



Waves and currents propagation through porous media: model experiments and scale effects

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Abstract:

This note is related to the scaling effects of porous media consisting in emerging vertical cylinder array. Wave and current experiments were carried out in a 10m-long flume. Three cylinder diameters are considered in order to study the role of the specific surface while keeping the porosity constant. Both porous media length and water depth are selected to scale with the cylinder diameters. The collected data show the influence of the specific surface on interference process via the reflection coefficient. Then, a theory of wave amplitude attenuation is developed using a force expression based on the work of O'BRIEN & MORISON, 1952. This model is calibrated with drag and inertia coefficients. Finally, scaling emphasizes the importance of the flow regime within the porous media to verify flow similarity.

Keywords: Porous structure, specific surface, wave, current, scale effects, reflection, dissipation.

1. Introduction

Physical model in basin or wave flume are generally used to mimic fluid flow dynamics using scaling laws. In this context, several studies exist concerning the scale effects through various porous structures (DELMONTE, 1972; PEREZ-ROMERO *et al.*, 2009; ANDERSEN *et al.*, 2011; ALTOMARE & GIRONELLA, 2014; and references herein). However, the influence of specific surface is rarely explicitly highlighted for scaling analysis although this parameter changes with the scale even if the porosity is constant. This work presents a study of scaling effect comparing three model porous media keeping the porosity constant while the specific surface, defined as a fluid-solid surface contact per volume unit (GUYON *et al.*, 1991), varies with the cylinder diameter.

2. Experimental set-up

The laboratory flume (SeaTech, University of Toulon, France) used for the experiments is 10 m long, 0.30 m wide and 0.50 m high. The model porous media are made of a regular array of emerging vertical cylinders of constant diameter. The cylinders are regularly disposed along two perpendicular axes forming a 45° angle with the longitudinal axis. The entire experimental set-up, including the positioning of sensors, are detailed in the previous study dealing with regular waves propagation through porous media (ARNAUD *et al.*, 2014). Regular waves of frequency in the range 0.2-1.8 Hz are considered.

Table 1. Summary of experiment conditions.

<i>Cylinder diameter D (m)</i>	<i>Medium porous length L (m)</i>	<i>Water depth h (m)</i>	<i>Specific surface s (m⁻¹)</i>	<i>Porosity γ</i>
0.050	1.80	0.36	22	0.7
0.032	1.15	0.23	33	0.7
0.020	0.72	0.14	52	0.7

3. Scale effects on the wave reflection and transmission

3.1 The linear model

The linear potential theory is used to describe the wave propagation in porous media. Details are presented in ARNAUD *et al.* (2014). The velocity potential for each domain is expressed by the following equation:

$$\Phi_j(x, z, t) = \varphi_j(x, z) \sin(\omega t) = \frac{a_j^\pm \omega \cosh[k_j(z+h)]}{k_j \sinh(k_j h)} \sin(\omega t \pm k_j x) \quad (1)$$

where a is the wave amplitude, k_j is the wave number and $\omega=2\pi f=2\pi/T$ is the angular frequency. Moreover, the influence of the evanescent modes, which appear in the presence of vertical discontinuities, was found to be negligible in the present work. The wave amplitude coefficients a_j^\pm vary within the porous medium with the longitudinal propagation due to the energy dissipation process detailed in the following sub-section (3.2). Damping is neglected on both parts of the porous medium thus the coefficients a_j^\pm are constant in these two domains. The present problem is solved using an integral matching method of the pressure and momentum continuity conditions at the porous vertical interfaces $x=0$ and $x=L$ (YU & CHWANG, 1994):

$$\varphi_i = S_r \varphi_j \quad \& \quad \frac{\partial \varphi_i}{\partial x} = \gamma \frac{\partial \varphi_j}{\partial x} \quad (2)$$

where index i corresponds to either upstream ($x \leq 0$) or downstream ($x \geq L$) domains on each side of the porous medium and index j to the porous medium. The reactance S_r (eq. 5) involves the added mass coefficient C_m adjusted to fit the theoretical model with

the interference process of experimental data. The general form of the dispersion relation keeping only the inertial effects (YU & CHWANG, 1994) is written:

$$\omega^2 S_r = g k_j \tanh(k_j h), \text{ with : } S_r = 1 + C_m \frac{1-\gamma}{\gamma} \quad (3)$$

where γ is the media porosity and g is the gravity acceleration. $S_r = 1$ for upstream and downstream domains. The relation dispersion defined in eq. (3) implies that the wavelength in the porous medium depends on the added mass C_m .

3.2 Wave amplitude evolution

The energy dissipation rate is assumed to be the sum of the drag effect of each of the cylinders. This rate is calculated along an elementary length Δl with the hypothesis $L \gg \Delta l \gg D$. The drag stress due to one cylinder is given by (eq. 4).

$$F_d = \int_{-h}^0 \frac{1}{2} \rho C_{d,s} D U |U| dz = \frac{1}{8} \rho C_{d,s} D a^2 \omega^2 \frac{2k_j h + \cosh(4k_j h)}{k \sinh^2(k_j h)} \quad (4)$$

where ρ is the fluid density, $C_{d,s}$ is the drag coefficient for a single cylinder, D is the cylinder diameter, U is the fluid velocity, h is the water depth and a is the wave amplitude a_j . The dissipated energy ΔE_N (eq. 5) related to drag force is defined as the integrand over a wave period T_w of F_d .

The cylinders number is calculated using the porosity parameter defined by:

$$N = (1-\gamma) \frac{4 \Delta l B}{\pi D^2} .$$

$$\Delta E_N = N \int_0^{T_w} F_d U dt = -\frac{16}{9\pi} (1-\gamma) \rho C_{d,s} \frac{a_j^3 \Delta l B}{D} g \tanh(k_j h) \left(\frac{3}{\sinh^2(k_j h)} + 1 \right) \quad (5)$$

where B is the porous width.

Moreover, another expression of dissipated energy is provided by the balance of energy flux between upstream and downstream vertical surface of this element of length Δl .

$$E_N = \rho g C_g B T_w a_j \frac{\partial a_j}{\partial x} \Delta l, \text{ with : } C_g = \frac{\partial \omega}{\partial k} = \frac{g}{2\omega S_r} \left(\tanh(k_j h) + \frac{k_j h}{\cosh^2(k_j h)} \right) \quad (6)$$

C_g is the group velocity. Finally, the behaviour of wave amplitude in porous media can be obtained by equating both expressions of dissipated energy (eq. 5) and (eq. 6).

$$\frac{\partial a_j}{\partial x} = -C_{damp} a_j^2, \text{ with : } C_{damp} = -\frac{16}{9\pi^2} (1-\gamma) C_{d,s} \frac{k_j}{D} \frac{3 + \sinh^2(k_j h)}{\sinh(k_j h) \cosh(k_j h) + k_j h} \quad (7)$$

Assuming $C_{d,s}$ does not depend on the position x , we obtain : $a(x) = a_0 / (a_0 C_{damp} x + 1)$. For the present, $a^-(x) = a_0 / (a_0 C_{damp} x + 1)$ and $a^+(x) = a(L) / (a(L) C_{damp} (L-x) + 1)$ with a_0 is the wave amplitude at the upstream medium for the incoming wave, downstream for the reflected wave.

4. Results and discussion

The presented results focus on wave reflection through the porous media versus a dimensionless parameter kh . Experimental data (symbols) and model previsions (lines) are presented in Figure 1 for the three cylinder diameters. The reflection coefficient shows an oscillating behaviour due to interference process between the two successive jumps of medium index at the porous interfaces $x=0$ and $x=L$. The experimental data show a varying pattern of these oscillations for the three cylinder diameters. Indeed, for the smallest cylinder diameter the number of oscillations is more important than for the two other diameters. However, the reflection coefficient fluctuate is the same range (0.05-0.4) for the three diameters at equivalent kh . The results of the theoretical model, calibrated on the interference process ($C_m=0.3$) and on the wave damping ($C_{d,s}$), give a good representation of reflection coefficients excepted for the smallest diameter. Indeed, the number of oscillations is more important for experimental data than for model previsions but the amplitude range is well predicted.

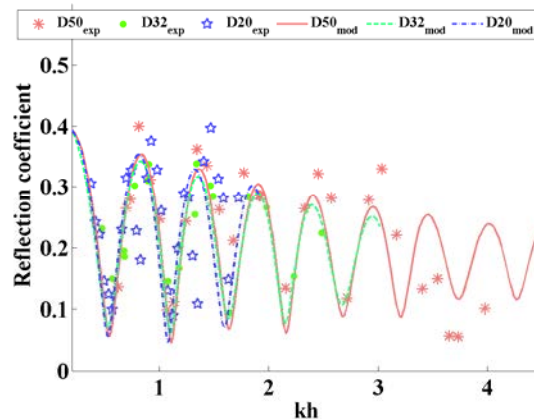


Figure 1. Reflection coefficient versus kh for $D=0.050m$ (red), $D=0.032m$ (green) and $D=0.020m$ (blue).

The major differences between the three cylinder diameters can be explained by including our results (Figure 2) in the regime diagram proposed by GU & WANG (1991) which depicts the Reynolds number $Re = UD/\nu$ as a function of the ratio between the Reynolds number and the Keulegan-Carpenter number $Kc = UT_w/D$. It is first observed that the regimes reached during the present experiments are close to a transition regime. More finely, it appears that for the smallest diameter, the three forces (laminar, turbulent and inertial) are equivalent while for the largest diameter where the laminar effects tend to be negligible for most cases. It is also noted that, for the smallest diameter, water depth is very shallow and the bottom viscosity might become important.

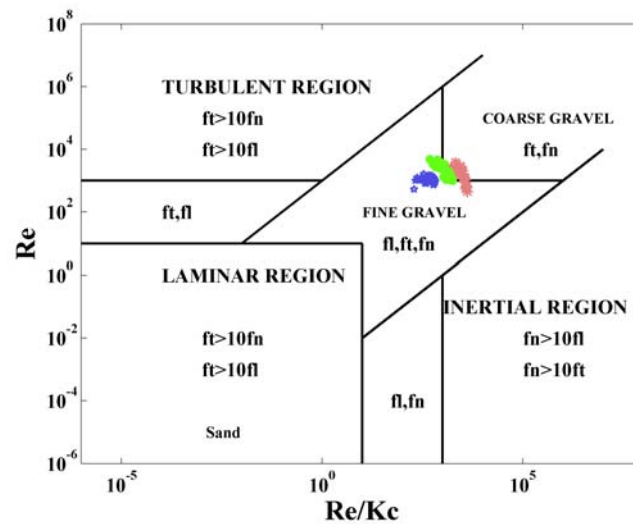


Figure 2. The resistance forces (GU & WANG, 1991) for $D=0.050\text{m}$ (red), 0.032m (green) and 0.020m (blue).

5. Conclusion

This study of scale effects on porous media presents good agreements between experimental data and model prediction. The scaling law study shows the influence of the added mass expressed with the oscillation patterns of reflection coefficient for the three porous media. The energy dissipation due to the propagation through arrays of cylinders is almost similar for the large and intermediate diameters of cylinders in porous media. The limit of results concerns particularly the smallest scale. Indeed, the dissipation through piles is not mostly responsible of wave damping because the water depth is too weak and the bottom effect is not anymore negligible. Further additional studies of scale models are planned to evaluate the irregular wave effects as well as 3D effects.

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