Numerical modelling of porous flow in permeable coastal structures

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Abstract

The modelling of the flow within a porous coastal structure is of great importance to determine its functionality and stability. In this paper it is shown how a commercial solver, FLOW3D, is used to model the porous flow. The model is validated by means of a test case. An outline of future work is given.

I. Introduction

Artificial and natural porous structures such as rubble-mound breakwaters are of great interest in coastal and harbour engineering since they are capable to largely dissipate the incident wave energy by friction inside the porous structure.

To determine the functionality and the stability of this kind of structures, it is important to have an accurate knowledge of the flow motion in and around the porous structure and the corresponding pressure and velocity fields.

In recent years, significant progress has been achieved in the field of numerical modeling of wave and permeable structure interaction. The modeling is based on the coupling of two models describing the flow acting on the structure and trough the porous structure.

II. Porous flow model

Due to the complexity of the internal geometry of a porous medium it is difficult to determine the intrinsic flow field inside the pores. In practice, the characteristics of the flow are determined in large portions of the porous structure and an averaging process is used in the analysis of the flow.

The frictional forces exerted by the porous media are commonly described by the Forchheimer equation, which in the case of nonstationary flow takes the form:

$$I = a \cdot u + b \cdot |u| \cdot u + c \cdot \frac{\partial u}{\partial t} \qquad (1)$$

where I is the pressure gradient; a , b and c are dimensional coefficients; and u is the discharge velocity. On the right-hand side of (1), the first term refers to the laminar and the second term to the turbulent contribution. The last term is the inertia term accounting for the convective macroscopic acceleration. The friction coefficients a (s/m), b (s^2/m^2) and c (s^2/m) are dimensional and contain several parameters determined by the characteristics of the porous medium, such as porosity, grading, aspect ratio or orientation of stones. Many empirical and semi-empirical formulae have been derived from measurements. For more information on these coefficients, see eg. Van Gent [1] or Burcharth and Andersen [2].

III. Numerical modelling

A. *Governing equations*

A commercial solver, FLOW3D, is used to model porous flow. It is based on the Navier-Stokes equations and makes use of the Volume-of-Fluid (VOF) method to track the free surface. The flow is described by the general Navier-Stokes equations:

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$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial u_i}{\partial t} + u_j \cdot \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + g_i \tag{3}$$

where ν is the molecular viscosity, u_i is the ith component of the instantaneous velocity in the pores, p the instantaneous effective pressure and g_i the ith component of the gravitational force.

To account for the porous flow resistance, the momentum eq. (3) is modified by adding a drag term, taking the form of the Forchheimer eq. (1).

B. *Test case*

A 1-D flow through a porous sample with mean stone diameter d_{50} and porosity n is considered. Three different samples are used, of which the coefficients a and b in (1) were experimentally determined by Burcharth and Christensen, and shown in Table 1. The inertial coefficient c was discarded in this case (steady flow conditions).

Table 1. Sample properties

sample	**d_{50} [mm]**	**n [-]**	**a [s/m]**	**b [s^2/m^2]**
1	20.1	0.451	2.80	89.54
2	38.5	0.471	2.31	36.86
3	18.1	0.391	7.55	140.57

In the numerical model, a porous sample (length 0.4 m and height 0.1 m) is located in the center of a 'pipe' of 1 m length. A uniform grid spacing of 0.025m in horizontal and 0.1 m in vertical direction is used. The flow velocity varies between 0 and 1 m/s, and must satisfy the condition of a fully turbulent regime ($Re=V.d_{50}/\nu > 3000$) in which the coefficients were experimentally determined.

When representing the proportion of pressure gradient to the flow velocity I/u as a function of u, a linear relationship between I/u and u is expected. This is confirmed by the numerical model (see Figure 1).

It is concluded that the numerical model is able to correctly predict the flow losses in a porous medium, using the Forchheimer equation.

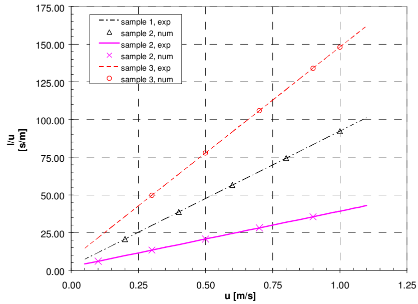

Figure 1. Comparison between experimentally and numerically determined pressure gradient *I/u* for 3 different porous samples

IV. Conclusion & Future Work

A numerical model, FLOW-3D has been used to model porous flow. The porous flow resistance is modeled using the Forchheimer equation, included in the momentum model equations.

In order to investigate the wave interaction with coastal structures, the model is adjusted to operate as a numerical wave flume. The validity of the current porous flow models for rigid porous media with macroscopic pores, such as artificial block layers in rubble mound structures requires further analysis. In the near future, tests will be carried out to determine the performance of the model in case of large porosities and stone diameters.

References

[1] van Gent, M.R.A. (1993). Stationary and oscillatory flow through coarse porous media. Communications on Hydraulic and Geotechnical Engineering. TUDelft. ISSN 0169-6548. Report 93-9

[2] Burcharth, H.F and O.H. Andersen (1995). On the one-dimensional steady and unsteady porous flow equations. Coastal Eng. 24: 233-257