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Wave-porous structure interaction modelling using Improved Meshless Local Petrov Galerkin method

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ABSTRACT

This paper presents the application of the Improved Meshless Local Petrov Galerkin method with Rankine source (Sriram and Ma, 2012) Sriram and Ma (2012) for wave interaction with porous structure model. The mathematical model is based on a unified governing equation that incorporates both pure fluid and porous region. The porous flow model is based on the empirical resistance coefficients. The interface between the pure fluid and porous region is numerically treated using background nodes having the porosity information and interpolated over the particle using simplified finite difference interpolation method. The model is validated using the available experimental results for wave damping over the permeable bed. The developed model is used to analyse the different shape of the seawall such as flaring shaped seawall, recurve wall and vertical wall. Then the validated model is used for analysing the overtopping amount due to the effect of porous layer in-front of the different sea wall profile. Numerical expression for overtopping amount has been provided for the different configurations from the numerical model.

1. Introduction

Wave structure interaction plays an important role in coastal hydrodynamics. The wave force acting on a structure depends on the properties of the structure, because most of structures in coastal engineering are porous in nature like Breakwaters, sea wall, groins and so on. Sometimes the structure itself may be impermeable like concrete sea wall, but it will be defended in-front by rubble mound structures or some kind of porous structures. Since, wave energy dissipation is higher in the case of permeable structure, so the total forces acting would be lesser in magnitude than impermeable structure. This would be difficult to incorporate in the design; hence, coastal engineers normally test the structure in the physical model after the preliminary design from the empirical equations. In physical models, the structure is scaled down and constructed in a wave facility, including core material, filter, and armour layers. Since the small scale model has higher viscosity and friction between stones normally remedial measures such as painting the stones are done to overcome the scale effects. In recent years, due to the computational power and techniques, the present state of the art numerical models by assuming the structure to be impermeable are well established. However, these models give more conservative results, since in reality not many coastal structures are completely impermeable. In order to carry out the simulation more accurate, research was carried out to incorporate porous effects in models.

Governing equation for porous flow was initially suggested by the classical work of [8] in which the pressure gradient of the flow was found to be directly proportional to the flow velocity by introducing the permeability coefficient, which for higher value means higher fluid flow in the porous region. Darcy's law was valid for laminar flows having less permeability. Later, [12] introduced a non-linear term to account for turbulent flows in which a non-linear drag force is directly proportional to the square of fluid velocity. The porous flow model was extended by incorporating virtual mass coefficient in the local acceleration term [32]. Recently, [24] considered the transitional flow by incorporating the drag force proportional to square root of velocity. Thus, for modelling the wave porous structure, in the governing equations additional resistance terms such as the linear drag coefficient representing the laminar flow, non-linear drag coefficient representing the turbulent flow, coefficient for the transitional flow and virtual mass coefficient for inertia terms were incorporated. [5] compared the different porous flow equation which was extended and generalized by [24] and as follows.

$$\nabla p = a\vec{u}_D + b.|\vec{u}_D|\vec{u}_D + c.\sqrt{|\vec{u}_D|}.\vec{u}_D \qquad (1)$$

where ∇p is the pressure gradient,$\vec{u}_D$ is the Darcian Velocity, a is the linear drag coefficient dominating in laminar flows, b is the non-linear drag coefficient dominating in turbulent flows and c is

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the transitional coefficient dominating in transitional flows. If in Eq. (1), *b* and *c* are zero, then the equation reduces to Darcy's law. In numerical modelling of wave porous structure interactions, the normal practice is to incorporate the porous coefficient as a drag form (which will be discussed in Section 2), which is obtained from the experimental measurements.

The numerical studies on the wave porous structure can be carried out in two different ways,

i) Coupling of pure fluid and porous flow equations, in which the fluid flow was solved for Navier Stokes equation and porous flow with different porous flow model, after which the interface was coupled by matching the flow properties. It can be explicit, implicit or iterative in nature.
ii) Based on unified or single governing equations to model both porous structure and fluid flow.

The former is computationally expensive as one need to solve this iteratively at each time step. Various numerical methods were used for solving the porous flow equation. Both mesh and meshless methods are used.

In mesh based methods, Finite element method was used by [31], Finite difference method was used by [21] and Finite analytic method was used by [17,18]. [20] developed a two phase model (fluid and air) based on the volume of fluid (VOF) method, that was extended to include interaction with porous media. Further, developments are reported in Karim et al. [44] and [14]. The model presented in [22] was developed in [23] based on VOF, where overtopping of rubble mound breakwaters was investigated. In Manuel del Jesus et al. [45], a new model development was presented by using resistance terms. A detailed description of this model was reported in [25] for model formulation and validation, respectively. Examples of the use of OpenFOAM for wave structure interactions such as breakwaters, modelling of scour around structures can be referred in [25], [39]. Further, application of OpenFOAM in coastal engineering was presented in [15] and [16].

All the above methods are based on Eulerian framework. On the other hand, Meshless methods are quite popular now-a-days that avoids the use of mesh. Notable works are carried out in Incompressible Smooth Particle Hydrodynamics (ISPH) by [37], where porous flow is solved separately, Incompressible smooth particle hydrodynamics in porous medium (ISPHP) by [1] and Weakly compressible smooth particle hydrodynamics (WCSPH) by [34]. In all these methods, the coefficients used in the governing equations are different. In handling, the governing equations using any numerical methods, interface treatment plays an important role, since one need to satisfy the boundary conditions between pure fluid and porous region. When using two set of governing equations for fluid and porous region, the flow properties, such as velocity and pressure needs to be matched. Notable works can be seen in [37] using SPH. In particle based method while using the unified governing equations, [1] used background nodes having the porosity values and then it is interpolated based on SPH interpolation for each particle. The background nodes are made finer so that more porosity information can be obtained. The position and porosity information was updated at each time step. [34] suggested a transition zone in which the porosity value of the background nodes are linearly varying. The method suggested by [34] though being the simplest to be incorporated, the limitation is that it requires special treatment of porosity or velocity using higher order interpolation. Sometime these approximation, reduce the accuracy of the results and compromise in the flow properties near to the interface. Further, background nodes usage throughout the domain may increase the computation time. The lower order SPH interpolation carried out for each particle to update the porosity value at every time step leads to accumulation of error. The meshless methods so far attempted are based on strong form of equation for the unified equation; that may not handle discontinuous flow. In our previous publications, Improved Meshless Local Petrov Galerkin Method with Rankine source (IMLPG-R) is applied for sloshing, wave-elastic structure interactions, breaking waves and so on [27,29,30]. In IMLPG_R, the local weak forms are being used. The weak forms are generally obtained by the weighted residual method, which provides a way to transforms partial differential equations to an integral form. It is well known that the integral form of equations can handles the discontinuity well compared to differential equations which assumes the variables are continuous. Further, this integral equation helps to "smear" out the possible error induced by the function approximations, so as to stabilize the solution and improve the accuracy. The integral operation can also reduce the requirement for the order of continuity on the approximate function. Thus, this paper extends the IMLPG_R based on weak formulation to solve the unified governing equation to handle the wave-porous structure interactions.

By using the developed numerical model, new type of sea walls were analysed in this paper. There are lot of research works undergone in the profile of sea wall to reduce the effect of overtopping. [19] through experimental studies suggested a new type of sea wall profile Flaring Shaped sea wall (FSS) in which different circular curves was fitted in such a way that the wave is smoothly guided back towards the sea side. [2] has done experimental investigation of this FSS wall and compared its performance with two other curved wall namely Galveston and Cubic spline curved wall. [38] has done large scale experiments on Recurve fitted above the vertical wall, where three circular curves of different radius and height were used. [33] analysed these three types of recurve wall for the impact pressure and overtopping performance in large scale and reported higher wave energy dissipation for large recurve. Thus, FSS and Recurve profile with large curve was taken for further analysis in this paper to understand the overtopping performance with and without porous structure in-front of this wall.

The main objective of the present paper are: (i) implementation of the porous flow models in a meshfree weak formulations (ii) numerical algorithms to treat the interface boundary in weak formulations and (iii) Comparison between different resistance terms used in porous models.

The paper is arranged in the following order. The governing equations in weak formulations as well as the numerical methodology are first reported. Initially, the model is validated with the large scale experiments on wave-recurve wall as well as with the available literature for porous structure. Further, different porous model effects will be discussed. Then, systematic study is being carried out for different types of sea wall on wave overtopping effects without any porous structure in front. Later, a porous structure introduced in-front of the sea wall to investigate the reduction in overtopping amount; appropriate numerical expressions for wave overtopping are obtained and reported.

2. Governing equation and boundary conditions

As reported earlier, the governing equation for the porous model is a modified Navier Stokes equation based on Darcy's law, Brinkman's effective viscosity, Forcheimmer's linear and non-linear drag force term and Lin's transitional velocity term along with Polubarinova −kochina inertia coefficients, which is given as,

$$\nabla.\vec{u}_D = 0 \tag{2}$$

$$\frac{C_r}{n_w}.\frac{D\vec{u}_D}{Dt} = \frac{-1}{\rho_w}\nabla P + \vartheta_{eff}\nabla^2\vec{u}_D - a\vec{u}_D - b\vec{u}_D|\vec{u}_D| - c\vec{u}_D\sqrt{\vec{u}_D} + \vec{g} \tag{3}$$