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Laboratory analysis on silt infiltration into a gravel bed RCEM 2015

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1. Introduction

Sediment dynamics at the catchment and reach scale is strongly modified due to human actions and land use changes. Subsequently, sediment input to streams is altered and the composition of river beds changes. In many situations, the sediment transported by the flow, either in suspension or as bed load, is finer than the material forming the bed. Thus, fine sediment infiltrates within the bed and modifies its characteristics (grain size distribution, porosity, structure). This alteration yields various hydromorphological, environmental, and socio-economic impacts.

The formation of a clogged bed modifies the exchange of water, oxygen and nutrients across the sediment-water interface (Grant et al. 2012). From an environmental point of view, this fact affects the survival rate of fish eggs (Wood and Armitage 1997), the habitats of benthic invertebrates and the root length of macrophytes. When infiltration affects only the bed surface layer, oxygen may be able to penetrate to the fish eggs but fries are prevented from emerging once they are born.

Concerning socioeconomic issues, the decrease in permeability associated with fine sediment infiltration has an impact on the recharge of the aquifers connected to the affected river, therefore increasing the cost of pumping operations for water supply. Dam is one of the main anthropogenic structures that influences sediment dynamics along rivers, the mentioned consequences oblige to apply a regulation on dam operations. Finally, fine sediment infiltration modifies the flow dynamics by decreasing bed roughness and increasing flow velocities which, in turn, may affect the suitability of the habitat for some specific species. Moreover, infiltrated fine sediments do not contribute directly to the morphological changes of the river, a fact that has to be taken into account when evaluating the channel evolution and sediment budgets (Frings et al. 2008).

Previous studies highlight two possible infiltration mechanisms depending on the relative size, Γ , between the fine sediment transported by the flow and the coarse sediment forming the bed matrix (Gibson et al. 2010). For large Γ -values, fine sediments are able to penetrate deep into the bed and the bed is clogged from the bottom upwards (unimpeded static percolation). On the other hand, when Γ is relatively small, fines sediment can be strained in the bed pore throats, a clogged layer is formed at the surface that prevents any deeper infiltration. The amount of fine sediments infiltrated is affected by different hydrodynamic and sediment parameters as the bed shear stress, suspended sediment concentration, fine sediment cohesion, arrangement of bed surface grains, occurrence of bed forms, existence

of a vertical hydraulic gradient within the bed and presence of a biofilm.

The infiltration of silt-sized sediments into a gravel bed gives place to a clogging process following the mechanism of unimpeded static percolation. Different studies analyzing deposition rates in these conditions provided divergent results. Einstein (1968) proposed a mathematical model in which he assumed that deposition rate occurs at the Stokes settling velocity. Taking this situation as a reference, those conditions generating higher deposition rates are classified as “enhanced settling” and those causing lower deposition rates are classified as “decreased settling” (Fries and Trowbridge 2003). Fries and Trowbridge (2003) and Fries and Taghon (2010) observed enhanced settling rates although the correlation with bed shear stress had opposite sign in each of these studies. On the other hand, Hamm et al. (2011) observed decreased settling rates, especially for increasing bed shear stress.

The importance of the impacts associated with fine sediment infiltration and the uncertainty of the state of knowledge in this topic are two facts that state the interest of deepening into this. This study presents laboratory experiments that aim to cast some light into the mentioned points and opens the door to further discussion. The development of a mathematical model currently in process is discussed.

2. Experimental setup

The series of experiments concerning this study was carried out in the Hydraulics and Hydromorphology Laboratory of Irstea-Lyon (France). Experiments were done in an 18 m long, 1 m wide and 0.8 m high tilting flume (Figure 1). The flume outlet is connected to a 35 m³ reservoir where two pumps are able to recirculate water and fine sediment in suspension. A 6 cm thick gravel layer was displayed along the channel. Gravel size ranged from 3 to 12 mm (D_{50} = 8 mm). Silt-sized silica was used as fine sediment. Its grain size distribution was comprised between 10 and 30 μ m.

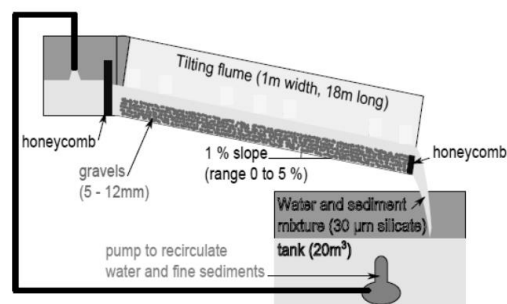


Figure 1. Recirculating flume used for the infiltration experiments

Water discharge, suspended fine sediment concentration and bed slope were specified for each run. **Erreur ! Source du renvoi introuvable.** shows the values of the different variables for each run. At the beginning of each run, fine sediments were added in the reservoir to obtain the desired concentration. A stirring system was installed to maintain sediment in suspension and establish a uniform concentration. Suspended sediment concentration was kept constant during each experiment, as this situation was interpreted as more representative of natural conditions. In order to ensure it, sediment was added periodically in order to correct the suspended concentration decrease associated with fine sediment infiltration and retention within the bed.

Run	1	2	3	4	5
Q (l/s)	30	30	30	30	55
C (g/l)	4.0	5.5	4.0	7.2	4.3
S (%)	1	0.1	0.1	0.1	0.1

Table 1: Experimental conditions (Q: water discharge; C: suspended sediment concentration; S: bed slope).

During each run, water depth is measured with ultrasonic sensors placed at three positions along the channel (inlet, central and outlet). An ADV profiler placed seven meters downstream of the channel inlet is used to measure flow velocities. Water samples are taken periodically filtered to measure fine sediment concentration. Samples are taken next to the turbidimeter positions, as well as in the reservoir at the downstream end of the flume. In order to avoid uncertainty from the turbidimeter calibration, the representative values of concentration corresponding to each run are those obtained from the water samples.

Six cylinders were placed within the bed before starting each run to quantify fine sediment content. The cylinders were made of a metallic grid with holes of 1 mm so that the influence on horizontal interstitial flow and fine sediment trajectories within the bed is minimized. The cylinders were placed in pairs at the longitudinal positions $x=6$ m, $x=9$ m and $x=12$ m (the flume inlet is considered as the origin of the x coordinate). Three of the cylinders, one at each longitudinal position, were extracted after the first eight hours of experiment and the other three at the end of the run (15 to 25 hours depending in the run). The content of the cylinders is analyzed afterwards and vertical profiles of fine sediment content are obtained. Additionally, lateral photos were taken at a central section of the flume to observe the evolution of fine sediment accumulation within the pores. Fine sediments clogged the bed from the base of the flume upwards and the photos allowed following the evolution of the clogged layer. Wall effects and validity of the lateral observations, were evaluated carefully analyzing two sections after one of the experiments. The depth of the clogged layer was found to be quite uniform in the transversal direction. Therefore, it was concluded that the results obtained from the lateral photos were representative of the whole section.

Each experiment was maintained until the whole gravel bed layer was clogged with fine sediment or when no

further evolution of the clogged layer was observed through the lateral walls.

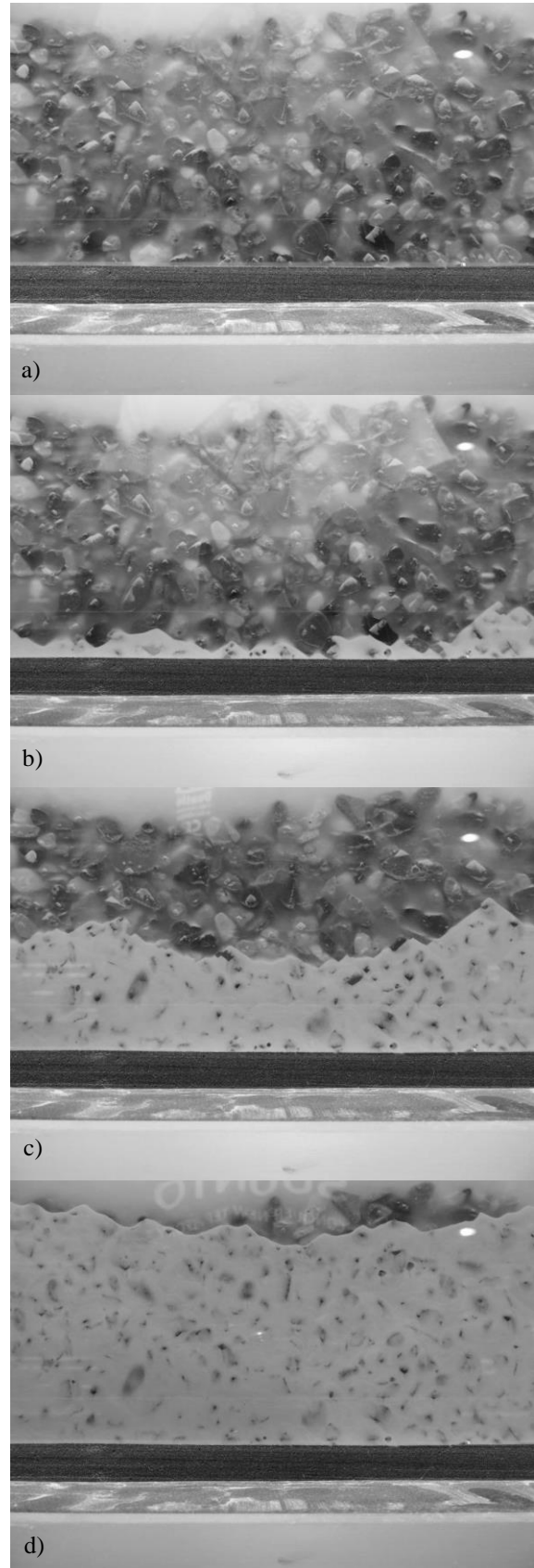


Figure 2. Lateral view of the clogged bed at four instants during run 2

3. Results

Firstly, the qualitative observations of the infiltration process are summarized. As the sediment-laden flow is

introduced over the initially clean gravel, water infiltrates within the bed and small piles of fine sediment are visible on the top of the gravel grains. The piles stop growing after 15 to 20 minutes of experiment until small destabilizations start occurring. This phenomenon pushes fine sediments towards the base of the flume. A clogged layer starts to form from the bottom upwards and grows as fine sediments fill the pores of the gravel bed layer. It should be noted that the ratio between coarse and fine sediment diameters is approximately 200 for the materials used in this experiments, therefore far from the threshold above which unimpeded static percolation is predicted (Gibson et al. 2010). Clogged layer thickness grows at an approximately constant rate until it reaches a specific distance from the bed surface (3-5 gravel diameters typically). At this point, the rate of growth of the clogged layer starts decreasing. For some of the runs (2, 3 and 4), infiltration continues until the clogged layer reaches the bed surface. However, for runs 1 and 5, the clogging process stops before and there is a surface layer with a thickness of 1 to 3 gravel diameters that remains free of sediment in the equilibrium situation. **Erreur ! Source du renvoi introuvable.** shows the evolution of the clogged layer during run 2. The average level of the clogged layer surface is measured referred to the base of the flume. The evolution in time of this level is shown in **Erreur ! Source du renvoi introuvable.** for the different runs. There is an initial and short phase during which no accumulation is observed at the bottom of the flume yet. This period corresponds to the phase of growth of fine sediment piles on the top of the gravel grains. After the initial phase, the clogged layer grows at a rate which is approximately constant, as shown by the good correspondence with the linear regression. Once the clogged layer reaches a certain level the rate of growth decreases until the equilibrium situation, in which the clogged layer surface remains stationary. This phase starts at a height between 30 and 35 mm above the bottom of the channel, which corresponds to 3 to 5 gravel diameters below the bed surface.

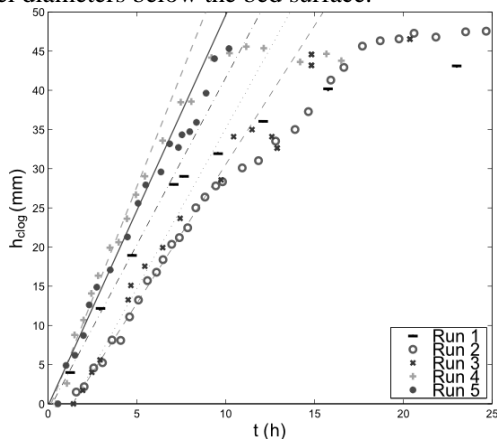


Figure 3. Time evolution of the clogged layer height. Straight lines show the linear regression corresponding to the phase of uniform growth

The evolution in time of the clogged layer height can be used to evaluate fine sediment infiltration rate. If it is assumed that the observed values are representative of

the average evolution along the flume, this rate can be computed as:

$$J_{z1} = \rho_f \frac{(1-\theta_g)c}{1-c} S \quad (1)$$

where J_{z1} is the fine sediment mass flux (mass of fine sediment that penetrates into the bed per area and time unit), ρ_z is fine sediment density, θ_g is gravel porosity, c is fine sediment content defined as $V_f / (V_f + V_g)$ (V_f : fine sediment volume; V_g : gravel volume) and $S = dh_{clog} / dt$ is the slope of the clogged layer height versus time curves.

The cylinders installed within the bed provide a different way to quantify fine sediment infiltration rate. **Erreur ! Source du renvoi introuvable.** shows, for each run, the comparison between the fine sediment content of the cylinders extracted after the first eight hours and at the end of the experiment. Each represented profile corresponds to the average of the three cylinders extracted at the associated moment. Even if measurements were performed carefully, it should be noted that the higher values at the deeper layer can be at some point influenced by the methodology used to separate de different layers. The comparison between the two profiles of each run shows the evolution of fine sediment accumulation within the bed. On the other hand, taking into account the period of time from the beginning of the experiment to the extraction of the first cylinder, fine sediment infiltration rate can be calculated as:

$$J_{z2} = \frac{m}{A_c \Delta t} \quad (3)$$

where m is the fine sediment mass between in the first cylinder of each run, A_c is the area of the cylinder and Δt is the time between the extraction of both cylinders.

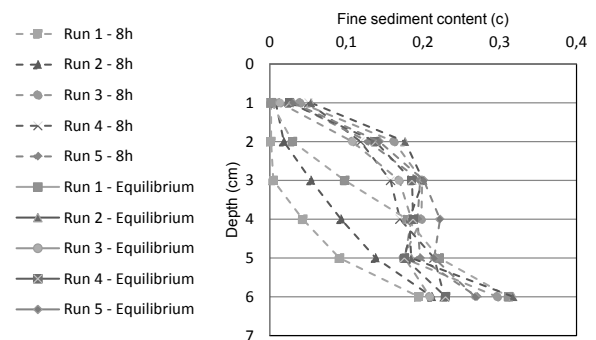


Figure 4. Fine sediment content profile with depth after eight hours of experiment and at the end of the run. The values are obtained from the cylinders introduced before the experiment and divided in layers of 1cm.

A third method to quantify fine sediment infiltration rate is based on the suspended concentration measurements performed at the upstream and downstream ends of the flume. As the sediment-laden flow goes through the channel, fine sediment is infiltrated into the bed. Therefore, part of the incoming fine sediment is absent at the flume outlet and a decrease in suspended sediment

concentration is expected when comparing upstream to downstream values. Based on this concentration difference, the sediment infiltration rate can be computed by means of the mass balance equation:

$$J_{z3} = \frac{Q\Delta C}{A} \quad (4)$$

where Q is the water discharge, ΔC is the difference in suspended sediment concentration between the upstream and downstream ends of the channel and A is the surface through which fine sediment is infiltrated. Taking into account the previous results, fine sediment infiltration rate was calculated based on the previous three methods, using equations (1), (3) and (4) respectively. The results are shown in Figure 3.

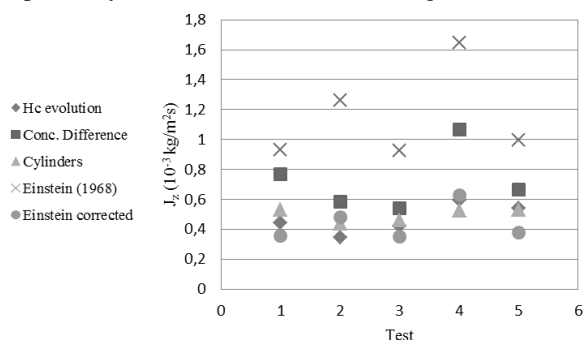


Figure 3. Fine sediment infiltration rates obtained through equations (1), (3) and (4) compared to Einstein (1968) and the correction proposed herein

4. Discussion

Some discrepancy is observed between the values of fine sediment infiltration rate obtained from the different methods. The values calculated from the longitudinal difference of concentration are higher than the ones obtained following the other two methods. The difference in concentration between the upstream and the downstream samples was often observed to be variable in time even if downstream values were always lower than upstream ones. This uncertainty could be a possible reason of the observed discrepancy.

It is interesting to compare the obtained results with the deposition rate obtained from considering settling due to gravity with the Stokes fall velocity (Einstein 1968). These theoretical values are also included in Figure 3. Experimental values are clearly lower than the theoretical prediction in all the runs, therefore corresponding to decreased infiltration rates. Apart from the physical reasons of this behaviour, according to the authors' opinion, Einstein's model lacks from considering bed porosity in the predicted deposition rate. Only the part of the bed corresponding to pores between the gravel grains contribute to the downwards infiltration rate (Grant et al. 2012). If the theoretical infiltration rates are corrected by multiplying them by the porosity, the obtained results are much closer to the experimental ones (Figure 3).

A certain trend towards enhanced settling however is observed, especially when considering infiltration rates calculated from the concentration difference between the upstream and downstream ends of the flume. One reason for this enhancement can be the ability of the bed to trap

infiltrated fine particles and avoid their resuspension. Fine sediment entrainment is lower in permeable beds than in impermeable ones, due to the effect of bed gravel grains sheltering fine grains and decreasing the shear stress exerted on them. Moreover, enhanced settling can also be caused by fluid incursions towards the bed at different scales. Although these incursions must be compensated by ejections that make the mass balance possible, the asymmetry between the two kinds of events in terms of frequency and intensity can generate a net flux of fine sediment towards the bed (Fries and Trowbridge 2003, Fries and Taghon 2010).

5. Conclusions

A series of experiments on silt-sized sediment infiltration into an initially clean gravel bed is presented. As predicted by previous studies (Gibson et al. 2010), the clogging of the bed occurs as unimpeded static percolation and the bed pores are filled from the bottom upwards. Based on laboratory results, fine sediment infiltration rate is calculated from the clogged layer evolution, bed samples and concentration difference between the flume inlet and the outlet.

When compared to a previous theoretical model proposing an infiltration rate based on Stokes velocity, the obtained results are found to be significantly lower. This fact is interpreted as a consequence of the theoretical model not taking into account bed porosity, which determines the area through which fine sediments can be infiltrated.

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