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LABORATORY ANALYSIS ON SILT INFILTRATION INTO GRAVEL BED

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ABSTRACT

Fine sediment infiltration into a gravel bed may have significant impact on environmental, socioeconomic and river morphodynamics issues. Several human activities enhance fine sediment flux, either in the production zone due to changes in land use or within the river system due to reservoir flushes or dredging. Understanding the mechanisms that control this phenomenon can help to minimize impacts of such anthropic actions. A set of experiments has been performed in the new tilting flume (18 meter long and 1 meter wide) of Irstea-Lyon hydraulics laboratory. Silt sized silica (10-30 microns) and gravels (3-12 mm) are used as fine and coarse sediments, respectively. Fine sediments are introduced for a specified concentration in a flow with fixed discharge, water depth and bed slope. All the explored conditions correspond to fine sediment travelling in homogeneous suspension (wash load). Keeping the concentration constant during each test, the process of infiltration of fine sediments into the gravel bed is analyzed and the influence of flow velocity and fine sediment concentration is discussed. Fine sediment deposition takes place as a progressive filling of the bed starting from the base of the channel and ending one to three diameters below the bed surface. The thickness of the surface layer that remains unclogged in the equilibrium situation depends mainly on the bed shear stress. On the other hand, a positive correlation is found between the suspended sediment concentration and the rate of infiltration with time. Water mass exchange and turbulent structures that occur at the flow-bed interface seem to be the key mechanisms that control fine sediment infiltration

Keywords: infiltration, silt, gravel, hyporheic exchange, laboratory work

1. INTRODUCTION

Human activities and land use changes modify sediment dynamics at the catchment and at the reach scale. As sediment input to rivers changes, the composition of river beds is altered. When the river bed is formed by relatively coarse sediment, fine sediment transported either in suspension or as bed load can infiltrate within the bed, therefore modifying its characteristics. This alteration has different environmental, socioeconomic and hydromorphological impacts.

From an environmental point of view, the formation of a clogged bed modifies the exchange of water, oxygen and nutrients across the sediment-water interface (Grant et al. 2012), therefore affecting the survival rate of fish eggs (Wood and Armitage 1997, Greig et al. 2007), the habitable regions for benthic invertebrates (Jones et al. 2012a) and the root length of macrophytes (Jones et al. 2012b). When infiltration affects only the bed surface layer, oxygen is able to penetrate to the fish eggs but fries are prevented from emerging once they are born (Koski 1966). Moreover, modification of the surface decreases the possibilities to find a shelter and to refuge from predators for some species. Concerning socioeconomic issues, the decrease in permeability associated with fine sediment infiltration has an impact on the recharge process of the aquifers connected to the affected river, therefore increasing the cost of pumping operations for water (Blaschke et al. 2003). On the other hand, the presence of a clogged layer can act as a filter for some harmful substances transported by the water, hence improving the quality of the water arriving to the aquifer (Ray et al. 2002). Dam is one of the anthropogenic structures that influences on sediment dynamics along rivers, the mentioned consequences oblige to apply a regulation on dam operations (Cui et al. 2006). 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 (Jones et al. 2012a). 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 between the fine sediment transported by the flow and the coarse sediment forming the bed matrix (Gibson et al. 2009). When both sizes are significantly different, fine sediment is able to penetrate deep into the bed until some layer below, which is relatively impermeable, and the bed is clogged from the bottom upwards (unimpeded static percolation). On the other hand, when fine sediment is coarse enough to be strained in the pore throats formed by the bed grains, a clogged layer is formed at the surface that prevents any deeper infiltration. The amount of fine sediment infiltrated is influenced by different hydrodynamic and sediment parameters as the bed shear stress (Evans and Wilcox 2013), suspended sediment concentration (Khullar et al. 2013), fine sediment cohesion (Packman et al. 2000), the arrangement of bed

surface grains (Cooper and Tait 2009), the occurrence of bed forms (Packman and MacKay 2003), the existence of a vertical hydraulic gradient within the bed (Schälchli 1992) and the presence of a biofilm (Arnon et al. 2010). Nevertheless, divergent conclusions have been highlighted by different authors, especially concerning the role of bed shear stress on the infiltration process.

The infiltration of silt-sized sediment 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 also 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 encourage the scientific community to deepen into this area of sediment dynamics. This study presents laboratory experiments that aim to cast some light into the mentioned points and opens the door to further discussion and the development of a mathematical model that is currently in process.

2. EXPERIMENTAL SETUP

The experimental work performed during this analysis was carried out in the Hydraulics and Hydromorphology Laboratory of Irstea-Lyon (France). The tests were done in an 18 meter long, 1 meter 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 back to the channel inlet. A 6 cm thick gravel layer was displayed along the channel. Gravel size ranged from 3 to 12 mm ($D_{50} = 8$ mm). Concerning fine sediment, silt-sized silica with diameters ranging from 10 to 30 microns was used in all the tests.

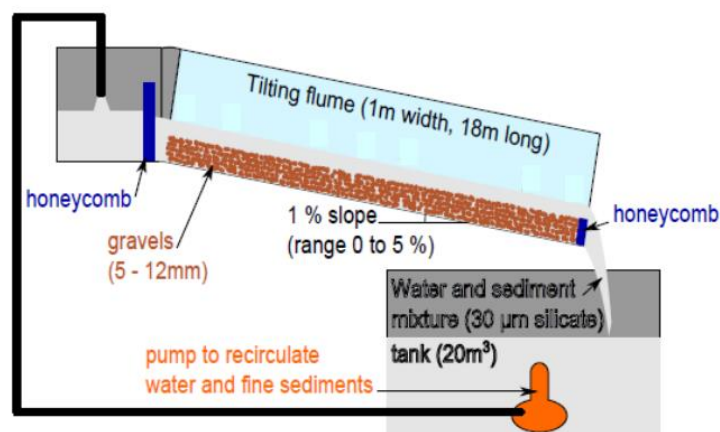


Figure 1. Recirculating flume used for the infiltration experiments

For each run, water discharge, suspended fine sediment concentration and bed slope were specified. The values of these variables are shown in Table 1 for each of the performed experiments. At the beginning of each test, the amount of fine sediment corresponding to the desired concentration was added in the reservoir, and left there long enough to be well-mixed, thanks to a stirring system installed in there. Suspended sediment concentration was kept constant during each experiment. In order to make it possible, sediment was added periodically in order to correct the suspended concentration decrease associated with fine sediment infiltration and retention within the bed. This operation was carried out based on the concentration measurement of two turbidimeters installed near the inlet and the outlet of the channel. Suspended concentration was kept constant during the tests because it was interpreted as a more realistic reproduction of natural conditions. Indeed, sediment infiltration in a natural river reach does not generate a decrease in the concentration of the flow affecting that reach. However, in a recirculation channel as the one used in this analysis the concentration evolves as a consequence of fine sediment infiltration, and unrealistic conditions are obtained if suspended concentration is not corrected.

Table 1. Experimental conditions corresponding to the different tests (Q: water discharge; C: suspended sediment concentration; S: bed slope)

| Test | 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 |

During each test, 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 near bed flow velocities which are then used to calculate bed shear stress. Water samples are taken periodically and fine sediment contained in them are filtered so that sediment concentration can be obtained. The samples are taken next to the turbidimeters position, as well as from 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 test are those obtained from the water samples.

In order to quantify fine sediment content in the bed, six cylinders were placed within it before starting each test. 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 x coordinate) and at a distance of 30 cm from the channel walls. 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 test. The content of the cylinders is afterwards analyzed. One centimeter thick layers are separated and gravel is separated from silt in such a way that fine sediment content can be determined at each layer. Additionally, lateral photos of one central section of the flume were taken in order to observe the evolution of fine sediment accumulation within the pores. Fine sediment clogged the bed from the base of the flume upwards and the photos allowed following the evolution of the clogged layer. In order to evaluate the wall effects and the validity of the lateral observations, two sections were analyzed carefully 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.

The duration of each experiment lasted until the whole gravel bed was clogged with fine sediment or when no further evolution of the clogged layer was observed through the lateral walls.

3. RESULTS

Firstly, the qualitative observations of the infiltration processed are summarized. As the sediment-laden flow was introduced over 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 and small destabilizations start occurring that push fine sediment towards the base of the flume. A clogged layer starts to form from the bottom upwards and grows as fine sediment fills the pores between the gravel grains. 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 the near bed layer (3-5 gravel diameters). At this point, the rate of growth of the clogged layer starts decreasing. For some of the tests (2, 3 and 4) infiltration continues until the clogged layer reaches the bed surface. However, for tests 1 and 5, the clogging process stops before and there is a surface layer of 1 to 3 gravel diameters that remains free of sediment in the equilibrium situation. Figure 2 presents four lateral photos that show the evolution of the clogged layer during Test 2.

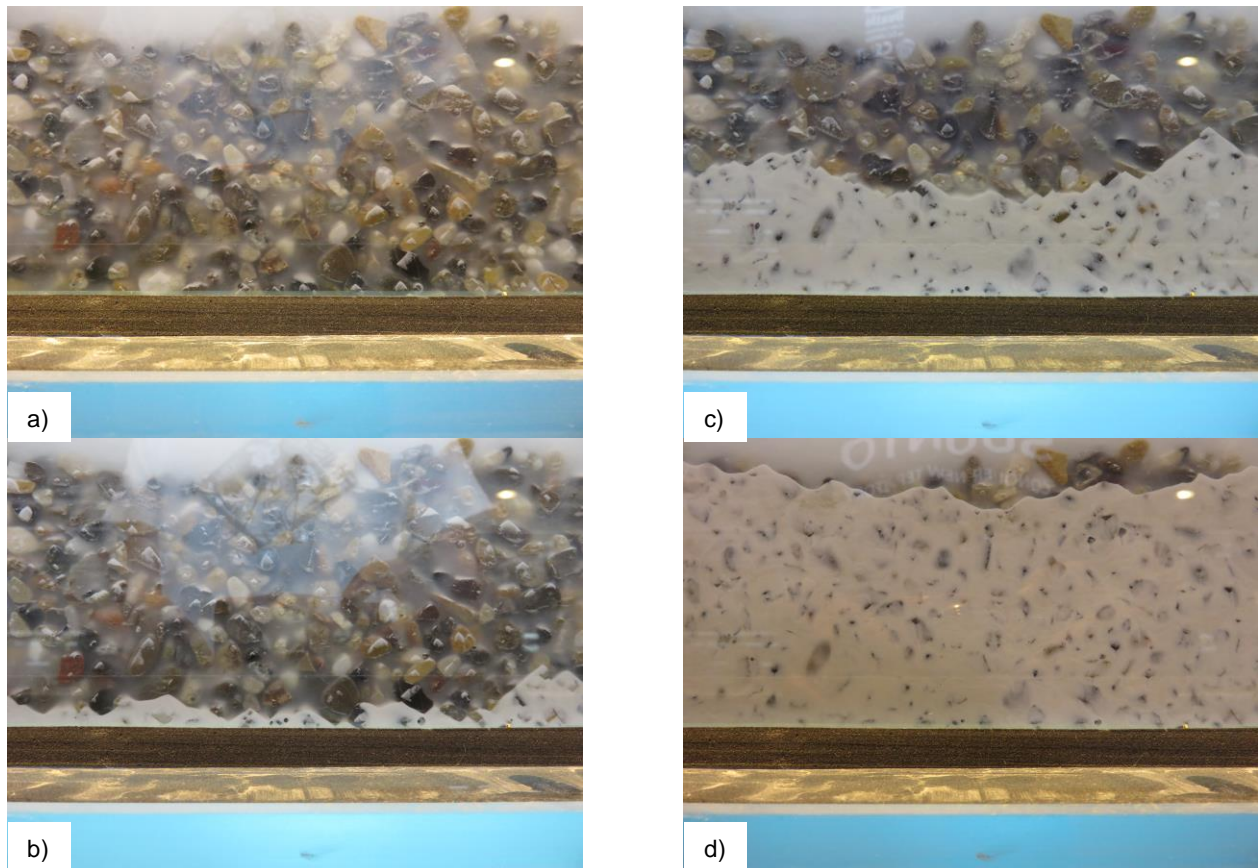


Figure 2. Lateral view of the infiltrated gravel bed at four different times during test 2

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 Figure 3 for the different tests. 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. There is also a small level difference between the base of the flume and the visible part of the walls that introduce a short lag between the beginning of the clogged layer formation and the moment when it is visible. 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 35mm above the bottom of the channel, which corresponds to 3 to 5 gravel diameters below the bed surface.

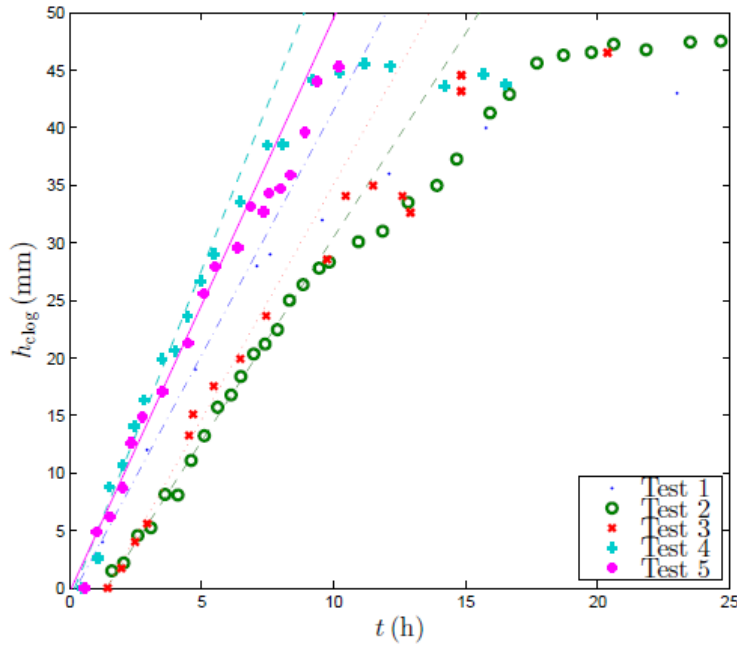


Figure 3. Height of the clogged layer for the different tests. The different lines show the linear regression corresponding to the phase of uniform growth.

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:

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

where J_z is the fine sediment mass flux (mass of fine sediment that penetrates into the bed per area and time unit), ρ_f 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. Figure 4 shows, for each test, 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 the different layers. The comparison between the two profiles of each test shows the evolution of fine sediment accumulation within the bed. The equilibrium profiles show how fine sediment content tends to a uniform value. It is interesting to compare it with the theoretical value corresponding to the complete clogging of gravel pores by fine sediment:

$$c = \frac{V_f}{V_f + V_g} = \frac{(1-\theta_f)\theta_g}{(1-\theta_f)\theta_g + (1-\theta_g)} \quad (2)$$

The porosity values of gravel and silt used in these experiments are 0.38 and 0.55 respectively. Therefore, maximum fine sediment content in a totally clogged layer is 0.22. This value corresponds quite well with the observations at equilibrium. On the other hand, taking into account the period of time from the beginning of the experiment to the extraction of the first cylinder, these data provide another way to calculate fine sediment infiltration rate:

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

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

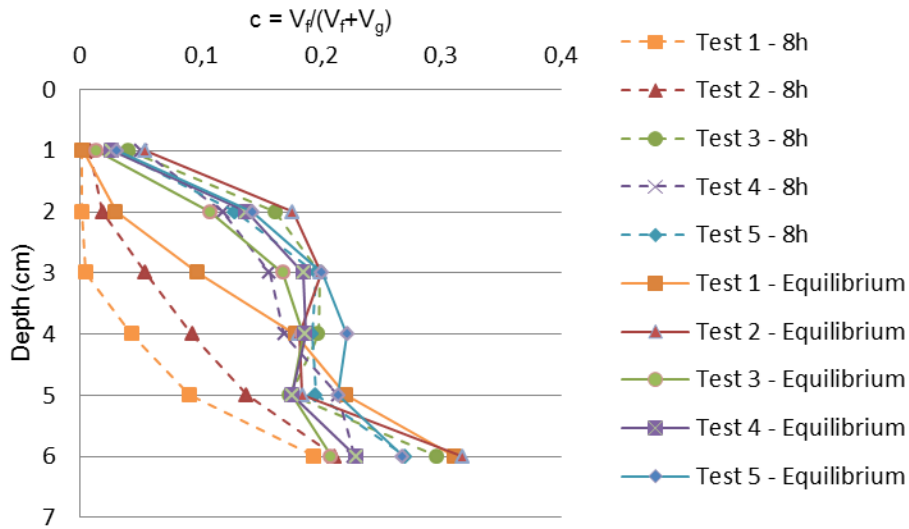


Figure 4. Fine sediment content profile with depth after eight hours of experiment and at the end of the test. The values are obtained from the cylinders introduced before the experiment and divided in layers of 1cm

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:

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

where J_z is the fine sediment mass flux, 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 clogged layer height evolution, the fine sediment content observed in the cylinders and the difference in suspended sediment concentration between the upstream and downstream ends of the flume, using equations (1), (3) and (4) respectively. The results are shown in Figure 5.

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. On the other hand, the measurements of clogged layer height were performed in a section close to the center of the flume, so the hypothesis of them being representative of the global average along the channel seems plausible.

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 5. Experimental values are clearly lower than the theoretical prediction in all the tests, therefore corresponding to decreased infiltration rates. Apart from the physical reasons of this behavior, 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 5).

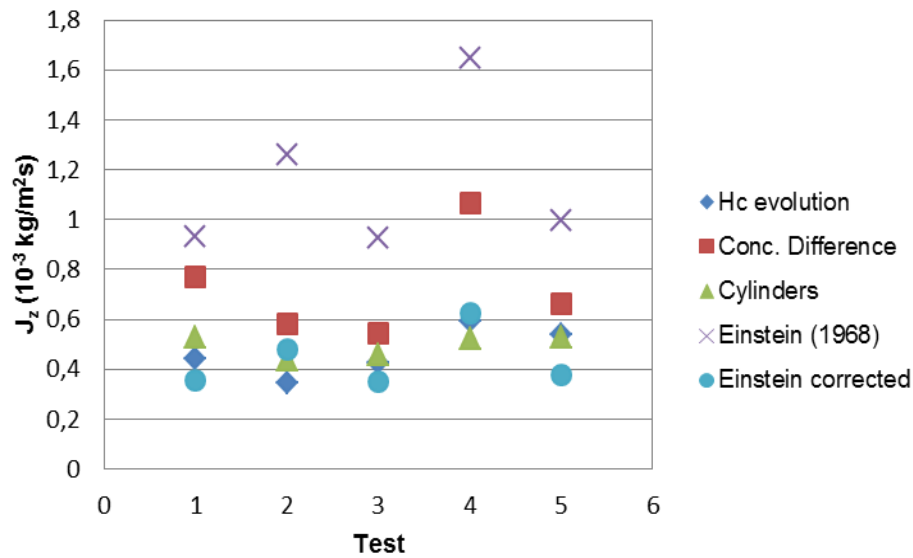


Figure 5. Fine sediment infiltration rates calculated from the clogged layer height evolution (diamonds), the concentration difference between the upstream and downstream ends of the channel (squares) and the mass of sediment retained in the cylinders (triangles). Theoretical values obtained following the model of Einstein (1968) are represented by crosses and their correction considering bed porosity are plotted as circles.

However, a certain trend towards enhanced settling 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 to 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 (Hoyal et al. 1997). 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).

The only variable that changed between tests 2, 3 and 4 was suspended sediment concentration. Measured infiltration rates may be expected to be proportional to suspended concentration. Rates obtained from concentration difference follow quite well this pattern (Figure 6). Data obtained from the cylinders and from clogged layer height evolution do not correspond to it exactly although a certain increasing trend is observed in fine sediment infiltration rates for increasing suspended sediment concentrations. A certain positive correlation is observed concerning bed slope when comparing the results from test 1 and test 3, with increased infiltration rates for the higher slope of test 1. This fact would be consistent with the positive correlation between bed shear stress and fine sediment infiltration observed in some previous studies (Fries and Taghon 2010). However, the different methods used to estimate the infiltration rate show diverging results. This divergence has also been observed in previous works so the influence of shear stress is not completely clear. With regard to water discharge, the comparison between tests 3 and 5 show a positive correlation between this variable and the infiltration rate. A higher discharge is also associated with a higher bed shear stress. Therefore, it could be inferred that the infiltration rate is positively correlated with bed shear stress. However, further observations on the flow patterns influence on fine sediment trajectories near the bed, are needed to clarify this point.

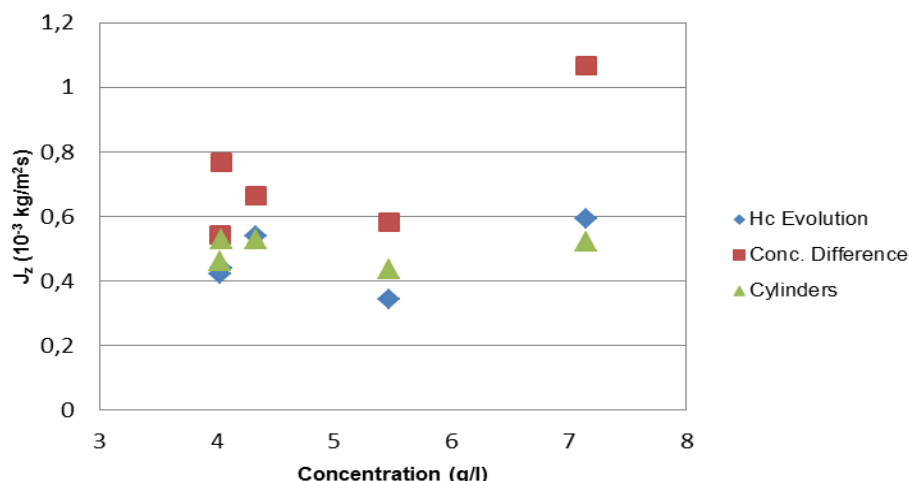


Figure 6. Fine sediment infiltration rate as a function of suspended sediment concentration

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. Three phases are distinguished during the infiltration process: an initial phase during which fine sediment deposits on the top of the gravel grains; an intermediate phase where fine sediment falls to the impermeable bottom and a clogged layer is formed at a constant growth rate; a final stage when the rate of fine sediment accumulation with time decreases until the system reaches an equilibrium where the clogged layer surface is one to three diameters from the bed surface. The final position of the clogged layer depends mainly on the bed shear stress of the flow.

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. Moreover, bed filtration and fluid incursions at different scales are proposed as other mechanisms that can influence on fine sediment infiltration rate.

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