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Stationary and oscillatory flows through porous media: effects of the specific surface

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Abstract:
The purpose of this work was to study the effects of the specific surface on the energy dissipation through a "model" porous medium constituted by a network of emerging vertical cylinders. Experiments have been performed in a ten metres long hydraulic open-channel. Three porous media were used with various cylinder diameters. The porous structure models consisted in regular networks of cylinders of constant diameter. The effect of specific surface have been analysed by using three different cylinder diameters while keeping constant the porosity. Two series of experiments are presented. On one hand, measurements in stationary flow conditions, with various velocities and depths, demonstrated the significant influence of specific surface on pressure drop through the porous media. On the other hand, a second series of experiments has focused on the propagation of regular waves through the porous structures. The role played by the specific surface both on wave attenuation and interference processes was shown to be significant. The greater is the specific surface, the stronger is the damping.

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1. Introduction

Nearshore areas are particularly exposed, and vulnerable, to incoming wave energy. Structures have been engineered from decades to mitigate the effect of waves on shoreline or coastal facilities. Among the first science-based approach, CALHOUN (1971) studied the rubble-mound breakwater for Monterey harbour (California). This pioneering field measurements showed the role played by such permeable coastal structures on wave dynamics, inducing swell reflection and transmission up to 40% and about 10 to 20%, respectively. The energy dissipation within the structure is caused by interference and multiple reflections processes. When waves propagate above porous medium, the attenuation is often related to inertial and non-linear effects (GU & WANG, 1991, and following cited references) which can be taken into account using a complex dispersion relation. SOLLITT & CROSS (1972) experimentally studied wave transmission and reflection by permeable breakwaters of various shapes. The reflection coefficient has been observed to decrease with decreasing dike width and wave length and increasing porosity and permeability. Conversely, the transmission coefficient decreases with decreasing wave length, porosity and permeability, and increasing wave height and dike width. MADSEN (1983) proposed a theoretical solution of linear wave reflection by a porous wall in the shallow water case. The reflection coefficient is thus determined as a function of incident wave parameters and porous structure properties (structure width, grains diameter, porosity). The analysis of wave transmission and reflection by a permeable structure was extended to the case of oblique incident waves on porous wall by DALRYMPLE (1991). Wave dynamics through superimposed porous blocks has been studied by YU & CHWANG (1994) for weakly to strongly dissipative conditions, including the influence of "evanescent" modes related to media index discontinuities in the propagation direction. Although each one of these models based on a linear representation of dissipation effects, high Reynolds number flows can be described by quadratic approach (MOLIN, 2011) for thin porous media.
The first section of this paper presents the experimental setup and methods. The second section is dedicated to the description of experimental results with, on one hand, the study of pressure loss by permanent flows through porous media and, on the other hand, the analysis of wave dynamics through the porous media including a frequency analysis of reflection and transmission coefficients. A particular attention is paid on the role played by specific surface which is defined as the ratio between the fluid-solid contact surface and the volume unit (GUYON *et al*., 1991). Conclusion and prospects are given in the last section of the manuscript.

2. Experimental set-up

2.1 Hydrodynamic wave tank and porous media

The experiments have been carried out in the SeaTech wave tank in Toulon, France. This wave/current flume is 10m long, 0.3 m wide and 0.5 m high.

The model porous medium consists of a dense network of emerging vertical cylinders, evenly disposed along two perpendicular axes forming a 45° angle with the longitudinal axis (Figure 1). Three cylinder diameters, D = 0.020, 0.032 et 0.050 m, have been used. The porosity is constant and equal to 0.7. The specific surface S decreases with increasing D and is equal to 52, 33 and 22 m^{-1} for the above mentioned diameters, respectively. The porous structure length varied during the experiments (see hereinafter).

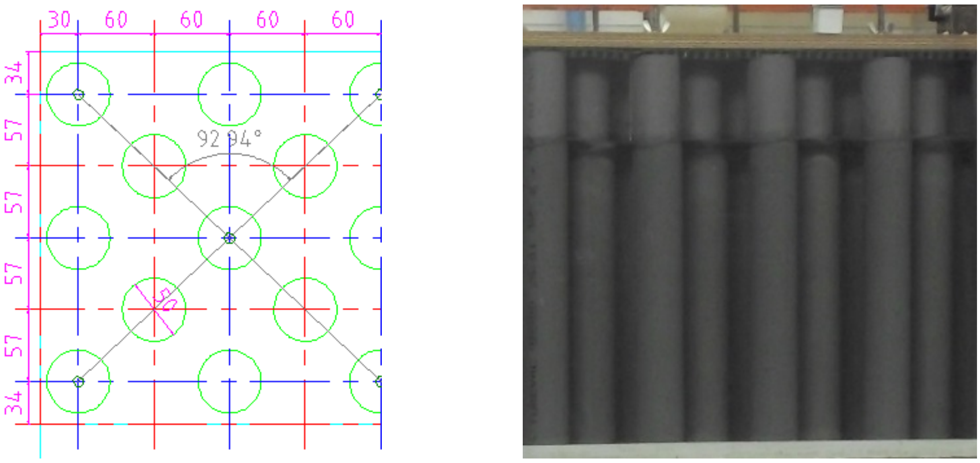

Figure 1. Top view scheme (left) and photo of side view (right) of the geometry of the cylinders for the porous medium.

2.2 Experimental conditions and instrumentation

The free surface level is measured with 7 synchronized resistive wave gauges, with a sampling frequency of 32 Hz. High-frequency (200 Hz) velocity measurements are performed using 5 acoustic Doppler currentmeters (NortekMed Vectrino©) .

For the stationary flow case, the porous structure length was L = 4.80 m. The five synchronized currentmeters were installed upstream, every 1.20 m in the porous medium and at the downstream outlet of porous medium, respectively. The studied flow rates and velocities ranged between 3×10^{-3} and 16×10^{-3} m^3/s and 0.04 and 0.20 m/s, respectively (note that free surface elevation was not kept constant).

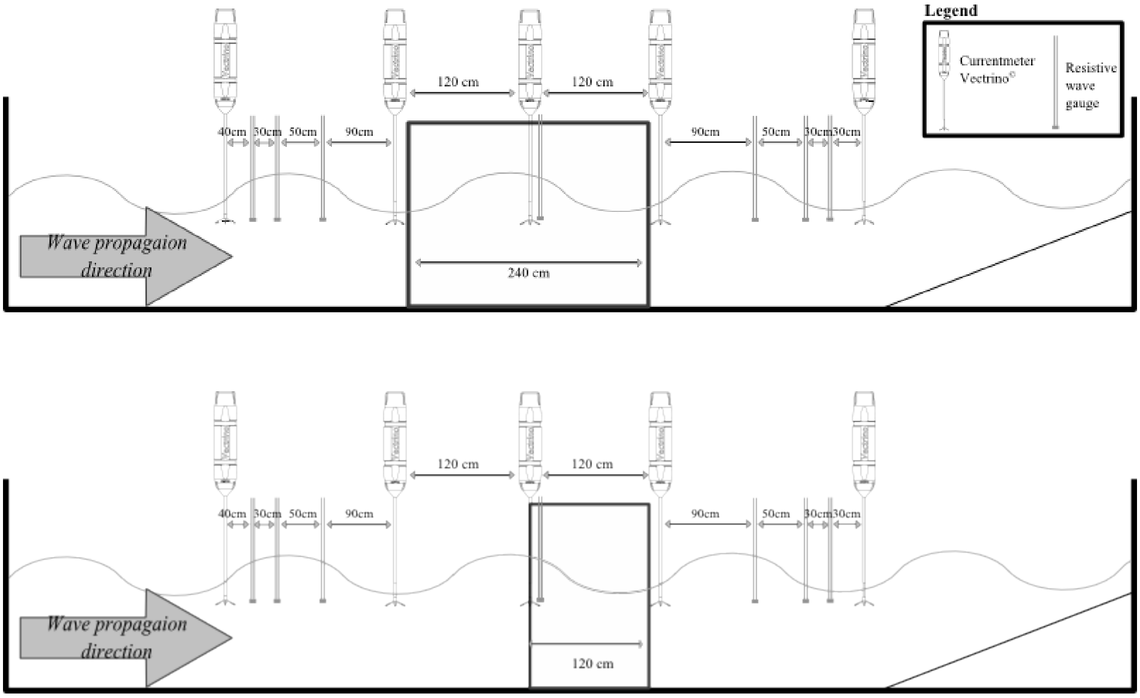

Figure 2. Sketchs of the experimental set-up for oscillating flow, up: L=2.40m and down: L=1.20 m.

The wave experiments have been carried out using two lengths L of porous, 1.20 et 2.40 m, for a constant water depth $h = 0.23$ m. Wave periods range from 0.55 to 2s. A set of wave gauges was deployed to characterize wave reflection, transmission and damping thanks to the three probes method (MANSARD & FUNKE, 1980), see Figure 2 for positioning. In addition, five currentmeters have been positioned on either side and within the structure. A gentle sloping beach was located at the downstream end of the flume to maximize the dissipation of the transmitted wave energy and avoid spurious reflection.

3. Experimental results

3.1 Pressure loss for steady flow

Inertial effects are generally neglected in low Reynolds number flows. The Darcy Law is thus used to define the water flow Q through a surface S as a function of the pressure gradient ΔP:

$$Q = U.S = -\frac{K}{\mu}\frac{\Delta P}{L} \qquad (1)$$

In this equation, μ is the fluid viscosity, U is the mean velocity of flow and K is the intrinsic permeability of porous media, which is a function of the medium geometry, and L is the length of the porous medium.

For higher flow regimes, the inertial effects must be taken into account by adding a Forchheimer-type term, leading to the following quadratic expression:

$$\frac{\Delta P}{L} = \alpha U + \beta U^2 \qquad (2)$$

Equation 2 can be rewritten in the form of Darcy's law (see eq. 4) in which the permeability depends on the velocity of the flow as $K_{app} = K(U)$ (see eq. 4).

$$U.S = -\frac{K}{\mu(\alpha + \beta U)}\frac{\Delta P}{L} \qquad (3)$$

$$K_{app} = \frac{K}{\alpha + \beta U} \qquad (4)$$

Figure 3 depicts the pressure drop dependence on the upstream velocity. One notes first that the pressure gradient shows a quadratic rather than linear dependence on the flow velocity, indicating that inertial effects can not be neglected. The pressure gradient is observed to increase, as expected, with the flow velocity but also to decrease with increasing cylinder diameter. This demonstrates the effect of the specific surface on the pressure head loss for constant porosity.

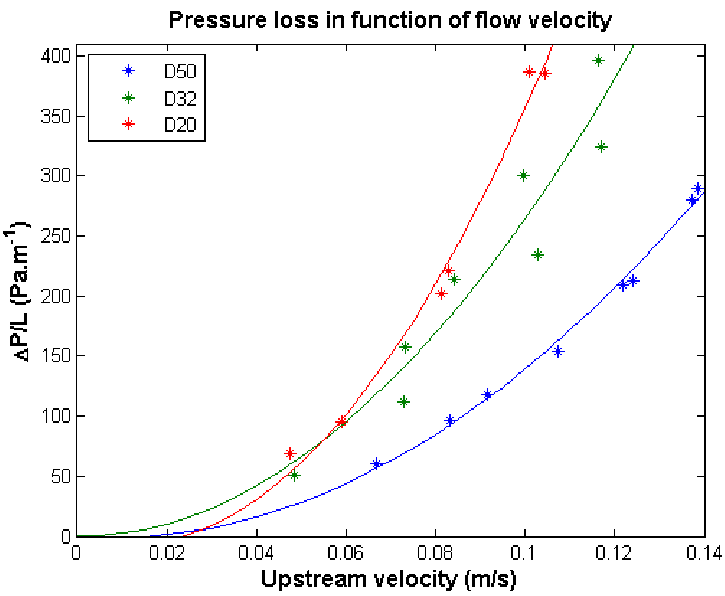

Figure 3. Pressure loss vs upstream velocity for the three cylinder diameters, stationary flow

In order to compare our experimental results with the theory, the rate of energy damping is computed as follows:

$$\varepsilon_D = \int_h F_d N_t U dh = N_t \int_h F_d U dh \qquad (5)$$

ε_D is the rate of dissipated energy calculated on the basis of distinct cylinders assumption, F_d is the drag stress, N_t is the cylinder number in the porous structure, U is mean velocity and h is water depth. This term of power loss corresponds to the integrand over depth of the local work exerted by the drag stress on the cylinders. The drag stress F_d=1/2×$\rho U^2 A C_d$ is defined on a cylinder of cross section A for a fluid density ρ. The C_d coefficient is empirically adjusted for each porous in order to match measurements. The value of 1.2 is suggested for a single smooth cylinder (MUNSON *et al.*, 1990).

The experimental dissipated energy is proportional to the head loss through the porous structure:

$$\varepsilon_D = \rho g h_L \tag{6}$$

where $h_L = \dfrac{(h_2 - h_1)^3}{4\mathrm{h}_1 h_2}$ is the head loss calculated from the upstream and downstream free surface elevation.

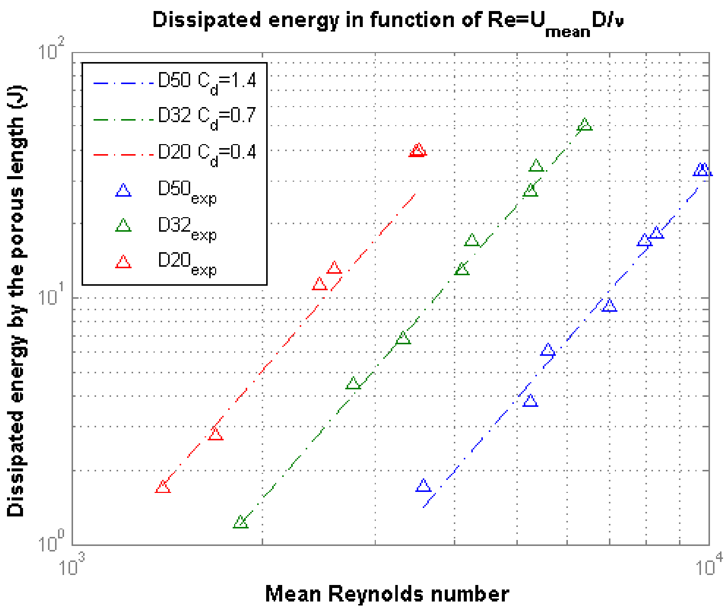

Figure 4. Dissipated energy as a function of the Reynolds number calculated upstream of the porous structure.

Figure 4 compares the experimental dissipated energy calculated from equation 6 with the best fit from theoretical expression (eq. 5). The drag coefficient is the empirical fitting parameter. One notes first the good agreement between measurements and fitted theory. The dissipated energy is observed, for a given diameter, to increase with increasing Reynolds number and, conversely, to increase with decreasing diameter for a given Reynolds number. This again highlights the role played by the specific surface on the flow dynamics. The slopes are very similar indicating that the dependency on the

Reynolds number tends to be independent on the diameter. The adjusted drag coefficients are shown to increase with increasing diameter, with C_d = 0.4, 0.7 et 1.4 respectively for D = 0.020, 0.032 et 0.050 m.

3.2 Reflection, transmission and damping of water waves

3.2.1 Theoretical approach

The theory proposed here to describe the wave behaviour through porous medium is based on a linear approach, i.e. the assumptions are made that wave amplitude is small and fluid flow derives from a velocity potential. Other typical hypothesis are that the characteristic scale of wave damping is much greater than the incoming wavelength and that wave amplitude is exponentially decaying that corresponds to a constant damping rate per unit length. The channel length is divided in three parts (j=1,2,3) respectively the upstream, the inner porous medium and the downstream domains. The abscissas origin corresponds to the beginning of porous medium. A stepwise method is used to solve this problem (REY *et al.*, 1992; REY, 1995). The velocity potential is computed for each domain using the following expression:

$$\Phi_j(x,z,t) = \varphi_j(x,z)e^{i(\omega t)} = A_j^{\pm} e^{\pm(ik_j x)} \cosh\left(k_{j,p}(z+h)\right) e^{i(\omega t)} \qquad (7)$$

with $k_j = k_{j,p} - ik_{j,d}$ the wave number, complex in porous medium with a dissipative term, and $\omega = 2\pi f = 2\pi/T$ the wave angular frequency. The unknowns are the coefficients $A_j^{\pm}$.. The dissipative term $k_{j,d}$ is assumed to be zero on each side of porous and is chosen in the form $k_{j,d} = k_{j,p}$ /n in the porous medium, where n corresponds to an attenuation rate by wavelength unit independent of the frequency. The evanescent modes, of significant contribution in the presence of bed discontinuities or discontinuity of the porous characteristics along the water column, are here neglected.

Considering the boundary conditions, the continuities of velocities and pressures at interfaces $x = 0$ and $x = L$ (YU & CHWANG, 1994) are written:

$$\varphi_i = S_r \varphi_j \quad et \quad \frac{\partial \varphi_i}{\partial x} = \gamma \frac{\partial \varphi_j}{\partial x} \qquad (8)$$

where the i is the index of upstream medium ($x \le 0$) and downstream medium ($x \ge L$), and j the porous index.

S_r is the medium reactance defined by eq. 9, with C_m the added mass coefficient. This coefficient is equal to zero in the domains upstream and downstream of the porous medium. Within the porous medium, C_m is used as the adjustable parameter to fit the theoretical model with experiments.

$$S_r = 1 + C_m \frac{1-\gamma}{\gamma} \qquad (9)$$

Finally, the general form of the relation dispersion (YU & CHWANG, 1994), keeping only the inertial effects, is:

$$\omega^2 S_r = gk_{j,p}\tanh(k_{j,p}h) \quad (10)$$

Thus, the wavelength in the porous structure which decreases while increasing S_r, depends only on the added mass coefficient C_m at given porosity γ.

3.2.2 Results: reflection and damping of the regular swell

Wave reflection by both porous structure and dissipating downstream beach as well as transmission through the porous media are measured to quantify the dissipation by the array of cylinders. Figures 5 to 10 show the evolution of reflection and transmission coefficients in the studied frequency range for each of the experiment. Solid lines and crosses represent the theoretical model predictions and experimental results, respectively.

Let us first look at the experiments results. One notes that, for a given length of porous structure, the transmission decreases with increasing cylinder diameter and increasing frequency. This latter trend is however only observed for frequency greater than 1 Hz. For lower frequencies, the transmission appears to be constant. This observation is discussed later on in the comparison between theory and experiments.

Focusing now on reflection coefficients, it is first observed that reflection over the dissipating beach is almost negligible in each of the considered cases. The reflection by the porous structure shows an oscillating character with respect to the frequency. Such oscillations are related to interference processes due to two successive jumps of medium index at boundaries in $x = 0$ and $x = L$. These oscillations are greater for large diameters and short porous structures, i.e. for lower dissipation and higher transmission. At high frequency, the interference-related oscillation patterns weaken and the reflection coefficient tends to a constant value, about 0.2, corresponding to an infinite porous medium.

The model has been calibrated with the above mentioned parameters using the high frequency experimental data where the decay of transmission coefficient with increasing frequency is well represented. Both adjustable parameters C_m and n play a different role in the theoretical modelling of wave dynamics. The added mass C_m does not affect the attenuation but controls the wave length in the porous medium. This parameter is thus adjusted to optimize the description of the oscillation patterns of the reflection coefficient in the frequency domain. At this step of the study, C_m is assumed to have a unique value independent of both cylinders diameter and porous structure length. The attenuation coefficient n mainly acts on the transmission through the porous structure via the damping term $k_{2,d}=k_{2,p}/n$ and, as such, has been fitted to best represent the decay of transmission coefficient for high frequency (see below for the discrepancy between model and experiments for the constant transmission frequency range). The best-fitted theoretical predictions are finally obtained with C_m=0.3 and n = 13, 20 et 25 for D = 0.020, 0.032 et 0.050 m, respectively.

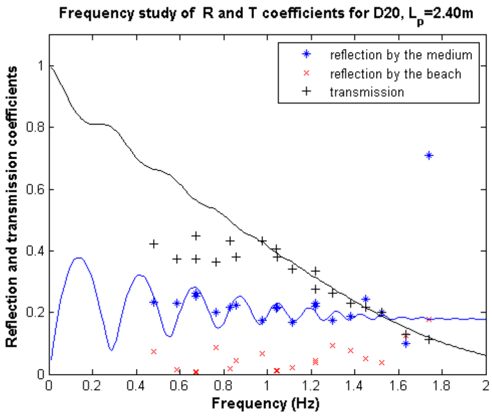

Figure 5. Reflection and transmission coefficients, L=2.40 m, D=0.020 m.

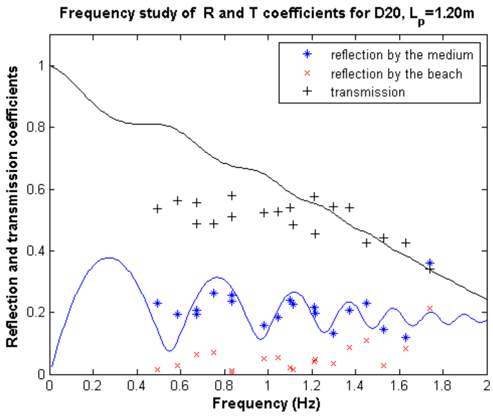

Figure 6. Reflection and transmission coefficients, L=1.20 m, D=0.020 m.

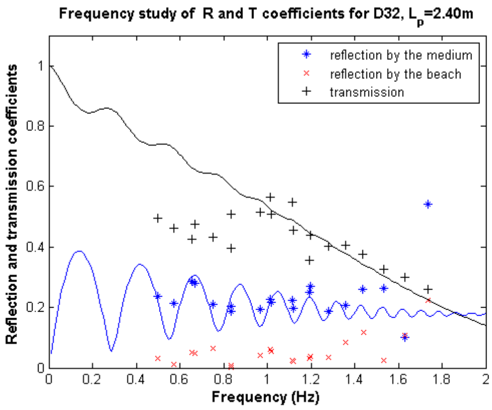

Figure 7. Reflection and transmission coefficients, L=2.40 m, D=0.032 m.

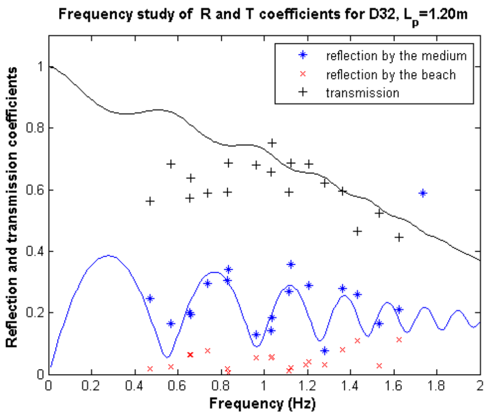

Figure 8. Reflection and transmission coefficients, L=1.20 m, D=0.032 m.

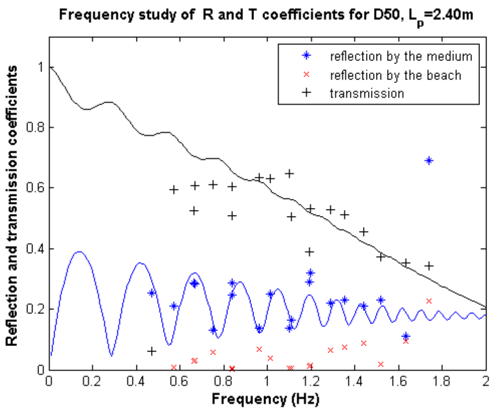

Figure 9. Reflection and transmission coefficients, L=2.40 m, D=0.050 m.

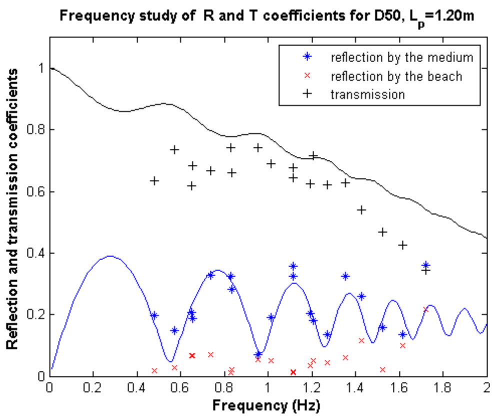

Figure 10. Reflection and transmission coefficients, L=1.20 m, D=0.050 m.

A good agreement is observed between calibrated theory and experiments for the reflection coefficient and its interference-related oscillations. Regarding the transmission coefficient, the model satisfactorily represents the observed decay for high frequency, but does not correctly describe the nearly constant transmission coefficient measured for frequencies lower than 1 Hz. Such discrepancy is expected to be related to the wave generation system: our wave maker does not allow a perfect control of wave amplitude in particular for low frequency. Measured wave amplitude for the cases discussed above varies from 0.015 to 0.03m. Additional test cases have thus been performed to better understand these issues including a study of amplitude influence (ranging between 0.015 and 0.055 m) for a constant frequency equal to 0.8 Hz, for the intermediate cylinder diameter and 2.40 m long porous structure.

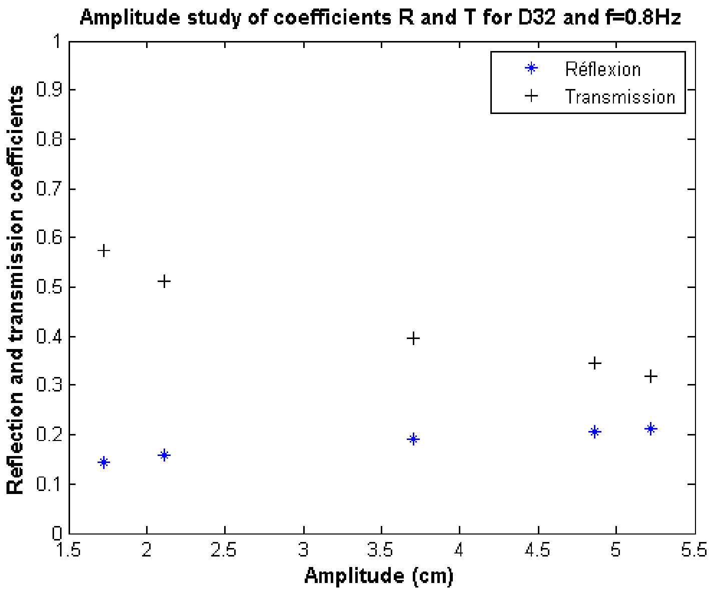

Figure 11. Study on amplitude of reflection and transmission coefficients

The results in Figure 11 show that wave amplitude has a much greater impact on transmission than reflection processes. The main trend is a clear decrease of transmission coefficient with increasing wave amplitude. For low amplitudes, the transmission coefficient order is 0.5 to 0.6 which is consistent with the nearly constant value observed during frequency study in the low frequency range for the same porous structure (see Figure 7). Thus it appears rather probable that at least part of the gap between theory and experiments transmission coefficient at low frequency can be attributed to the lack of experimental conditions control. Further technical and experimental works will be conducted to explore these issues.

4. Conclusions and prospects

The present study aims to experimentally analyse the influence of specific surface on the stationary flows and waves dynamics through a porous medium made of vertical cylinders. The stationary flows experiments have first shown the importance of inertial effects, which are well represented by including a quadratic term in the generalized Darcy's law (eq. 3). The main finding of our study is the demonstration of the role played by the specific surface both for stationary flow and wave experiment. The main trend is the greater the specific surface, the stronger the energy dissipation. The proposed wave model through porous structure highlights the importance of two key parameters: the added mass and the attenuation coefficient which have a significant influence on interference processes and wave dissipation/transmission, respectively. Once fitted to the experimental data, an overall satisfactory agreement is found between theoretical model and measurements. Two regimes are however observed in the evolution of transmission coefficient through the frequency range. At high frequency, the transmission monotonically decays with increasing frequency, which is in fair agreement with the model prediction, while for longer waves a nearly constant value of transmission coefficient is observed. This latter trend is probably to be related to variations of wave amplitude and additional work have to be engaged to address these issues.

Further model improvements mainly concern the implementation of a new attenuation term based on the energy dissipation by drag stress rather that the current exponential decay term. The wave amplitude decrease will be of the form $1/(1+Bx)$, B being independent of the location in porous medium. Another interesting prospect of the present research work is the comprehensive analysis of similitude scaling laws. For instance, the study of reduced porous model should imply a specific surface variation together with a regime change even if the porosity is constant.

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