



HAL
open science

Computations of trapping coefficient for fine sediment infiltration

Céline Berni, A. Herrero, B. Camenen

► **To cite this version:**

Céline Berni, A. Herrero, B. Camenen. Computations of trapping coefficient for fine sediment infiltration. 36th IAHR World Congress, Jun 2015, The Hague, Netherlands. 8 p. hal-01417301

HAL Id: hal-01417301

<https://hal.science/hal-01417301>

Submitted on 15 Dec 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

COMPUTATIONS OF TRAPPING COEFFICIENT FOR FINE SEDIMENT INFILTRATION

CELINE BERNI⁽¹⁾, ALBERT HERRERO⁽²⁾ & BENOITCAMENEN⁽³⁾

⁽¹⁾ *Irstea, Lyon-Villeurbanne, France, celine.berni@irstea.fr*

⁽²⁾ *Irstea, Lyon-Villeurbanne, France, albert.herrero@irstea.fr*

⁽³⁾ *Irstea, Lyon-Villeurbanne, France, benoit.camenen@irstea.fr*

ABSTRACT

River habitats are among the most important environmental issues at stake in recent years. Indeed, they have a strong impact on biodiversity. The numerous structures that are built in rivers such as dams, hydroelectric plants, dikes, etc. have dramatically changed the sediment dynamics in some rivers. This fact sometimes causes the clogging of the river bed, i.e. infiltration of very fine sediments within the coarser matrix forming the bed. It is essential to understand the dynamic of fine sediments within the bed to quantify how clogging develops. A trapping coefficient is usually used to describe clogging. It quantifies the amount (or the proportion) of fine sediment that is blocked by a layer of gravels when travelling down into the bed. Most previous models are based on fitting steady-state profiles of fine sediment contents using results of laboratory experiments to compute empirical trapping coefficient.

In this article, we explore the Lauck stochastic model (Lauck 1991) that is based on a geometrical analysis. The cumulative pore size distribution of the bed is computed and compared to the grain size distribution of the fine sediment. The convolution between these two distributions gives the percentage of fine sediment that is trapped by the bed. To compute the pore size distribution, a biased coarse sediment frequency distribution is used to take into account the different probabilities for coarse grains to contribute to a pore depending on their size. This computation can be updated as fine sediment infiltrates and modifies the grain size distribution of a certain layer. In this article, we present the computation of the trapping coefficient and analyze how the variation of the trapping coefficient with respect to fine content is affected by the bias applied in coarse sediment frequency distribution. It appears that whereas the bias has little effect on the trapping coefficient for a matrix of gravel void of fine sediments, it has a strong impact on how this coefficient varies with a small amount of sediment trapped within the bed.

Keywords: sediment mixture, gravels, silts, infiltration

1. INTRODUCTION

Water management is currently recognized to be one of the most important issues in the world. Water is not only of primary use (drinking, irrigation and hydro-electricity) but also a source of potential risks (floods, pollutions, erosion). Specific issues are related to river management for rivers with poorly sorted sediments such as alpine ones. One of these issues is to understand how infiltration of fine sediment particles into a river bed occurs. This has an implication on the general sediment budget of the river. More importantly, infiltration may cause a clogging of the river bed (i.e. infiltration of very fine sediments within the coarser matrix forming the bed) that reduces the hydraulic conductivity between the flow and the hyporheic area or groundwater table (Schälchli 1992). From an ecological point of view, benthos and fish habitat is deteriorated because the substratum is less oxygenated, therefore affecting the spawning process and egg survival (Wood and Armitage 1997). The vertical connectivity —i.e. water-mediated fluxes of material, energy, and organisms between the channel and the alluvial aquifer— is essential for the ecological functions of the river, and should be addressed since the EU Water Framework Directive obliges Member States to reach or maintain a “good” ecological status for water bodies no later than 2015 or 2027.

Infiltration dynamics has been widely studied over the last fifty years. Numerous laboratory experiments have been carried out to characterize the fine sediment content in a gravel substrate at equilibrium when recirculating fine sediments over a coarser bed (e.g. Einstein, 1968, Hamm *et al.* 2011). Previous studies have shown that fine sediment can either be localized at the top of the bed (bridging or sealing profiles) or with a homogeneous content throughout the vertical (unimpeded static percolation named hereafter USP) depending mainly on the grain size distribution of fine and coarse sediments (Beschta and Jackson 1979, Packman and Mackay 2003, Gibson *et al.* 2009 and Gibson *et al.* 2010). The two types of fine sediment content profiles are schematized in Figure 1.

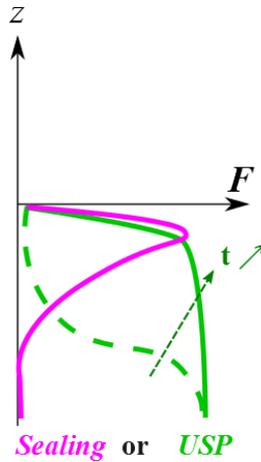


Figure 1. Schematic diagram to illustrate the two different infiltration profiles Sealing (or bridging) and USP.

It should be noted that flow variables and so bed shear stress also have an influence on the occurrence of either on type of profile or the other, as well as fine sediment concentration. These influences will not be discussed in this work.

An analysis of the shape of the sealing profile at equilibrium was undertaken by Wooster *et al.* (2008) and Cui *et al.* (2008), among others. They developed a filtration model based on a trapping coefficient. This trapping coefficient quantifies the proportion of fine sediment that is blocked in a layer of gravels when travelling vertically a unit distance. By assuming that this trapping coefficient is constant until the riverbed is clogged with infiltrated particles, an expression is derived for the steady-state fine fraction as a function of depth. Experimental data can be fitted with the resulted exponential profile and the trapping coefficient deduced empirically (Wooster *et al.* 2008).

Trapping coefficient is often estimated using empirical analysis (Wooster *et al.* 2008, Leonardson 2010). In this article, we explore the Lauck (1991) stochastic model to compute the trapping coefficient that is based on a physical analysis and apply this model to experimental data by Gibson *et al.* (2010).

2. TRAPPING COEFFICIENT COMPUTATION

2.1 Computation steps

Two different populations of sediments are considered. The first one forms the matrix of the bed and corresponds to the coarse fraction. The second one corresponds to the fine fraction that can infiltrate the bed. The computation of a trapping coefficient quantifying the proportion of fine sediment trapped in the bed using a stochastic model can be achieved as follows (see Lauck 1991):

- First, assuming that we know the cumulative weight distribution of the two populations of sediment, the distribution in terms of occurrence of particles, i.e. the probability to find a particle of a specific size, is computed;
- Then, the cumulative distribution of the pore size formed by the bed made of coarse particles is determined;
- Finally, the trapping coefficient is computed as the convolution between the fine sediment distribution and the pore size distribution, which corresponds to the probability for a randomly chosen fine particle to be trapped in a pore formed by three coarse particles also randomly chosen. It can be interpreted as the percentage of fine particles that can be trapped in a layer of the coarse substrate.

It should be noticed that this percentage is in terms of the number of particles and can be also expressed in terms of weight. Each step of this process is detailed in the following section.

2.2 Grain size distribution : from weight distribution to probabilities of particles occurrence

A mixture of sediments is commonly described by a weight distribution defined at several diameters that correspond to the diameter of the sieves used to sort the mixture. At each sieve diameter (x_i , i integer between 1 and n , the number of sieves), the percentile by weight distribution curve, $G(x_i)$, is formed by adding the weight that passed through the sieve and dividing by the total weight of the sample, w . From this distribution, the distribution in occurrence $f(x)$, defined as the probability of particle occurrence with a diameter between x and $x+dx$, needs to be computed. The weight of particles of diameter between x_i and x_{i+1} can be expressed as

$$w (G(x_{i+1}) - G(x_i)) = \int_{x_i}^{x_{i+1}} \alpha x^3 N f(x) dx \quad [1]$$

where N is the total number of particles in the sample of total weight w , α is a coefficient so that αx^3 is the weight of one particle of diameter x , and $N f(x) dx$, the number of particles of diameter between x and $x+dx$. No information is available to

know how particles are distributed between x_i and x_{i+1} . We will assume that particles of each size are uniformly distributed within the interval with a probability $f(x)$, so that:

$$w(G(x_{i+1}) - G(x_i)) = N \alpha f(x_i) \int_{x_i}^{x_{i+1}} x^3 dx \quad [2]$$

and

$$f(x_i) = \frac{4 w}{N \alpha} \frac{G(x_{i+1}) - G(x_i)}{x_{i+1}^4 - x_i^4} \quad [3]$$

The total number of particles can be obtained integrating $f(x) dx$ for all diameters

$$\sum_{i=1}^n f(x_i) (x_{i+1} - x_i) = 1 \quad [4]$$

$$\Rightarrow N = \sum_{i=1}^n \frac{4 w}{N \alpha} \frac{G(x_{i+1}) - G(x_i)}{x_{i+1}^4 - x_i^4} (x_{i+1} - x_i) \quad [5]$$

Moreover, we will assume that particles are spherical with a density ρ_s so that $\alpha = \frac{\pi}{6} \rho_s$.

As an illustration, both distributions (the cumulative weight distribution G and the probability to find a particle of a specified diameter f) are presented on Figure 2 for the sand 3 used by Gibson *et al.* (2010). The probability is directly related to the slope of the grain size distribution. It should be noted that as the proportion of particles within an interval $[x_i, x_{i+1}]$ is given by $f(x)(x_{i+1} - x_i)$, $f(x)$ can take values larger than one.

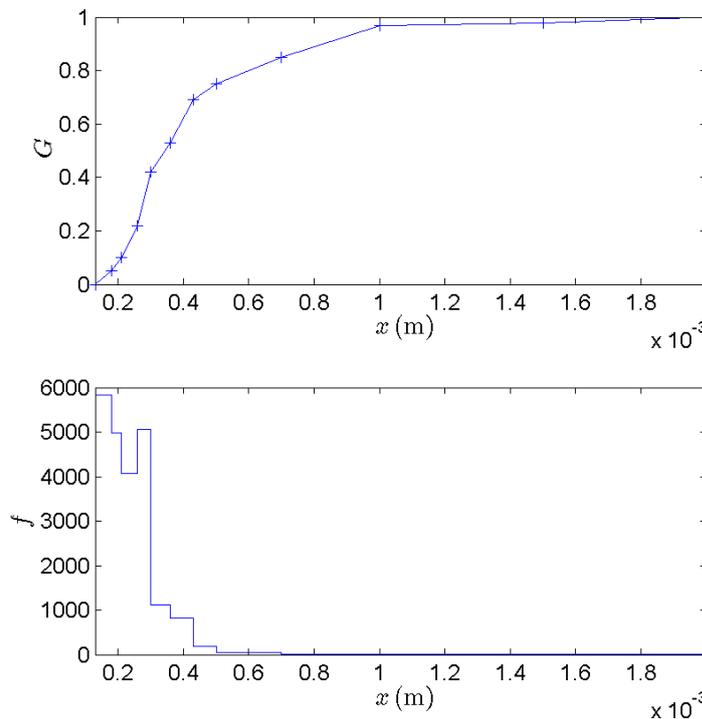


Figure 2. Cumulative weight distribution G and to find a particle of a specified diameter f for the sand 3 used by Gibson, *et al.* (2010).

2.3 Pore throat size distribution

The probability distribution of occurrence of the coarse sediments can be computed as presented above. Using this distribution we can compute the pore throat size distribution. Firstly, three diameters in the coarse sediment distribution are picked, d_1 , d_2 and d_3 and the diameter d_p of the pore throat constituted by three grains of these diameters is computed using Heron formulae (Lauck 1991):

$$\begin{aligned} \sqrt{(d_1 + d_2 + d_3) d_1 d_2 d_3} &= \sqrt{(d_1 + d_2 + d_p) d_1 d_2 d_p} \\ &+ \sqrt{(d_1 + d_p + d_3) d_1 d_p d_3} \\ &+ \sqrt{(d_p + d_2 + d_3) d_p d_2 d_3} \end{aligned} \quad [6]$$

The probability distribution of pore size d_p is then computed based on the probability of size-occurrence of each of the three grains that contribute to the pore. A bias needs to be introduced to take into account that the probability for a grain to participate to a pore is not directly given by its probability of occurrence (Lauck 1991). Indeed larger grains participate in more pores considering their surface but in a sediment layer, the number of finer grains is larger. The bias is introduced by multiplying the probability distribution $f(x_i)$ by x_i^m as it seems to be related to the size of the sediment. The value of m can be taken as 2 if we consider that the probability for a grain to participate to a pore is proportional to its surface or 3 if it is proportional to its volume. This value could be minored if we considered that within a layer of a specified thickness, the probability to find a grain is inversely proportional to its diameter. Considering these different options, it seems reasonable to consider that possible values for m range between 0 and 3.

Thus, for each trio, the probability to obtain a pore of size d_p is given by:

$$p[d_p] = f(d_1)d_1^m \times f(d_2)d_2^m \times f(d_3)d_3^m \quad [7]$$

This probability is computed for each possible trio and the cumulative probability $P[x]$ to get a pore which size is lower than a specified diameter x is computed by summation.

2.4 Trapping coefficient

The trapping coefficient β can be obtained as the convolution between the cumulative pore size distribution P and the fine sediment distribution f :

$$\beta = \sum P[x]f(x)dx \quad [8]$$

It gives the probability of a random fine particle to be smaller than a random pore

For a large number of fine grains, this is the proportion of fine particles that are trapped in a bed layer. Now, larger fine particles are more likely to be trapped in a pore throat than smaller ones. Thus, to have an idea of the mass of sediment trapped within the bed, it could be more appropriate to use weighted-values of f . A trapping coefficient in terms of weight is then computed using the same process as exposed in section 2.2 as:

$$\beta_M = \int P[x]f(x)\alpha x^3 dx = \sum P[x_i]f(x_i)\alpha \frac{x_{i+1}^4 - x_i^4}{4} \quad [9]$$

As the particles trapped are the largest ones, the trapping coefficient in terms of weight β_M is larger than the trapping coefficient in terms of the number of particles β .

3. RESULTS

In this section, trapping coefficients will be computed for the sediments used by Gibson, *et al.* (2010).

3.1 Overview

Gibson, *et al.* (2010) carried out different experiments of fine sediment infiltration into a gravel bed. Eight types of gravels and ten types of fine sediments (silt and sands) were chosen. Fine sediments were recirculated over a gravel bed and the equilibrium profile of fine sediment content was measured. From these profiles, each combination of fine and coarse sediment was identified as a couple generating unimpeded static percolation, bridging or an intermediate state. We computed the trapping coefficient in terms of weight (β_M) for each of these couples (Figure 3) with two values for the bias coefficient m , $m=1$ (left) and $m=2$ (right). In both cases, it seems that bridging occurs if $\beta_M > 10^{-4}$ and unimpeded static percolation if $\beta_M < 10^{-6}$. These values may appear to be low. We will try to understand first what the effect of changing the bias coefficient is as it seems not significant here. Secondly, to better understand whether this trapping coefficient is appropriate and what bias to choose, we will investigate its sensitivity to the presence of low fine sediment content in the bed.

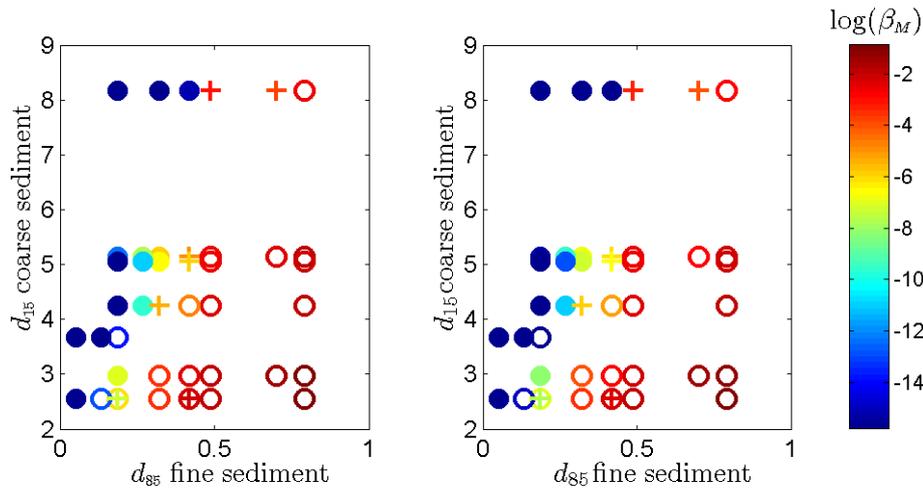


Figure 3. Experimental data of Gibson *et al.* (2010) plotted by the d_{85} of the sand and the d_{15} of the substrate with bridging (open circles, unimpeded static percolation (filled circles) and transitional processes (cross). The color of each symbols corresponds to $\log(\beta_M)$, β_M trapping coefficient in terms of mass computed with two different bias coefficients, on the left $m=1$, on the right $m=2$.

3.2 Bias in the pore throat size distribution

Results in the previous section have been computed considering two different values of the bias coefficient ($m=1$ and $m=2$) for the computation of the pore throat size distribution. As explained in section 2.3, these two values correspond to two different estimations of the probability for a grain to participate in a pore. Indeed, we can assume that the number of pores in which a grain participates is proportional to its surface x^2 . On the other hand, there are less large grains than small grains in a layer of a given thickness and the proportion of sediment with a diameter d is inversely proportional to x . As a consequence, the probability for one grain of diameter x to participate to one pore is $f(x)x^2/x = f(x)x$. However, one can argue that a grain participates to a number of pores proportional to its volume and not its surface or that the thickness should not be taken into account. It is then interesting to see the influence of this parameter in detail and understand why the difference is so small between the figures presented above.

The pore size distribution for the gravel G6 ($d_{15} = 3$ mm) computed for two values of m ($m = 1$ and $m = 2$) along with the distribution in occurrence for the sand 3 ($d_{85} = 0.68$ mm) of Gibson *et al.*, 2010 are presented in Figure 4. The trapping coefficient β_M obtained was 0.26 for $m = 1$ and 0.23 for $m = 2$. The value of the bias coefficient for the pore size distribution parameter has an impact on the trapping coefficient. Nevertheless, considering the range of values of β_M , the sensibility of β_M to the coefficient m appears to be limited. Indeed, the pore size distribution remains almost identical considering the resolution of the initial cumulative weight distribution. But, in our opinion, this is mainly due to the fact that the gravels considered are quite sorted. In the case of a gravel bed with fine sediments already trapped in the bed, we expect its influence on β_M to be more pronounced. This hypothesis is tested in the following section.

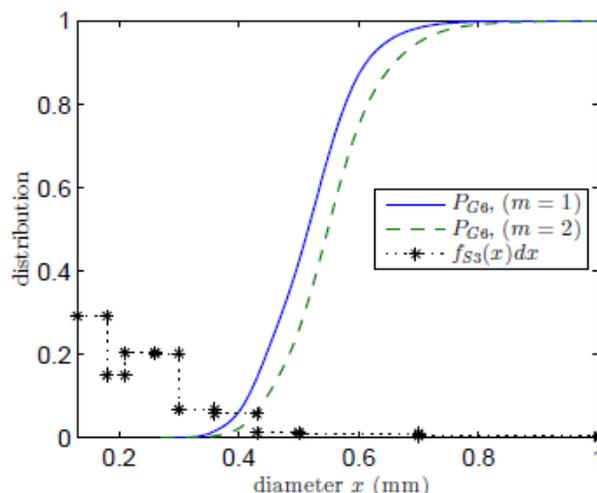


Figure 4. Pore size distribution for two types of gravels (G6, plain; G1, dash-dotted) and grain size distributions (in occurrence) of two types of fine sediments (Sand 3, stars; Sand 6, cross). For each type of gravel, the two curves correspond to $m = 0, 1, 2, 3$, from left to right. Value of β_M are summarize in the adjacent table.

3.3 Influence of fine sediment content in the bed

In this section, we try to better understand the process of bridging by quantifying how the trapping coefficient increases as fine sediments are added into the bed. With such computation, we can discuss the hypothesis of Cui *et al.* (2008) in their theory of fine sediment infiltration into immobile gravel bed. They propose the following model for β with respect to the fraction of fine sediments in the deposit relative to the total volume F :

$$\beta^*_{cui} = \beta_0^* \exp\left(\phi \frac{F/F_s}{1 - F/F_s}\right) \quad [10]$$

where β_0^* is the trapping coefficient for the clean gravel bed ($F=0$); Φ is a dimensionless coefficient that defines the shape of the β to F/F_s relationship ($\Phi>0$); and F_s is the value of F when the bed matrix is saturated with fine sediments. This maximum sand fraction was computed according to empirical relationship developed by Ridgway and Tarbuck (1968):

$$F_s = \theta_{gr}(1 - \theta_s) \left[1 - 2.35 \frac{d_{85, \text{fine sediment}}}{d_{15, \text{coarse sediment}}} + 1.35 \left(\frac{d_{85, \text{fine sediment}}}{d_{15, \text{coarse sediment}}} \right)^2 \right] \quad [11]$$

The trapping coefficient is defined as the fraction of fine sediment-load trapped in the bed when traveling vertically a unit distance. To be compared to the above definition, it should be noticed that it needs to be multiplied by a characteristic length Δz that represents the average distance between two pores. Following the work of Leonardson (2010), we will assume that this distance is the geometric mean of gravels diameters. For the range of fine sediment content studied, this geometrical diameter is approximately constant and

$$\beta^*_{cui} \Delta z = \Delta z \beta_0^* \exp\left(\phi \frac{F/F_s}{1 - F/F_s}\right) = \beta_{0, \text{this study}} \exp\left(\phi \frac{F/F_s}{1 - F/F_s}\right) \quad [12]$$

Thus, using β_0 value we obtain with the model presented herein should lead to a dimensionless trapping coefficient.

On figure 3(a) we present the trapping coefficient values for the gravel G1 from the experiment by Gibson *et al.* (2010) infiltrated with three sands, S2, S3 and S6 as well as G6 infiltrated with S3 for a bias coefficient $m = 1$. The same computation with $m = 2$ leads to the results presented in figure 3(b). As expected, in both cases, an increase of fine sediment content reduces the pore size. An increase in fine sediment content causes a decrease in the expected pore size and an increase of the trapping coefficient. However, results with $m = 2$ show a significantly different behavior. Whereas for $m = 1$, a very small amount of fine sediment drastically changes the value of β from almost zero to one even for couples of sediments that provides USP profiles, for $m = 2$, the increase of β is less pronounced. It seems much more realistic as the building of sand piles on top of gravel grains can lead to a small amount of fine sediment without reducing the size of the pore throats. It underlines a major issue for this model: the mixture is considered as homogeneous, which is not the case when fine sediments deposited on coarser grains. It seems though that modifying the bias can partially overcome this difficulty and leads to variations of β with F in agreement with the model proposed by Cui *et al.* (2008).

Differences between couples can be analyzed for $m = 2$ (figure 3(b)). The transitional process type (red crosses) shows interesting features as it evolves in a similar way as USP case (filled squares) for small fine sediment contents but joins bridging curves for higher fine sediment content. The model presented herein may be used to better analyze and understand how and when this transitional process occurs.

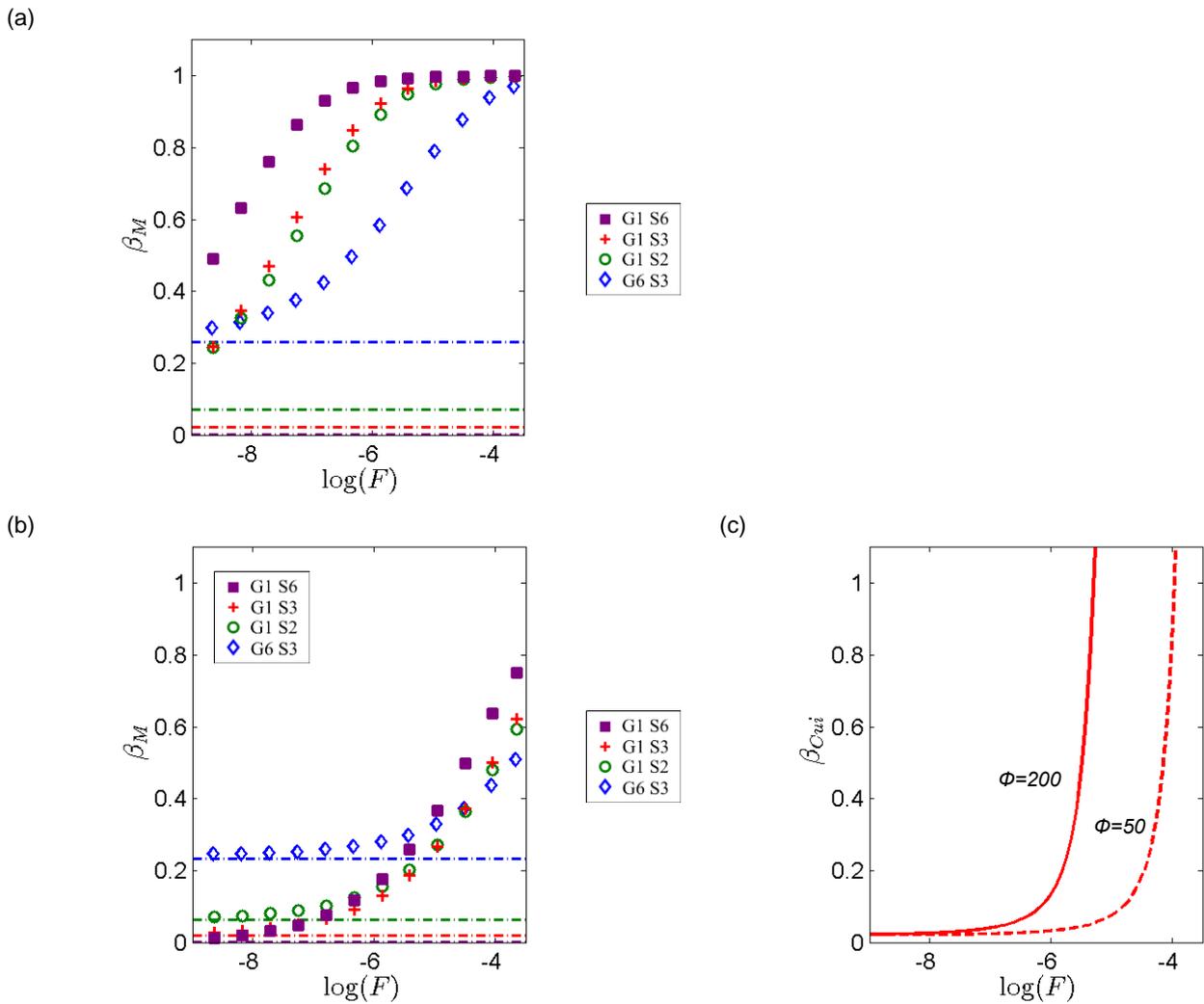


Figure 5. Trapping coefficient (in terms of weight) with regards to fine sediment content within the bed. (a) model presented in this article applied to gravel G1 (Gibson *et al.* 2010) infiltrated with sands S2 (green circles), S3 (red crosses) and S6 (purple squares) and gravel G6 sand S3 (blue diamonds) for different values of fine sediment content and $m = 1$. The value for $F=0$ is indicated with the horizontal dash-dotted line. (b) Same results with $m = 2$. (c) Dashed and plain lines: Cui 2008, eq [6] for $\Phi=50$ and 200 respectively, β_0 computed as presented herein for G1, S3 and F_s computed as Ridgway and Tarbuck (1968).

4. CONCLUSIONS

Following the work of Lauck (1991), a stochastic model has been developed to compute the trapping coefficient in terms of weight. Computations have been carried out considering gravels and different types of sands corresponding to the Gibson *et al.* (2010) experiments. Values of the trapping coefficient can be used to distinguish bridging and unimpeded static percolation cases. It also appears that even if the bias needed to compute the pore size distribution of gravels is not critical in the determination of the trapping coefficient for the sediment deposit void of fine sediment, it has a strong impact on the way it evolves with fine sediment content already trapped within the bed. Further studies are necessary to better take into account the building of sand piles on top of gravel grains that leads to inhomogeneous bed not well reproduced here.

ACKNOWLEDGMENTS

Irstea is acknowledged for the funding of Albert Herrero in post-doctoral position at Irstea Lyon-Villeurbanne.

REFERENCES

- Beschta, R. L. and W. L. Jackson (1979). The intrusion of fine sediments into a stable gravel bed. *Journal of the Fisheries Board of Canada* 36(2): 204-210.
 Cui, Y., Wooster, J. K., Baker, P. F., Dusterhoff, S. R., Sklar, L. S., and Dietrich, W. E. (2008). Theory of fine sediment infiltration into immobile gravel bed. *Journal of Hydraulic Engineering*, 134(10), 1421-1429.
 Einstein H. (1968). Deposition of suspended particles in a gravel bed. *J. Hydraul. Div. Am. Soc. Civ. Eng* 94 (5): 1197-1205.

- Gibson S, Abraham D, Heath R, Schoellhame RD. (2009). Vertical gradational variability of fines deposited in a gravel framework. *Sedimentology* **56**(3): 661-676.
- Gibson, S., Abraham, D., Heath, R., and Schoellhamer, D. (2010). Bridging Process Threshold for Sediment Infiltrating into a Coarse Substrate. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(2): 402-406.
- Hamm N.T., Dade, W.B., and Renshaw C.E. (2011). Fine particle deposition to porous beds. *Water Resources Research* **47**.
- Lauck, T. J., (1991) A Simulation Model for the Infiltration of Sediment into Spawning Gravel, M.S. thesis, Humboldt State University, California, United States.
- Leonardson R. (2010). Exchange of fine sediments with gravel riverbeds. PhD Thesis: Department of Civil and Environmental Engineering, The University of California-Berkeley.
- Packman, A. I. and J. S. MacKay (2003). Interplay of stream-subsurface exchange, clay particle deposition, and streambed evolution." *Water Resources Research* 39(4).
- Ridgway and K. J. Tarbuck (1968). Particulate mixture bulk densities. *Chemical and Process Engineering*, 49(2).
- Schälchli U (1992). The clogging of coarse gravel river beds by fine sediment. *Hydrobiologia*, 235(1):189–197.
- Wooster, J. K., *et al.* (2008). Sediment supply and relative size distribution effects on fine sediment infiltration into immobile gravels. *Water Resources Research* 44(3).
- Wood P.J., and Armitage P.D. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management* 21 (2), 203-217.