Revue Paralia, Volume 1 (2008) pp 1.15-1.28
Keywords: Alveolar foam, Interface, Ultrasonic Doppler Velocimetry (UDV), Porosity, Sediment, Reynolds number, Shear stress.

Analysis of the velocity field inside a sedimentary bed associated to a free surface steady flow

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Abstract:
The physical processes associated with the sedimentary transport were approached until now only starting from analyses of the velocity field within the fluid vein. The majority of the models were established for flows on impermeable bottoms. The purpose of our technical study is to exploit the ultrasonic technique UDV to analyze the velocities field within a permanent flow on a porous sedimentary bottom. Velocities are measured for several sedimentary beds, both within the fluid flume and the sediment. Our results highlight:
- An exponential velocities distribution inside the sediment.
- A velocity discontinuity of the interface water/sediment, between velocity in the free flow and velocity within the sediment.
These results highlight the need for basing the analysis of sedimentary transport which must consider the reality of the physical processes at the interface water/sediment.

Received 4 February 2008, accepted 9 June 2008, available online 16 June 2008.
Translated version not certified, published under the responsibility of the article authors.

How to cite the original paper:
MIHOUBI M.K., BELORGEY M., LEVACHER D., KETTAB A. (2008). Étude de la répartition des vitesses interstitielles au sein d'un lit perméable sous un écoulement à surface libre. *Revue Paralia*, n° 1, pp 1.1–1.14.
DOI: 10.5150/revue-paralia.2008.001 (disponible en ligne – http://www.paralia.fr)

1. Introduction

The sedimentary phenomenon of transport is very complex and the physical processes which are associated with it are still badly known.

Indeed, due to a lack of adapted instrumentation, the modelling of this phenomenon is still based on two standards of studies, independent, but exploited as complementary:

- Analysis of the velocities field in the free flow.
- The measurement of interstitial velocities within a flow in uniform porous environment with constant hydraulic gradient.

The majority of the studies which led to the modelling of the velocities' field in the free flow were carried out on an impermeable bottom with a null velocity assumption of the wall. The constraint of friction of the wall, essential to the modelling of sedimentary transport, either uses the velocity gradient near the wall, or uses the logarithmic law of Prandtl and Von-Karman (GRAF & ALTINAKAR, 1995). The studies in this field are very numerous.

The studies concerning the measurement of interstitial velocities within a porous environment, with constant hydraulic gradient, have as reference works of Darcies based on a linear formulation and those of Forch Heimer which presented a nonlinear relation in the case of more significant velocities, for example, for the coarse sands and the gravels, the relation is written:

$$i = a_o * u + b_o * u^2 \qquad (1)$$

where:

a_o and b_o are coefficients which characterize the structure of the porous and tortuous environment.

Recently, in this context, it is advisable to quote work of WARD (1964), AHMED and SUNADA (1969) who propose models based one the Reynolds number of the pores. More recently, WAHYUDI *et al*. (2002) determined the coefficients of the polynomial of second order resulting from the law of Forchheimer, equation (1), for homogeneous sands of porosity "n" varying between 0.32 and 0.38. We can quote the works of MONTILLET (1995) which expresses the hydraulic gradient starting from the velocity of flow in the pores, taking into account the porosity and the tortuous aspect of the porous environment.

According to size of the pores in the porous environment, we can say that there are two fields of the porosity, a capillary porosity for a diameter of small pores, D_p is less than 2 mm and a effective porosity for a medium with macroporosity of a diameter D_p superior to 2 mm (COMITI & RENAUD, 1989). In addition, WAHYUDI (1998), gives a classification of the flows in porous environment according to the diameter of the particles and velocity of infiltration.

The studies relating to the problems of interface between porous environment and fluid under flow at free surface are very restricted. The first bases were given by SHIMIZU *et al.* (1990) (*in* KLAR, 2005) which presented formulation of an exponential type for a flow in very permeable environment, by considering that speed is function of the velocity of infiltration and slip resulting from the change of interface.

However, such studies do not correspond to the physical processes related to the velocities field generated by a free surface flow within a sedimentary bottom, and this for the following reasons:

- Because of the existence of an interstitial velocity of the interface water - sediment, the velocity of the fluid in the free flow is not null at the wall.
- The velocities distribution within the sediment is not uniform and there is a velocity gradient function of depth.

In order to better understand the physical processes associated with this phenomenon, we adapted the technique of velocimetry Doppler ultrasonic (UDV) to the instantaneous local measurement of interstitial velocities within a porous mass. This measurement technique, which is relatively recent, has known a great success in the study of the opaque and charged flows where other methods, such as laser velocimetry, were inoperative (LHERMITTE, 1983; WILLEMETZ, 1990). We have already exploited it at the laboratory in the case of flows with variation in temperature (MICHAUX-LEBLOND *et al.,* 1996) and work of CARPENTIER (2006), relating to measurements velocity within the base of a dam subjected to the action of the swell, which moreover validated the method by experimental tests of Darcy type in the case of alveolar foams and with bubbles. The results which we present here correspond to the case of a free surface flow on a sedimentary bottom. The velocity measurements of interstitial flow made it possible to know the velocity profile whether in its fluid part or in the porous part of the bed flow.

2. Technical measurement by UDV

The device of measurement used (ultrasonic Doppler velocimeter, functioning in pulsated mode: DOP 1000 (model 1032), allows, thanks to the use of the Doppler effect on pulsated waves ultrasonic, to directly determine interstitial velocity at the level of the pores of the considered ground.

The principle is the sending of an ultrasonic wave of known frequency f_0, which, at the meeting of a moving particle in the fluid, returns a wave of shifted frequency f_r by Doppler effect. This allows, thanks to the difference in recorded frequency $f_D=f_0-f_r$, to determine the velocity measurement of the particle in the flow in this point:

$$u = \frac{c.f_D}{2f_0.\cos\theta} \qquad (2)$$

c is the velocity of sound in water. Value validated for alveolar foams and with bubbles and preserved for the balls of glass and sand.

θ is the angle of the ultrasonic beam with the axis of the flow.

If we add to this frequency measurement the determination of running time (back and forth) of the wave train we reach the position of the particle. Thus, in pulsated mode, we can reach the desired space-time resolution *i.e.* to establish the velocities profile on an adapted exploration depth along the ultrasonic beam. However, in our case we limited ourselves to a definite position (gate) in the center of the fluid flume.

3. Experimental device and treatment technique of measurements

3.1 Flume with continuous flow

The device consists of a flume of an overall length of 3.5 m and a rectangular section (0.10 m x 0.25 m), making it possible to take measurements of velocity calibration by the ultrasonic Doppler velocimeter (figure1).

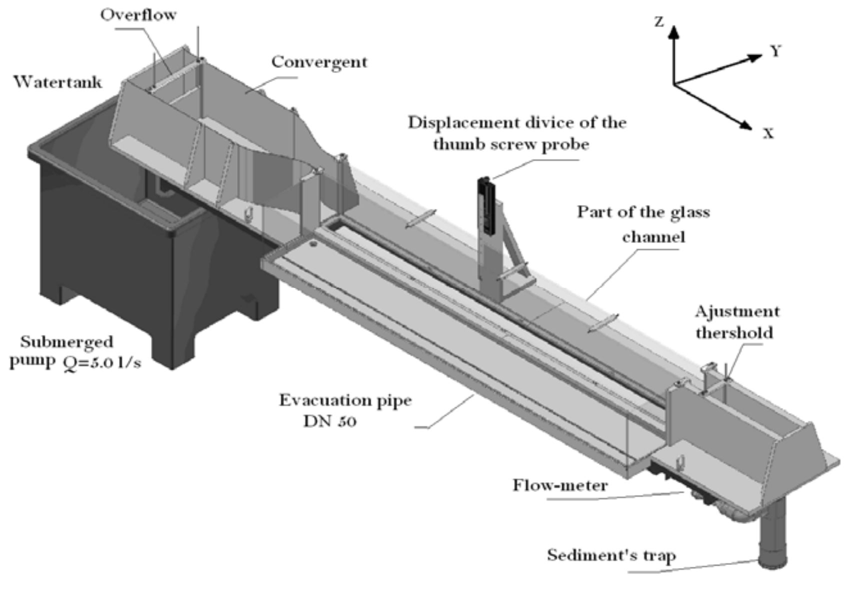


Figure 1. Description of the flume with a free surface steady flow.

The walls and the bottom of the flume are glazed by a 10 mm thickness, thus making it possible to make observations and optical measurements.

The flume is supplied by a tank with constant load out of PVC and of square-side section with dimensions of 0.30 m and 0.25 m height. The water arrives from a system of strainer; flow is homogenized by plates of foam of approximately 5 cm of thickness. In the flume, the flow is controlled by an adjustable threshold; the water overflow is evacuated towards the feed basin of the flume. The flume supply is ensured by a closed loop by means of a pump of maximum discharge (5.0 ± 0.1) l/s. For a better linearization of the flow and in order to reduce the effects of turbulence, two honeycomb cages were installed before the exit of the convergent one.

3.2. Principle of velocities measurements

The probe is a piezoelectric transducer with an emission frequency of 4 MHz and a diameter of 12 mm. It is placed on a support with a displacement of 24.0 mm in width, 400 mm in length and 2.7 mm in thickness, forming an incidence angle of 28° with the axis of the flume. The vertical displacement of the probe is ensured by means of a differential micrometric increment, which makes it possible to obtain maximum micro-displacements and a maximum of measurement points in the sedimentary bed and at the interface fluid/sediment. The minimal displacement ensured by the device of displacement of the UDV is 0.5 mm.

Taking into account dimensions of the ultrasonic beam, measurements are treated by a method of statistical filtration. The transducer and displacement support are protected by a punt from low curve (figure 2), forming a transducer box. In this recommended system we took into account the refraction between the media water-PVC and PVC-water.

We materialized the sedimentary bed by materials of different porosities and structure, alveolar foams and bubbles, balls of glass and sand. The thickness of the bed varies between 30 mm and 75 mm.

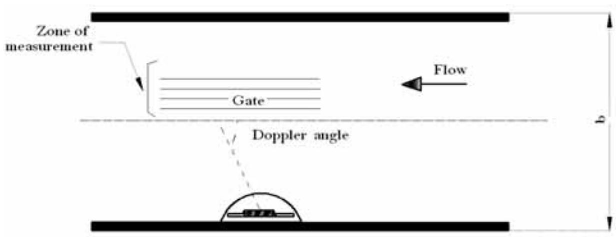


Figure 2. View in plane of the system of measurement in the flume.

The plate for the protection of the displacement device is circular, with a diameter of 49.0 mm and a thickness of 2.0 mm, and its base in the flume is equal to 8.0 mm.

3.3 Treatment of measurements

The ultrasonic beam delivered by the probe is cylindrical (slightly conical after a certain distance). In our case, it was placed in a horizontal plan perpendicular to the median plane of the flow. The particles subjected to this beam emit an echo, also collected by the probe. This echo, which depends on the angle between the ultrasonic beam and the direction of the flow, has two principal characteristics:
- Its frequency which gives access to the velocity of the particles (Doppler effect).
- Its intensity which depends on the size of the particles.

The treatment of the signal emitted by the particles is then approached in two different and quite distinct ways:
- That related to the size of the particles.
- That related to the dimension of the ultrasonic beam.

In this study of the interstitial velocity within the sediments, we have two sizes quite distinct from particles.
- Very large sedimentary particles.
- Particles (very small) in suspension in the fluid which circulate between the pores.

This fact:
- While eliminating, in the received signal, the echoes of great intensity, we eliminate the echoes resulting from the large sedimentary particles of which the speed, in addition, is null (except with the interface water sediment where there can exist a sedimentary transport, but this will be the subject of a forthcoming specific study). We thus preserve only the echoes resulting from the suspended particles in the fluid (with the traditional assumption that they have the same speed as this one).
- In addition, within the ultrasonic beam, the volume of measurement is a cylinder whose diameter is that of the beam (8 mm) and the length (0.74 mm) the depth of the gate (distance to which measurements are taken). The recorded measurements are thus those which are associated with the particles which cross this volume of measurement. However, taking into account the nature of the field speeds and the section of the volume of measurement (circular or slightly elliptic disc), the fastest or slowest particles cross the superior or inferior circular sectors, which are of weak section. These particles are thus very few in their category.

A statistical study of the recorded values confirms this. And the Gaussian form of the results allows us:

- To eliminate the very few, too large or too low values.
- To preserve an average value of the most probable velocities as being the measurement velocities at the level of the ultrasonic beam axis.

Figure 3 explicitly translates the distribution of the values measured according to the normal law. In the porous environment, velocities were given for intervals of probability varying from 70 to 75% compared to the value of the average velocity and the standard deviation of a volume of measurements. Absolute error estimated on velocity is equal to ±0.2 mm/s.

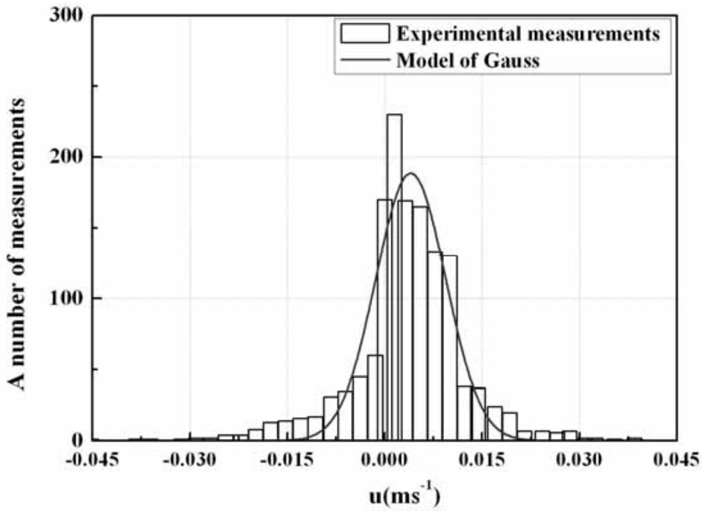


Figure 3. Velocities distribution compared with the normal law for a number of measurements in alveolar foam bed (Q=0.31 l/s and z=-3.0 cm).

3.4 Validation of measurements

In order to compare and validate the measurements obtained by UDV, measurements by laser Doppler velocimetry (LDV) were carried out in the case of a flow on an impermeable bed with smooth bottom. Figure 4 illustrates well the profiles determined by the two techniques. They are identical in overall, the only characteristic lies in the instantaneous frequency deviation of acquisition and the appearance of fictitious frequencies of the UDV close to the surface of the bottom of the flume outside the glass.

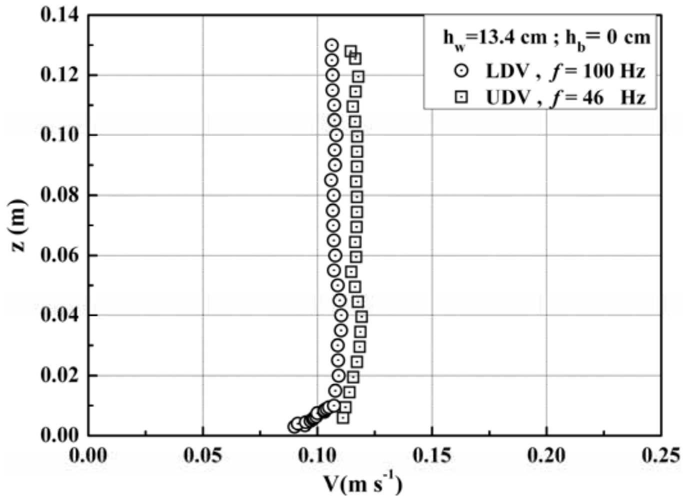


Figure 4. Comparative profiles of velocities obtained by measurements LDV and UDV for Q_f=1.47 l/s.

From the whole of the dimensional tests realized and validated we can initially give a representation of the instantaneous velocity of a free surface flow on a porous alveolar foam bed for three vertical positions different from the probe: within the bed, close to the interface bed/fluid and in the fluid (figure 5). This representation illustrates well the velocity ranges according to the height *z* as well as the effects of turbulence generated in the presence of a rough flow.

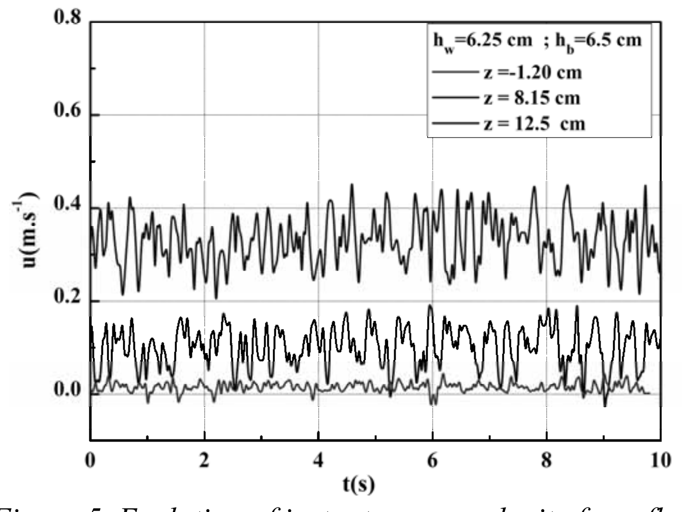


Figure 5. Evolution of instantaneous velocity for a flow on a bed out of alveolar foam (h=12.75 cm and Q_f=1.98 l/s).

Table 1 represents the physical characteristics of the porous bed and the conditions of flow for the whole of the tests carried out.

Table 1. Characteristics of the tests for various porous beds.

Type of bed	***h***	$\frac{h_w}{h_b}$	***u***	Re_p	***V***	R_h	***Qf***	***Re***	***Fr***
	(cm)	---	***(cm/s)***	---	***(cm/s)***	***(cm)***	***(l/s)***	$x\ 10^3$	---
Alveolar foam	*8.00*	*0.23*	*0.061*	*52. 52*	*7.30*	*1.15*	*0.11*	*0.84*	*0.19*
	11.70	*0.80*	*0.103*	*86.11*	*5.90*	*2.55*	*0.31*	*1.41*	*0.08*
	12.50	*0.92*	*0.124*	*106.8*	*22.80*	*2.73*	*1.37*	*5.84*	*0.30*
	12.75	*0.96*	*0.384*	*330.3*	*31.60*	*2.78*	*1.98*	*8.25*	*0.40*
Bubbles foam	*10.90*	*0.45*	*0.020*	*4.95*	*7.10*	*2.02*	*0.24*	*1.35*	*0.12*
	11.50	*0.53*	*0.076*	*12.43*	*14.60*	*2.22*	*0.58*	*3.04*	*0.23*
	12.90	*0.72*	*0.170*	*19.90*	*27.60*	*2.60*	*1.50*	*6.74*	*0.38*
Balls of glass	*11.00*	*2.67*	*0.340*	*14.95*	*5.94*	*3.08*	*0.47*	*1.72*	*0.07*
	11.40	*2.80*	*0.670*	*8.96*	*11.55*	*3.13*	*0.97*	*3.39*	*0.13*
	15.40	*4.13*	*1.020*	*22. 84*	*13.03*	*3.56*	*1.61*	*4.36*	*0.12*
Sand	*11.70*	*2.90*	*0.430*	*0.81*	*5.70*	*3.18*	*0.50*	*1.70*	*0.06*
	14.70	*3.90*	*0.850*	*1.55*	*11.50*	*3.50*	*1.35*	*3.78*	*0.11*
	15.40	*4.13*	*1.840*	*3.35*	*13.00*	*3.56*	*1.61*	*4.35*	*0.12*

Fixed parameters:

Alveolar foam bed - h_b=6.5 cm ; D_p=3.1 mm ; n=96.4%

Bubbles foam bed - h_b=7.5 cm ; D_p=0.9 mm ; n=94.5%

Balls of glass bed - n=37.5 % ; h_b=3 cm ; D =(3.8-4.4) mm

Sand bed - n=32.0 % ; h_b=3 cm ; D_{50}= 0.406 mm

4. Analysis of the experimental results

Figures 6(a) and 6(b) represent the velocities evolutions for various sedimentary beds and various flows according to the *z* axis (depth for the sediments and water height for the fluid in the flume). The dimension "0" corresponds to the interface water-sediment.

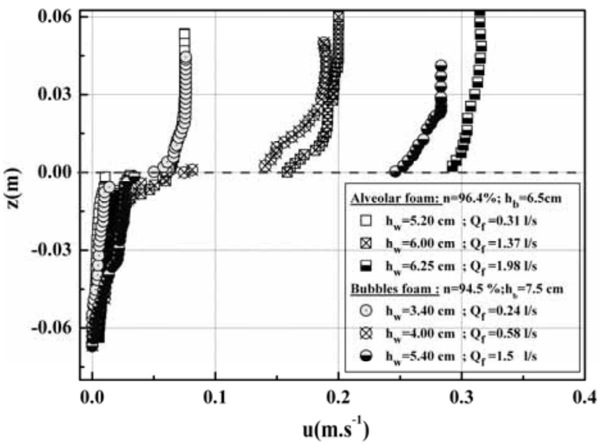


Figure 6(a). Velocities profiles for porous beds in alveolar and bubbles foam.

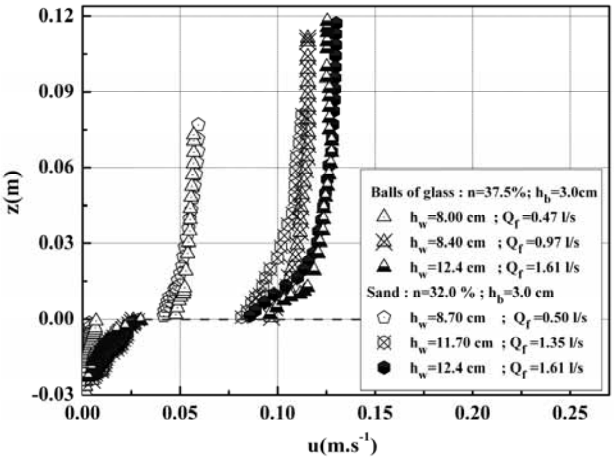


Figure 6(b). Velocities profiles for porous beds in glass balls and sand.

As shown in detail in figure 7 (case of a flow bed in alveolar foam). These results highlight:

- A strong "discontinuity" of velocities to the interface water-sediment. i.e. a very important gradient function of the flow and the sediment nature.
- A non null velocity at the bottom (for the fluid in the flume).
- An exponential velocities evolution within the sediment of the form:

$$u_{(z)} = A.e^{\alpha.z} \tag{3}$$

A and α are two experimental parameters which depend on the flow conditions in a porous environment and at the interface fluid-sediment. The parameter α characterizes the flow bed porosity and the flow mode in the pores of the bed.

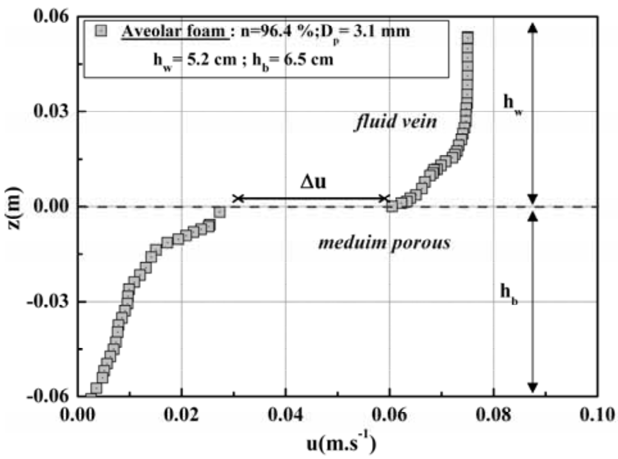
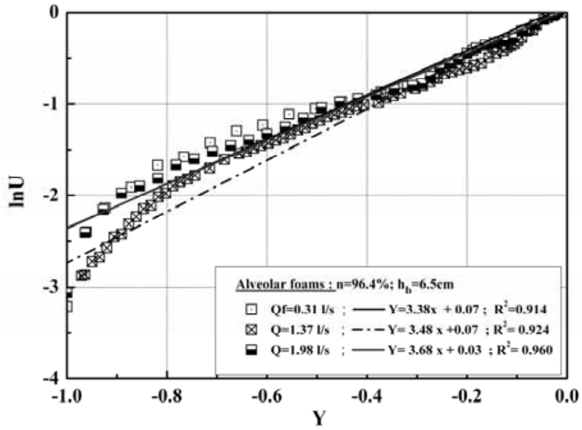


Figure 7. Detail of the velocities discontinuity at the interface Water-sediment (h=11.7 cm et Q_f =0.31 l/s).

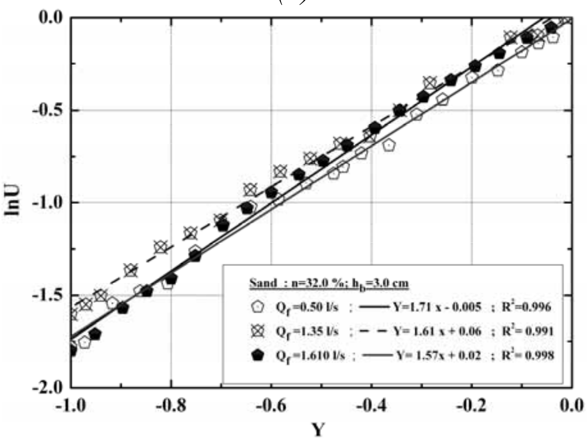
To better understand the evolution of the parameter α according to the characteristics of the porous environment one uses the following adimensional sizes:

$$U = \frac{u}{u_{\max}} \qquad \text{and} \qquad Y = \frac{z}{h_b} \qquad \text{with: } Y < 0 \tag{4}$$

From the layout of the graphs ln(U)=f(Y) which correspond to inertial speeds measurements in the porous bed, we can deduce the value from the parameter α starting from the directing coefficient of the right linear regression. It is noted that the parameter depends not only on the nature of the sediment but also on the mode of the flow on the scale of the pores. It is influenced by the size of the pores of the reconstituted bed (figure 8).



(a)



(b)

8. Evolution of the parameter α: (a) Case of the alveolar foam; (b) Case of sand.

The examination of the variation of parameter α according to the mode of flow of the porous environment according to the Reynolds number of the pores made it possible to note that it varies according to the size of the pores (figure 9). We noticed that there are two distinct fields. The first field characterizes the pores D_p< 2 mm. Parameter α is almost constant then decreases for Reynolds R_{ep}<10. On the other hand, for D_p>2 mm, the Reynolds number increases, thus characterizing the turbulent porous field.

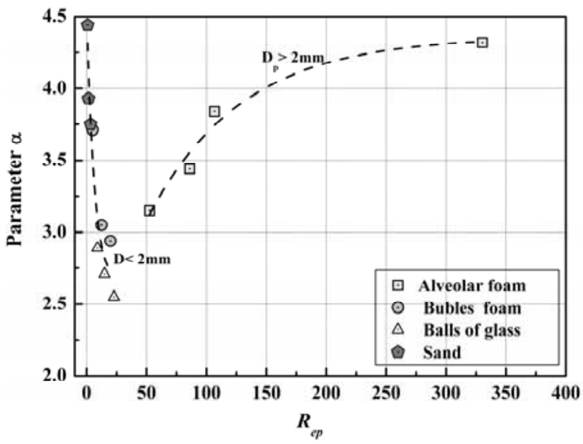


Figure 9. Variation of the parameter α according to the Reynolds number and of the size of the pores.

5. Conclusion

The results highlighted by the measurement velocities by the UDV technique within a free surface on a permeable bed show that the velocities profile is null inside the bed flow. The flow in porous environment has an exponential form which is characterized by an important speed gradient at the interface water sediment.

This shows that the traditional models for determination of the wall shear stress τ_p are not well adapted because they are based mainly on the characteristics of the free flow without taking into consideration the nature of the sediment, its characteristics (porosity) and the characteristics of the interstitial flow (Reynolds number of the pores).

This friction stress τ_p is associated with the threshold of movement. It thus seems significant to us to define it while taking it into account. This objective is our current work which consists in studying the effect of shearing under the action in particular the swash zone.

Acknowledgements

These works have been achieved thanks to financing within the framework of intergovernmental cooperation programme of high training between Algeria and France (PROFAS). Otherwise, we have been supported by Dr J-C Willemetz, manager of Signal Processing SA Society and we thank him for his availability.

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Nomenclature

a_o, b_o :	*coefficients of Forchheimer law*	*(s/m), (s^2/m^2)*
b :	*width of the flume*	*(cm)*
c :	*velocity of the sound in the water ($c \cong 1500$ m/s)*	*(m/s)*
f_0, f_D :	*emission frequency, Doppler frequency*	*(MHz)*
h_b :	*height of the bed of sediments*	*(cm)*
h_w :	*draught of the fluid in the flume*	*(cm)*
h :	*total draught, $h=h_w+h_b$*	*(cm)*
i :	*hydraulic gradient*	*(-)*
n :	*total porosity*	*(-)*
u :	*interstitial velocity*	*(cm/s)*
D, D_{50} :	*Diameter, mean diameter of the particles*	*(mm)*
R_h :	*hydraulic radius of the fluid in the flume*	*(cm)*
Q_f :	*rate of flow of the fluid*	*(l/s)*
α :	*parameter characterizes the flow bed porosity*	*(-)*
Re_p :	*Reynolds number of the pores;* $R_{ep} = \frac{\rho.u.D_p}{\mu(1-n)}$	*(-)*
D_p :	*average hydraulic diameter of pores ;* $D_p = \frac{2}{3}.\frac{n.D}{(1-n)}$	*(mm)*
Y :	*ratio of the position velocity on the height of the bed.*	*(-)*
U :	*velocity ratio on interstitial maximum velocity.*	*(-)*
V :	*velocity flow only;* $V = 0{,}82V_{max}\left[\frac{(1+0{,}6\sqrt{R_h})}{(1+0{,}9\sqrt{R_h})}\right]$	*(cm/s)*
Re :	*Reynolds number of the flow in the fluid flume only;* $\mathrm{Re} = \frac{V.R_h}{\nu}$	*(-)*
Fr :	*Froude number associated with the flume flow fluid only;* $F_r = \frac{V}{\sqrt{gh_w}}$	*(-)*