such as river habitat for fauna and flora and sediment flushing.

Sediment transport of fine particles is governed by suspension and is often considered as independent of coarser particles that are usually transported as bedload. When sediment transport occurs, it is usually assumed that there are no interactions between the two classes of sediment. Nonetheless, observations have shown that gravel bed transport can increase (lubrication effects) or decrease (consolidation/clogging) when mixed with fine sediments. It is difficult to describe the physical processes governing the incipient motion of coarse particles because of the number of parameters involved (nature of fine sediments (cohesive or not), particle arrangement, hydraulic conditions, concentration of fine sediments in the water, channel geometry, etc.).

Empirical laws have been used to predict the incipient motion and transport of sediment (*e.g*. Meyer-Peter and Müller, 1948; Cheng, 2002; Paintal, 1971; Nielsen, 1992; among others), and each one was established for specific conditions. Therefore, their validity is often questioned when applied to field data. Buffington and Montgomery (1997) reviewed several methods determining the incipient motion of sediment and showed that results differ significantly according to the chosen method).

The objective of this laboratory study is to analyze and understand the processes controlling the incipient motion of a bimodal mixture of gravels and silts. Numerous parameters control the incipient motion, such as slope, water depth, bottom velocity, water and sediments characteristics, grain arrangement, *etc*. Thus, a bias in the determination of the conditions for incipient motion can be easily introduced if one of the parameter is unknown.

First, we review the methods characterizing the incipient motion of sediment. Then, a series of preliminary experiments quantifying the bed shear stress for incipient motion are presented. The first experiment is with gravels only. Different definitions of the incipient motion are used to compute the critical shear stress. A comparison between an experiment with only a gravel bed and a second experiment with gravel bed fully clogged with silt-sized sediment is presented. Finally, results and uncertainty inherent to the laboratory experiments are discussed.

2. EXPERIMENTAL SET-UP

Tests have been conducted in one of the new flumes of the HHLab of Irstea Lyon-Villeurbanne (France). The flume is 18 m long, 1 m wide and 0.80 m deep (**Erreur ! Source du renvoi introuvable.**). Water is supplied with a recirculating system that can be filled with clean water or a mixture of water and silt. The channel slope ranges from 0 to 5 %. The tilting flume is made of glass, allowing optic measurements.

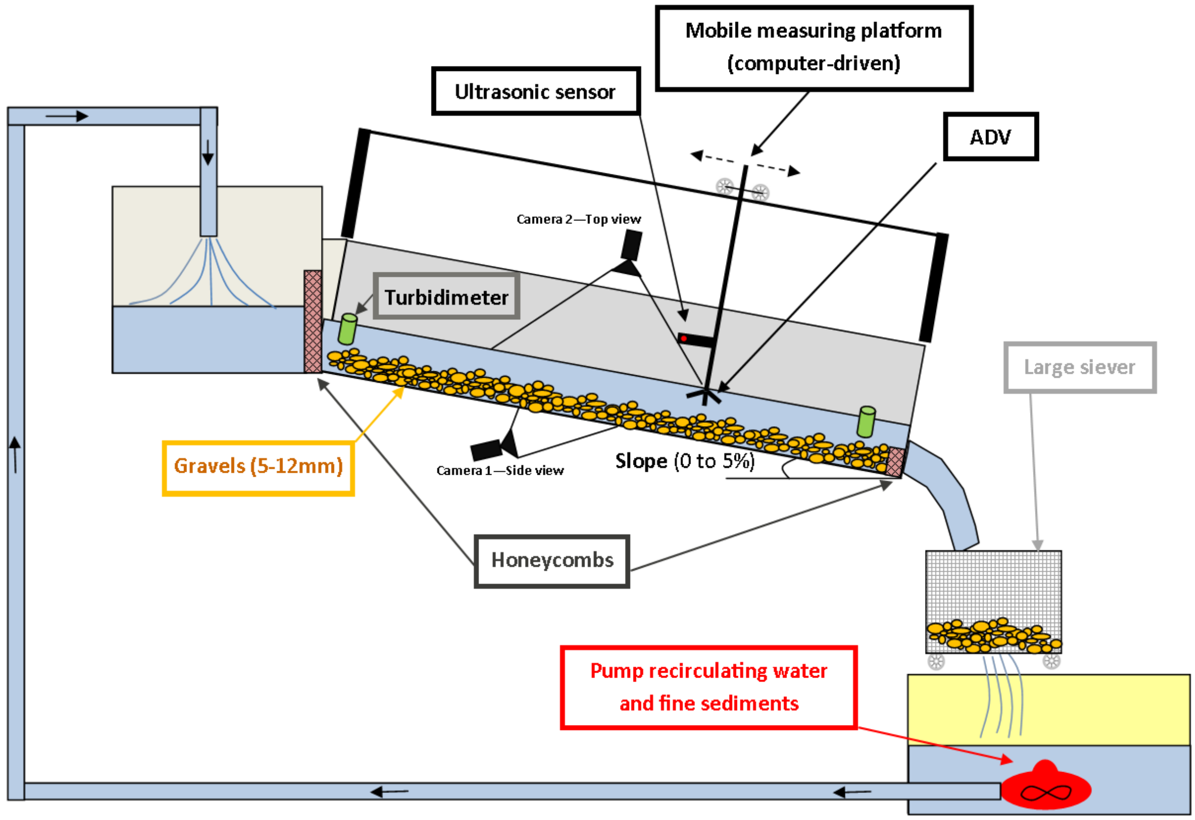

Figure 1 - Experimental set-up of the tilting flume of Irstea

A gravel bed of constant thickness is installed manually in the tilting flume. A large scraper is used to obtain a flat bed surface. There is no sediment feeding during the experiment. The flow discharge is fixed at a specified value. Regulation and measurement of the discharge are handled by an electromagnetic flow meter (KROHNE OPTIFLUX, error of accuracy: 1 $L.s^{-1}$) in the supply pipe. Honeycombs are placed in the inlet to break the turbulent structures of the entering flow, and at the downstream end of the flume to prevent grain fall and keep the bed level constant. The water surface elevation is measured with an ultrasonic sensor (BAUMER UNDK 20I6303/S35A, error of accuracy: 0.2 mm) at several locations along the flume. During the experiments, the silt concentration in the water is measured by two turbidimeters (HACKLANGE, probe SC200, transmitter Solitax) placed at the upstream and downstream ends of the channel.

A large sieve with a mesh of 1 mm at the downstream end of the tilting flume collects coarse sediments only. The gravel transport rate is computed as the ratio of the collected weight and the time of sampling. The dimensionless shear stress is computed under the assumption of uniform flow as:

$$\tau^* = \frac{\tau}{g(\rho_s - \rho)D_{50}} = \frac{R_h I}{g(s-1)D_{50}} \qquad [1]$$

where, τ is the bed shear stress (Pa), D_{50} is the mean diameter of the bed particles (m), R_h is the hydraulic radius (m), ρ_s is the particle density ($kg.m^{-3}$), ρ is the water density ($kg.m^{-3}$), g is the gravitational acceleration ($m.s^{-2}$), I is the energy slope and $s = \rho_s/\rho$ is the specific gravity of sediment.

Photos and videos are also taken in order to observe the particle movement in real time. The bed material can be of two types: a mixture of gravel only (ranged from 5 to 12 mm) or a bimodal mixture of gravel and silt (~ 15 - 30 µm). The sorting coefficient $\sigma = 0.5\,(D_{84}/D_{50} + D_{50}/D_{16})$ (Recking, 2006) for gravel is 1.3 (where D_x is the diameter such as *x %* of grains are finer). The characteristic diameters of the gravel material are reported in Table 1.

Table 1 – Grain size distribution of gravel material (mm).

D_{90}	D_{84}	D_{60}	D_{50}	D_{30}	D_{16}	D_{10}
10.4	10	8	7.3	6.2	5.8	4.7

3. REVIEW ON METHODS FOR THE CHARACTERIZATION OF SEDIMENT INCIPIENT MOTION

The concept of incipient motion of sediment is complex and is one the most important parameter used in sediment transport capacity formulae. Many authors have proposed different definitions. Most of them are based on the Shields analysis (1936). Unfortunately, the validity of these definitions is often questioned (Buffington, 1999). An interesting analysis on eight decades of studies reporting all the data used to characterize the incipient motion of gravel sediment is provided by Buffington and Montgomery (1997). Numerous differences between the existing methods have been noticed, partially due to the diverse approaches used to characterize the incipient motion (or to a lack of precision about the experimental conditions). This makes comparison of existing formulae of incipient motion difficult.

In this section, a list of methods used to define the incipient motion or more precisely the associated threshold is presented. Here, the term “threshold” corresponds to the value of shear stress at which particles are considered to be in motion. Lavelle and Mofjeld (1987) gave an exhaustive review of the methods used during the last century. They suggested four different methods to characterize incipient motion of sediments, which can be re-organized into two approaches, described herein.

3.1 First method : sediment flow conditions

The first method is based on measurements of sediment transport rate. The value of bed shear stress associated to an arbitrarily defined minimum sediment transport rate marks the incipient motion. Shields (1936) used this method. He approached the transport rate to the zero value and deducted the associated bed shear stress. This procedure involves knowing the behavior of the sediment transport rate function near zero.

The USWES (United States Waterways Experiment Station, 1935) used this definition. Unlike Shields, the threshold was fixed to a minimum value of transport rate corresponding to the incipient motion of representative sediments of the bed material. The minimum transport rate was set to $4.13.10^{-3}$ g (cm s)$^{-1}$ (*i.e.* $q_s = 1.55.10^{-7}$ m^{2}s^{-1}). It is important to note that this value was determined for sand (diameter < 0.6 mm). The isolated movement of gravel can rapidly satisfy this condition even if they are not representative of the entire size particles of the bed. If this method is used for gravel, or in different beds, it is necessary to impose a new criterion for the minimum sediment transport rate.

The main inconvenient of this method is that it requires a large dataset. It also strongly depends on the minimum sediment transport rate criterion that we choose.

Some authors used the estimation of the erosion rate to find the incipient motion. This method is often used for very fine and cohesive sediments. The erosion rate is quantified and extrapolated to a point of “no-erosion”. The threshold of incipient motion corresponds to this state.

3.2 Second method : visual observations

This approach focuses on the particle movement and visual observations. The method consists of increasing progressively the bed shear stress value and evaluating when the movement of particles is detected (with measurement of the water depth or velocity for instance). However, visual criteria are arbitrarily applied to characterize the incipient motion of particles. This method strongly depends on the experimenter. Measurement conditions are generally not detailed (duration of the observations and surface observation frequency are usually missing).

Many authors have produced data with this method, but each author used his definition of incipient motion. For instance, Kramer (1935) conducted experiments on a mixture with an extended particle size distribution (sand mixture) and observed four level of sediments transport:

- First level: no transport. No particles are in motion;
- Second level: weak transport. The smallest particles are in motion at isolated spots;
- Third level: medium transport. The particles of mean diameter are in motion at a small rate;
- Fourth level: general transport. All particles are moving at all spots on the bed and at all times.

The threshold of incipient motion corresponds to the value of critical shear stress associated to the fourth level. The main difficulty of this method remains in the visual distinction between these four levels. Inspired by Kramer’s works, Petit (1994) identified two thresholds of incipient motion.

- The first threshold is the one that enables the incipient motion, where a signification portion (20 %) of particles of a certain size are transported;
- The second threshold is associated to the general transport. The quasi-totality of grains is in motion.

Recking (2006) distinguished experimentally three regimes related to the bed resistance.

- First regime: no bedload transport is observed. The grain resistance to the flow decreases when the relative depth (hydraulic radius/mean diameter) increases.
- Second regime: bedload transport appears and can be measured, increasing with the relative depth while the grain resistance is constant;
- Third regime: bedload transport is clearly identified. It increases with the relative depth and the grain resistance to the flow is increasing too.

Following Recking (2006), two different definitions of the threshold may be proposed based on bedload rate and flow resistance.

Vanoni (1964) presented a completely different method based on the single particle movement. He defined the threshold of incipient motion when at least one grain is in movement every two seconds at any spots of the bed. This definition is dependent on the experimenter and may be difficult to apply for poorly sorted sediments. Today, most of the experiments can be filmed. Analyze and image processing help providing more precise measurements on the incipient motion.

4. EXPERIMENTS RESULTS

4.1 Experiment with only a gravel bed – discussion on incipient motion criteria

This first set of experiments was realized on a bed made of gravels only. The objective was to compare and verify the applicability of the different methods for estimating incipient motion. In this experiment, a comparison between the different critical flow discharges for the sediment incipient motion was made. In all experiments, the slope was fixed at 1 %. The flume was adjusted to this slope after the bed was completely under water, limiting the disturbance of the bed with the incoming flow. There was no fine sediment in suspension during the experiment. The bed was considered as well settled (not loose) tending to be armored.

The water discharge increased following a succession of steady stages from 30 $L.s^{-1}$ to 65 $L.s^{-1}$ (every 15 minutes). The measurement (slope, water depth, bed-load transport rate) were made at each successive discharge after reaching the equilibrium state.

We compare several methods based either on the estimation of a minimum transport rate (Table 2) or on a visual approach. For the transport rate method, a transport rate criterion has to be fixed arbitrarily. The USWES criterion cannot be used here because it is appropriate for sediment transport of sand.

In the present work, the transported mass or the number of transported particles has to be significant compared with the quantity of sediments present in the channel. The channel is composed with around $2.8.10^3$ kg of gravels. Table 2 summarizes the three selected criteria. The number of grains is estimated using the density of particles (ρ_s = 2650 $kg.m^{-3}$). Each particle is assumed spherical and described by the median diameter (D_{50}). The mass of one particle is considered equal to 0.54 g. Verification was made by counting all particles. The first criterion is associated to a small mass of sediment, and consequently to a small number of grains (~ 150). The transport rate associated to this criterion is probably too small and too exposed to uncertainties of measurement. The sediment masses corresponding to the second and third criteria are quite significant, and represent respectively 740 and 1470 grains. It should give more reliable criteria, being statistically more representative.

Table 2 - Proposition of different criteria of transport rate.

	VALUE OF MINIMUM TRANSPORT RATE ($m^2.s^{-1}$)	MASS COLLECTED IN 5 MIN (g)	NUMBER OF GRAINS ASSOCIATED
CRITERION 1	10^{-7}	79.5	~150
CRITERION 2	5.10^{-7}	400	~740
CRITERION 3	10^{-6}	795	~1470

Concerning the visual criterion, the incipient motion is often linked to the movement of representative particles of the bed. Thus, it is necessary to know the size distribution of the mixture and that of transported particles collected at the downstream end of the channel. The general mass distribution of the bed is a result of an average of three different samples (1.3 kg each).

Table 3 - Characterization of sediment samples collected at the downstream end of the flume. The total mass is the sediment mass collected at the downstream of the flume during five minutes at one given discharge.

	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 7	SAMPLE 8
ASSOCIATED FLOW DISCHARGE ($L.s^{-1}$)	30	35	40	45	50	55	60	65
TOTAL MASS (g)	1.4	0	3.4	16.3	52.7	259.4	636	1619.6
ASSOCIATED WATER DEPTH (cm)	5.8	6.1	6.7	7.1	7.5	7.8	8.1	8.4
CRITICAL SHEAR STRESS (dimensionless)	0.048	0.05	0.056	0.059	0.062	0.065	0.067	0.069

According to Figure 2, samples n°1, n°2 and n°3 are not representative of the general size distribution of the bed material. However, the total mass of these samples is very low (Table 3 - around 10 grains). These samples are probably composed of badly settled grains on the bed. The uncertainty is too large for these samples. They cannot be analyzed.

At discharge 50 $L.s^{-1}$ fine gravel grains are under-represented in comparison with the size distribution of the bed. Some particles probably penetrate into the coarse sediment more easily at this flow discharge. Consequently, they are hidden by coarse gravels and protected. This phenomenon refers to the well-known exposure/hiding concept. Large grains are more exposed to the flow than fine particles.

At discharge 65 $L.s^{-1}$, the grain size distribution is close to the one of the bed. All grain classes are represented in good proportions. All grains are transported whatever their size. This kind of transport is called « equal mobility » of grains (Parker and Klingeman, 1982; Andrews, 1983; Wilcock, 1988).

Table 4 reports all the values of critical discharge for the incipient motion according to each method. A large dispersion is noticed. Some methods may underestimate or overestimate the critical discharge. For instance, in the case of Kramer's method, the incipient motion of sediments is observed at high discharge (65 $L.s^{-1}$). Actually, this "incipient motion" represents a general movement of the bed and not a movement of a single particle. The value of critical discharge for criterion 1, 2 and 3 was deduced from Figure 3 which shows the evolution of the transport rate with the increase of flow discharge. According to the minimum transport rate criteria, the critical shear stress can vary between 0.063 and 0.068, namely a variation of 8 %. This variation points out the high sensitivity of the critical shear stress value. Thus, It is crucial to define one method of characterization for all our experimental work in order to enable comparison.

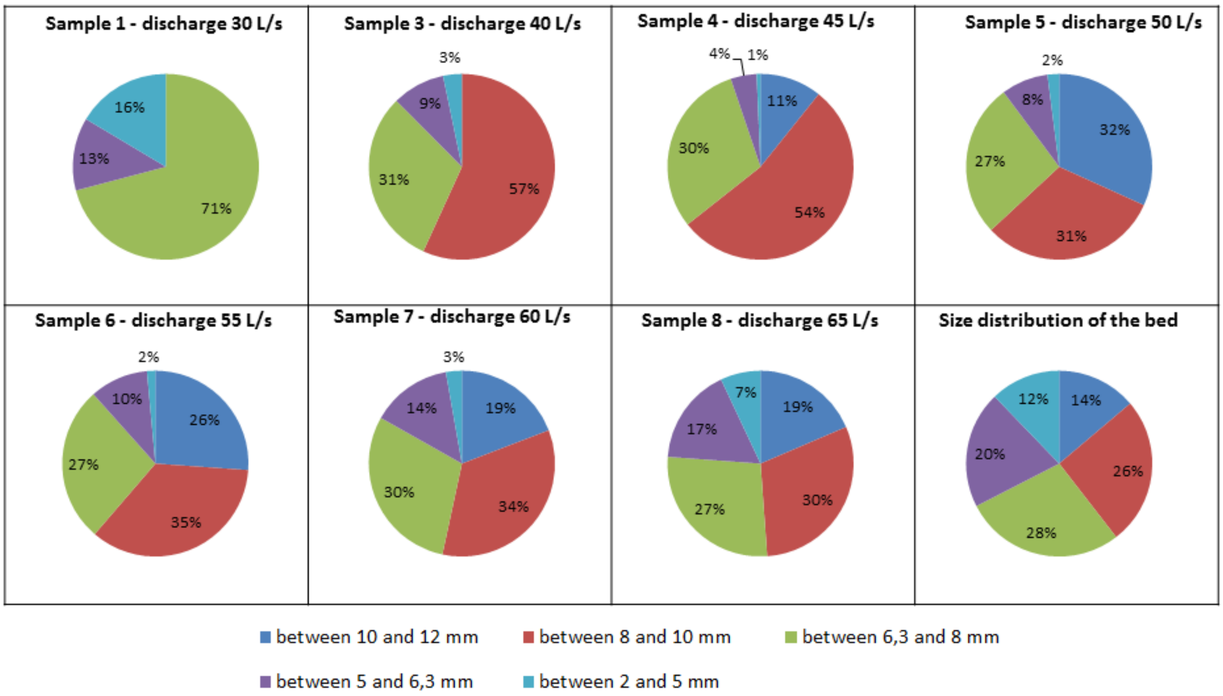

Figure 2 - Mass distribution in function of the size of particles. Each sample is composed of transported particles.

For the next experiments, the methods relative to the transport rate are used and in particular the one with a criterion of 10^{-6} m^2s^{-1}. With regards to the observations, this criterion turns out to be a good indicator for the incipient motion.

Table 4 - List of different critical discharges for incipient motion.

METHODS	VALUE OF THE CRITICAL DISCHARGE ($L.s^{-1}$)
1 – TRANSPORT RATE CONDITION FIXED AT 10^{-7} $m^2.s^{-1}$	51.2
2 – TRANSPORT RATE CONDITION FIXED AT 5.10^{-7} $m^2.s^{-1}$	57.3
3 – TRANSPORT RATE CONDITION FIXED AT 10^{-6} $m^2.s^{-1}$	61.3
4 – VANONI'S (DATE), 1 GRAIN IN MOTION EVERY 2 SECONDS	50
5 – KRAMER'S (DATE), GRAIN SIGNIFICANT OF THE BED, GENERAL MOVEMENT	65

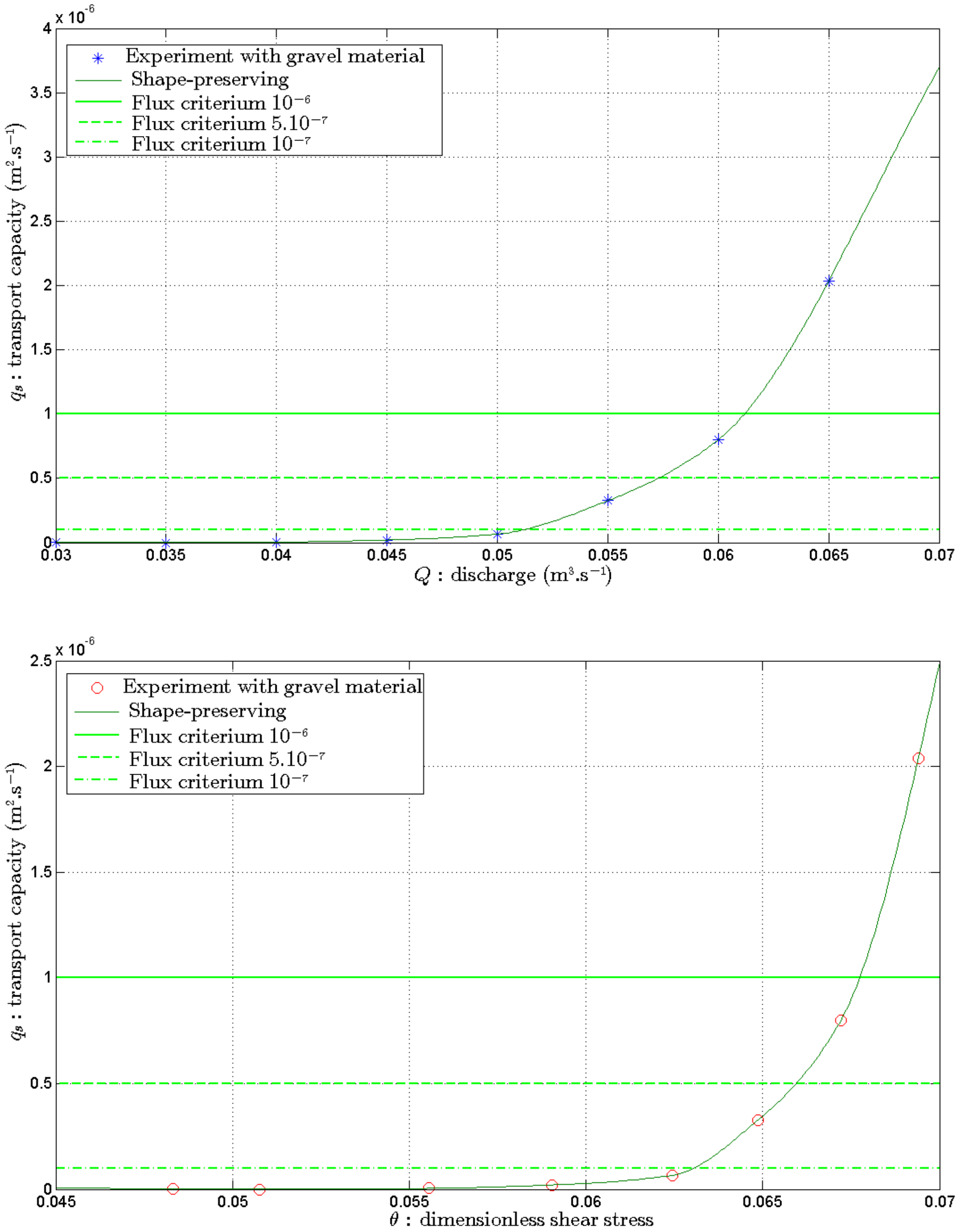

Figure 3 – Figure above: sediment transport capacity rate versus the flow discharge for only gravel bed material. Figure below: sediment transport capacity rate versus the dimensionless shear stress.

4.2 Comparison between a gravel bed and a gravel bed fully clogged with silt

This set of experiments shows a comparison between an experiment with only a gravel bed and a second with gravel bed fully clogged with silt-sized sediment.

Contrary to gravel bed experiments, the experiments with a clogged bed were handled with a sediment laden-flow. At the beginning of the two experiments, the bed was considered as loose. There was no obvious organization of bed particles. To obtain a fully clogged bed with silt-sized sediments, an infiltration experiment was made, consisting in submitting a coarse sediment matrix to a fine sediment-laden flow with water discharges being lower than the critical discharge for inception motion of the coarse particles. The fine sediments infiltrated into the bed, until a fully clogged bed was obtained. The fine sediment rate (varying between $c = 0.15$ for the surface to $c = 0.21$ for the bottom of the bed) in the coarse sediment matrix, characterizing the clogging rate, was close to the product of the porosities of the coarse grains ($\theta_g = 0.38$) and the fine sediments ($\theta_f = 0.557$), meaning that pores of the coarse sediment matrix were fully filled. This method should preserve the coarse bed from re-organization (loose bed).

The critical bed shear stress (deduced from the water surface slope, see Eq. 1) necessary to put the bed materiel into motion increases when the bed is clogged. It means that, for the same hydraulic conditions, a silt-gravel bed mixture will not be transported as easily as a bed made of gravels only (Figure 4). There is an effect of clogging of the bed due to the presence of fine sediments in the pore of the gravel bed matrix.

The difference of transport rate between the two types of bed is in the range 40 % - 50 % (Figure 4). This is an important variation, meaning that under the same hydraulic conditions the transport of silt-gravel mixture is 50% lower than that of gravel only. Percentages associated to the weak discharges (30 - 40 $L.s^{-1}$) are not significant and should not be taken into account. Indeed, the samples taken to estimate the corresponding transport rate are too small to be analyzed (~10 grains). Number of grains is in the range of the uncertainty (~ 10 - 20 grains). These grains can come from the honeycomb or from the flow guidance system at the downstream where sometimes a small quantity of sediments gets stuck.

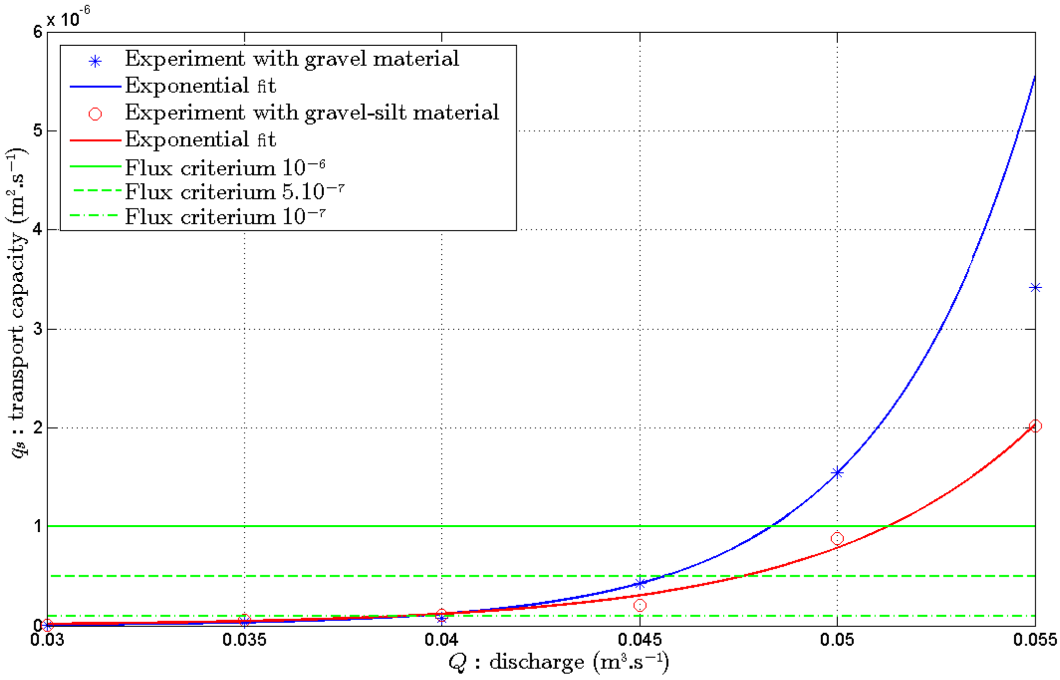

Figure 4 - Comparison of sediments transport rate between gravel bed and gravel-silt bed experiments.

Table 5 - Values of critical discharges according to the chosen transport rate criterion and nature of the bed (clogged or not). The first value is obtained with a shape-preserving interpolation of the transport rate/discharge curve and the second is obtained using an exponential fit of the same curve.

	VALUE OF THE CRITICAL DISCHARGE $L.s^{-1}$ (BED WITH GRAVEL ONLY)	**VALUE OF THE CRITICAL DISCHARGE $L.s^{-1}$ (CLOGGED BED WITH SILT-SIZE SEDIMENTS)**
METHOD 1 – TRANSPORT RATE CONDITION FIXED AT 10^{-7} $m^2.s^{-1}$	[40.8]-[39.3]	[39.2]-[39.1]
METHOD 2 – TRANSPORT RATE CONDITION FIXED AT 5.10^{-7} $m^2.s^{-1}$	[45.6]-[45.6]	[47.8]-[47.6]
METHOD 3 – TRANSPORT RATE CONDITION FIXED AT 10^{-6} $m^2.s^{-1}$	**[48]-[48.3]**	**[50.7]-[51.3]**

5. DISCUSSION

It has been shown that the dispersion in the values for the incipient motion threshold can be related to the used method. Figure 5 shows a large set of data from different incipient motion studies reported on the same Shields' diagram. The data from the first experiment (well-settled gravels bed) were included. All values obtained from different methods of characterization (Table 4) were plotted. We notice that our data are quite close to the fitting curve proposed by Guo (1990). A variation of 10 % for the value of Shields parameter and of 5 % for the particle Reynolds number Re_c^* can be observed between Kramer's method and Vanoni's method. This difference is significant but cannot be the only cause of this dispersion of data.

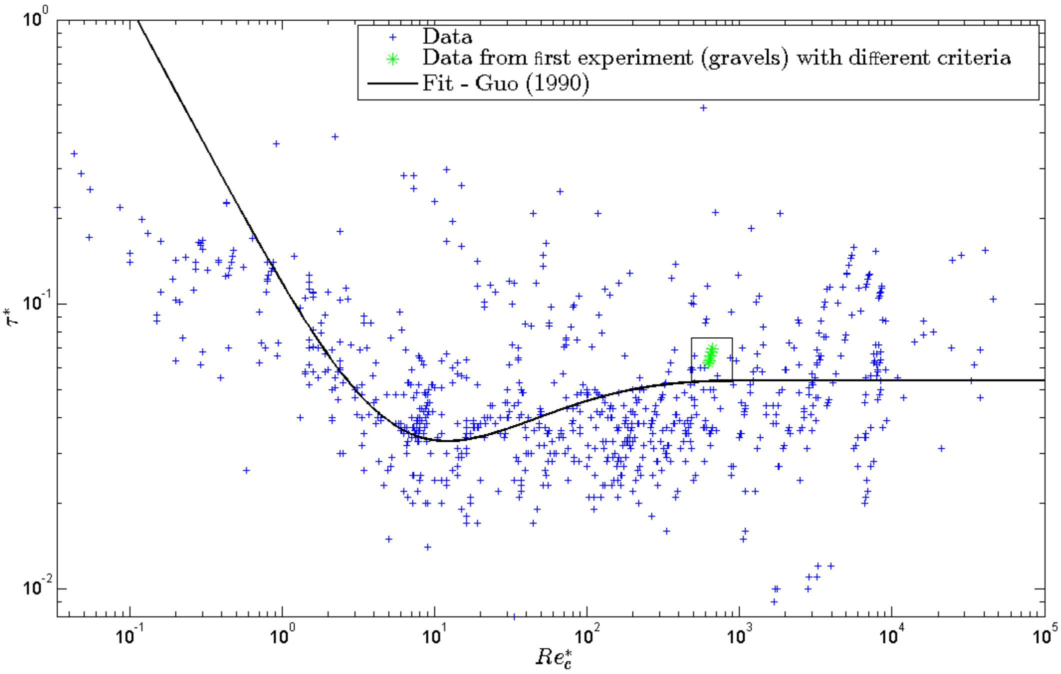

Figure 5 - Shields' curve for empirical data representing the incipient motion of sediment. The data presented are reported in Buffington and Montgomery (1997) and comes from different studies (Gilbert,1914; Shields, 1936; Casey, 1935; Kramer, 1935; USWES, 1935; Parker and Klingeman, 1982; Milhous, 1973; Wilcock and McArdell, 1993; Paintal, 1971; among others), from Recking (2009) (Meyer-Peter and Müller, 1948; Yang and Wang (2006); among others). The rectangle form representes the new data added for incipient motion according to different criteria (experiment with well-settled bed of gravels). The tendancy curve is the one proposed by Guo (1990).

Figure 6 reveals that the initial bed arrangement is probably a second source of dispersion. Data corresponding to the two experiments conducted on a bed composed of gravels only are added on the Shields' curve. In order to compare the data, the minimum transport rate of 10^{-6} $m^2.s^{-1}$ was chosen to characterize the incipient motion. A variation of 10 % between the two values of the critical shear stress is observed. We noticed that the experiment with gravels only (part 4.2 - Table 5) reached the incipient motion at the flow discharge Q = 48 $L.s^{-1}$ (or 48.3 $L.s^{-1}$ according to the approximated curves). The experiment with gravels only showed that the critical discharge value necessary to put into motion the sediments was 61.3 $L.s^{-1}$ (part 4.1 - Table 4), namely a difference of 20 % between the two discharges values. These two experiments were conducted on the same bed but at different times. In the first experiment (part 4.1), the bed was initially submitted to different flows (previous experiments) and appeared to be well settled. Thus, this significant difference observed between the two experiments can result from the arrangement of the initial bed (part 4.1 - well settled bed, part 4.2 - loose bed). The information about the duration of the measurement or about the geometric state of the bed in the incipient motion studies is crucial. One could question the capability to reproduce the incipient motion measurements. Does a single value of incipient motion threshold exist? Or can a range of values for the incipient motion threshold associated at one type of hydraulic conditions exist?

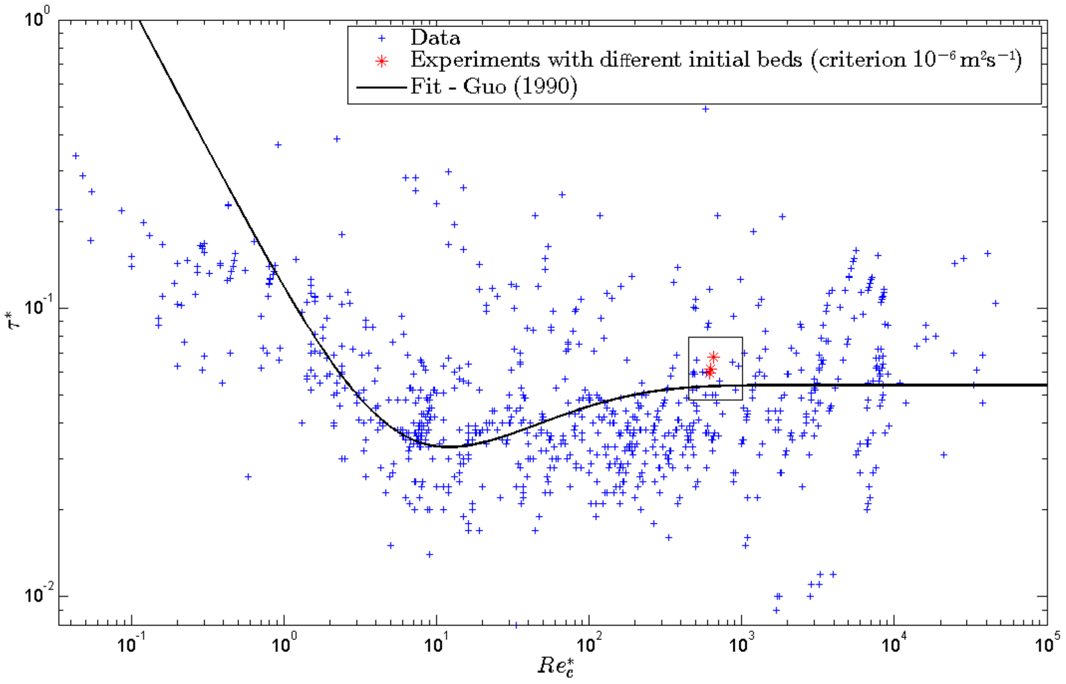

Figure 6 - Shields' curve for empirical data representing the incipient motion of sediment. The rectangle form representes the new data added for incipient motion according to one criterion corresponding to the minimum transport rate of 10^{-6} $m^2.s^{-1}$. In order to be compared, experiments with gravels only are plotted.

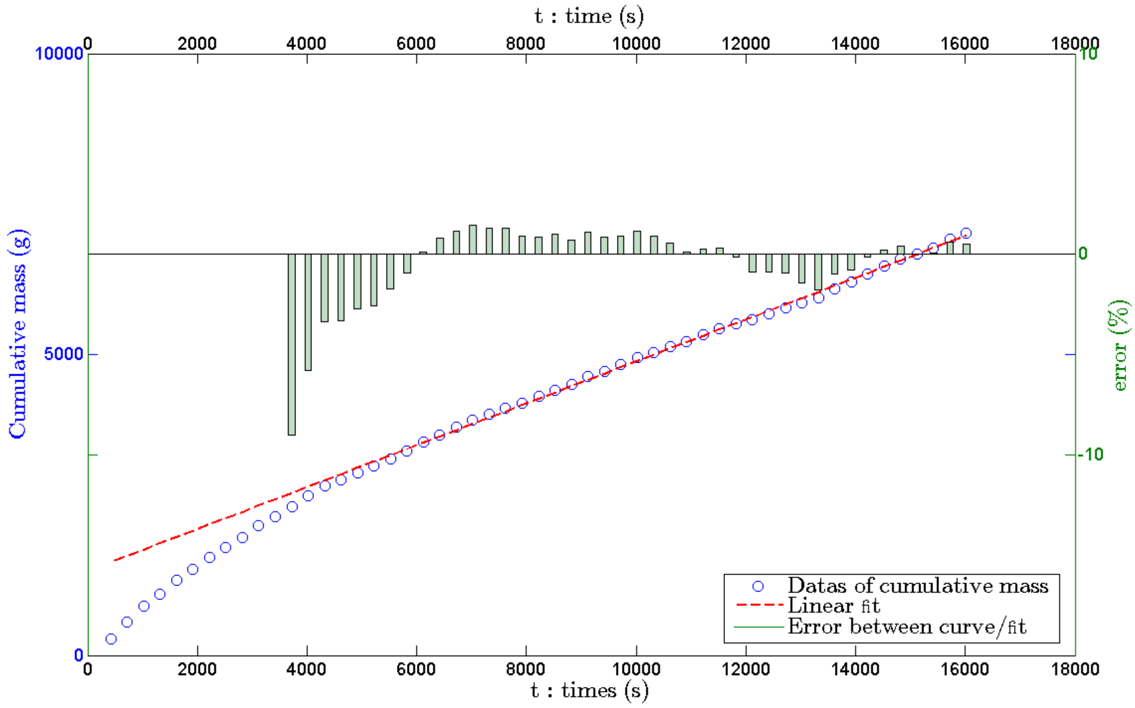

Figure 7 - Cumulative mass of sediment measured during a long experiment on a bed which is going to settle.

Figure 7 shows an example of cumulative mass measured during an experiment called “long” (4 h 30 min) at constant flow rate (55 $L.s^{-1}$). This discharge was close to the incipient motion for the first experiment – part 4.1 (criterion 2). For each measurement, gravels were collected during five minutes to obtain representative samples and average fluctuations of small scales. The initial state of the bed is the final state of the experiment in part 4.1. A transient state is observed between 0 and 6000 seconds followed by a linear increase of the mass between 6000 and 16000 seconds. The linear part corresponds to a constant mass flux at the end of the flume. The number of grains in movement decreases to reach an equilibrium state.

Figure 8 presents the evolution of sediment transport rate at the downstream end of the flume. This figure supports the assumption of an equilibrium state. The fluctuations around the equilibrium value can be generated by a reorganization of the bed surface due to the motion of particles placed at the upstream of the flume which can destabilizes locally the imbricated surface. They may be related to the length of the flume (particles from middle and upstream of the channel arrive to the downstream by intermittence). At equilibrium state, the criterion 2 for incipient motion was not respected anymore.

During the first part of the experiment, the decreasing trend of solid transport with time could be a consequence of the progressive filling of the geometrical irregularities of the bed. Then, in the linear part, particles have no more spots to imbricate each other and to be part of the bed organization. Consequently, they are over-exposed to the flow. The particles transport becomes constant. Thus, it can be judicious to characterize the incipient motion with two ranges of stresses:

- One can correspond to the incipient motion of loose particles (no imbricated);
- One can correspond to the incipient motion of imbricated or well-settled particles. They are more difficult to mobilize because a phase of erosion is necessary.

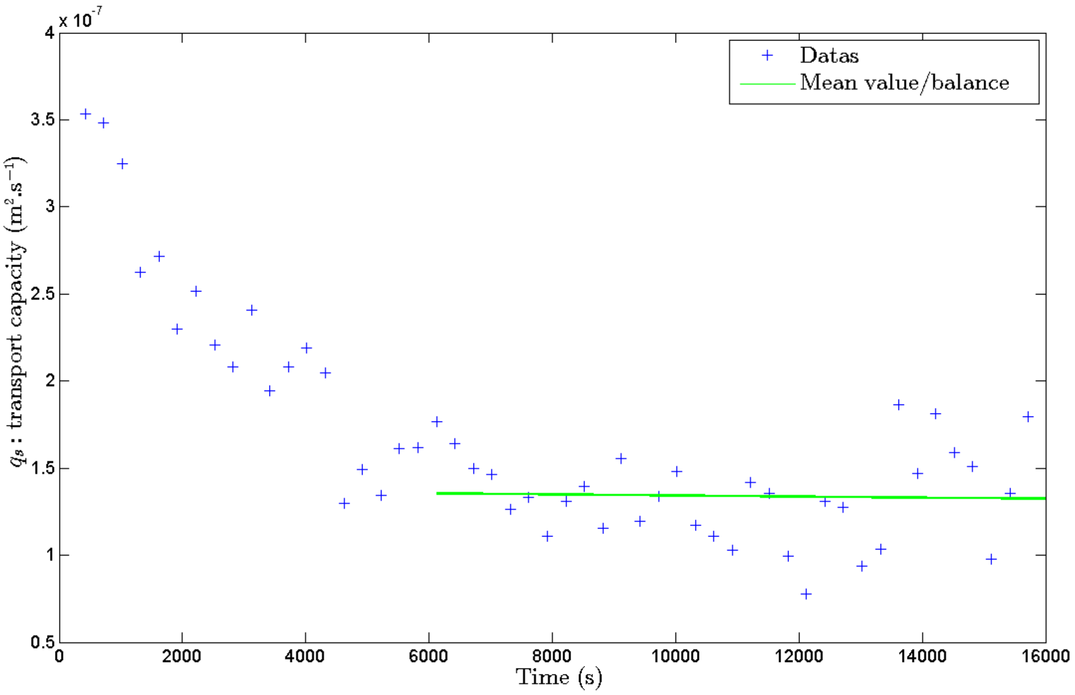

Figure 8 - Evolution of sediments transport rate during the experiments at the downstream of the flume.

This long experiment shows that there is not a unique value of incipient motion threshold but a range of values. Each of these values corresponds to an arrangement of the bed. For a homogeneous bed (well-sorted), Agudo and Wierschem (2012) observed that the critical shear stress of incipient motion was directly linked to the geometrical organization between particles. They showed that the critical Shields number can vary of about 0.05 with regards to the organization. One can assume that in a heterogeneous bed the variation of shear stresses is even more significant because the number of possible organizations of particles (range of porosity) increases.

6. CONCLUSIONS

To understand the incipient motion of riverbeds is a true challenge. Our experimental studies showed that conditions of incipient motion are difficult to define and can rapidly be exposed to uncertainties. This conclusion has been confirmed by analyzing previous experiments of other works. Comparison of data showed that a large scatter for the value of incipient motion is present.

This dispersion is in part due to the different methods used to estimate the critical shear stress for incipient motion. Our observations have shown that the critical discharge value for the incipient motion could vary of 23 % according to the used method. The lack of precision about the state of the initial arrangement of bed material can also explain the dispersion between the data. A bed is characterized with different possibility of arrangement between particles. These possibilities are directly link to different stability degrees of the bed. Our experiments showed that the threshold value for incipient motion increases with the level of armoring. Thus, it is important to precise the arrangement of the bed for each experiment. To conclude, the wide variation on the thresholds values found in literature is a consequence of both measurements/characterization methods used and the arrangement of the initial bed.

Experiments have been conducted on bimodal mixture. A comparison between unimodal and bimodal beds has been made. The arrangement of the bed was considered similar. The critical discharge and the critical shear stress necessary to put into motion sediments increase with the presence of fine sediments. Fine sediments are bounded to the gravels and offer them a kind of protection. A step of erosion of fine sediment is necessary before putting into movement the gravel particles. More energy from the fluid is required to counterbalance the clogging effect.

This work opened questions about how to define the incipient motion. It proposes to use a range of value for the threshold of incipient motion and not a unique value. This range of value is directly dependent on the bed arrangement.

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