### Numerical analysis of wave-induced current within the inhomogeneous coral reef using a refined SPH model

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**Abstract:** The effects of reef permeability on the spatial distributions of wave-induced current inside and outside the inhomogeneous coral reef body are investigated using an improved weakly compressible smoothed particle hydrodynamic (WCSPH) mixture model. The governing equations are formulated based on the two-phase mixture theory without considering the solid phase motion in terms of the intrinsic velocity and fluid density. The developed WCSPH mixture model is firstly validated by comparing the predicted results with the corresponding available data for Darcy seepage flow in a U-tube with permeable soil, wave damping over a permeable seabed and wave transformation over a permeable reef. The validated model is then applied to study the spatial distributions of wave-induced current inside and outside the permeable reef body with different porosity and porous layer thickness. Finally, a parametric study is carried out to investigate the effects of different porosity distribution types on wave-induced currents.

**Keywords:** WCSPH mixture model; Reef permeability; Wave-induced current; Inhomogeneous porous media; Turbulent model

#### Introduction

Coral reef is composed of coral framework, cavities and detrital material of assorted sizes, and usually develops to be an inhomogeneous porous structure under the effects of diagenesis and bioerosion. The reef permeability effect on wave dispassion is known to be significant in shallow water areas (Buckley et al., 2016; Hearn, 1999; Lowe et al., 2005; Symonds et al., 1995). The flow within the porous reef body can also have a significant influence on the dynamic and ecological environments of coral reef (Hearn, 2011; Lowe et al., 2008; Oberdorfer and Buddemeier, 1986; Parnell, 1986). However, the flow structures within the porous layer and their relations with porosity distribution remain largely unknown, which severely hinders the sustainable management of coral reef based on the understanding of its full hydrodynamic environment and ecological health.

The commonly adopted approach to quantify pore flow through the porous reef body is based on macroscopic continuum concept in which the flow properties are averaged over a volume scale much greater than that of a single grain (del Jesus et al., 2012; Higuera et al., 2014; Hu et al., 2012; Karunarathna and Lin, 2006; Lin and Karunarathna, 2007). In these models, there are three forces acting on the porous flow: inertial force, linear and nonlinear drag forces. The latter two forces are commonly described by the Forchheimer equation with the porosity of the porous media and average grain diameter (Liu et al., 1999; Van Gent, 1995).

Recently, Zhu et al. (2019) proposed an analytical solution for wave setup over the platform reef-flat and found that wave setup decreased with the increase of reef porosity and porous layer thickness but is insensitive to the mean diameter of the particles made up the porous reef body. To overcome the various limitations of the analytical model and to describe fully the flow fields within and outside the porous layer, a Navier-Stokes (N-S)-based porous model is required to solve this problem, especially for the case involving violent wave breaking over the coral reef with a steep reef-face and a complex reef topography in the deep-water area (Wen et al. 2018a). The model also needs to take into account the fact that coral reefs may have a wide range of porosity values in space because of the complex structures of the benthic organisms and the reef limestone. The porosity value near the bottom is usually small, where internal cavities have been infilled with detrital material of assorted sizes, while it is larger at the top due to the branching of coral framework (Cabioch et al., 2010).

Among the numerical methods based on N-S equations, the meshless particle methods (e.g. Smoothed Particle Hydrodynamic method and Moving Particle Semi-implicit method) have some advantages compared with the grid-based methods (Gotoh and Khayyer, 2018). The specific free surface capturing techniques are no longer necessary due to the Lagrangian framework of particle method. Moreover, the complicated reef morphology can be easily treated because of the adaptivity of partile method. In recent decades, particle methods have been greatly improved on enhancement of accuracy (Khayyer and Gotoh, 2011; Khayyer et al., 2017, 2019a, 2019b; Meringolo et al., 2019; Wang et al., 2019), and successfully used to study a number of fluid mechanic and fluid-structure interaction problems (Altomare et al., 2014; Bouscasse et al., 2013; Crespo et al., 2017; Harada et al., 2017; He et al., 2018; Khayyer et al., 2009, 2018a; Liu et al., 2014; Ming et al., 2016; Shao and Ji, 2006; Shi et al., 2017).

Recently, several SPH models can be found in the literature that are specially designed to study wave interaction with porous media. The first incompressible SPH (ISPH) porous model was proposed by Shao (2010). In his model, the computation of free and porous fluid regions was carried out separately and marching conditions were used at the interface between the two flow regions. Similar approach was recently taken by Zhou and Dong (2018) involving different matching conditions. To avoid the use of match conditions and solve the flows inside and outside the porous regions more efficiently, Akbari and Namin (2013) treated the interface as a transformation zone rather than a line and prescribed a series of background points with porosity information. By adopting similar idea, Gui et al. (2015) proposed a more straightforward interface treatment method in which Kernel-based averaging was performed in the transformation zone to smoothing the pressure field. More recently, Khayyer et al. (2018b) developed a novel projection-based SPH porous model on the basis of mixture theory and by reformulating the governing equations based on the volume fraction concept.

The aforementioned porous models are all based on the assumption of fluid incompressibility and need to solve the Poisson pressure equation, which is inconvenient to use the parallel computing technology. As an alternative to ISPH model the weakly compressible smoothed particle hydrodynamic (WCSPH) models are more popular as in these models the fluid pressure is explicitly calculated by the state equation, which enables parallel computing and results in less computational costs for the real world problems with large dimensions (Crespo et al., 2015; Molos et al., 2015; Rogers et al., 2011; Wen et al., 2016). Ren et al. (2014, 2016) developed a WCSPH porous flow model based on the Volume Averaged and Favre Averaged Navier-Stokes (VAFANS) equations and showed the importance of turbulence flows at the porous interface of the rubble mound breakwater. Recently, Akbari and Taherkhani (2019) used a similar model to study wave interaction with a composite breakwater located on permeable bed. Based on the MPI-OpenMP technology, Wen et al. (2018b) extended Ren et al.’ (2016) 2D model to a 3D model and studied wave interaction with a detached shore-parallel breakwater of two-layer porous media. Utilized the concept of mixture theory, Peng et al. (2017) developed a porous model without considering the turbulence effect. In their model, the common Tail equation is directly adopted to relate the pressure to the local density of water although strictly speaking the equation is not applicable to the mixture model since the bulk modulus is variable for the porous media with variable porosity (Shi et al., 2017). Moreover, the density diffusion form they have used cannot maintain the totally volume conservation (e.g. overestimating the free surface elevations during a long-time simulation), which have been addressed by Antuono et al. (2012) and Wen et al. (2018c). However, all these studies are limited to the homogeneous porous media without considering the effects of spatial variation characteristics of the permeability of porous media on the pore flow distribution.

As to the numerical solutions of SPH equations, the apparent density rather than the real fluid density was used both in Akbari’s (2014) ISPH porous model and Ren et al.’s (2016) WCSPH porous model. It requires the fluid particles that go into the porous media to change their densities from  to  ( represents the porosity of the porous media) and the particle spacing is correspondingly changed from  to . Although this approach is numerically convenient to implement it may lead to the numerical instability especially for the cases with small porosity. The changeable particle spacing also requires the use of varying smoothing length to attain the consistent particle-based interpolations inside and outside the porous media, which may affect the overall conservation properties of the results (Oger et al., 2006).

In this work, a WCSPH porous model is developed which solves for the intrinsic flow velocity instead of Darcy velocity as in Ren et al.’s (2016) model. The actual fluid density rather than the apparent quantity is used as well as a constant smoothing length. The local porosity is evaluated according to the volume fraction of surrounding solid phase particles, which enables the developed model to be capable of simulating fluid flow interaction with the inhomogeneous permeable structure. The drag force by the solid skeleton of porous media on the fluid flow is calculated using the well-validated linear and nonlinear resistance force form proposed by Du Plessis (1994), which is different from the forms used in the porous models of Khayyer et al. (2018b) and Peng et al. (2017). The Macdonald-Tail equation instead of the common Tail equation is used here to consider the variability of the bulk modulus in the mixture model following Shi et al. (2019), who have developed a two-phase model for massive sediment motion by using a complicated drag force form to represent the interphase force between the sediment phase and the fluid phase. A volume-conservative density diffusion form is also introduced in the present model. The turbulent effect is taken into account by the sub-particle-scale (SPS) turbulence closure scheme proposed by Gotoh (2001). The developed model is firstly validated against available data of Darcy seepage flow in a U-tube with permeable soil, wave damping over a permeable seabed and wave transformation over a permeable reef [topography](http://youdao.com/w/topography/#keyfrom=E2Ctranslation). It is then applied to study systematically the effects of porosity value and spatial variations on wave-induced current over a porous coral reef.

This paper is organized as follows: After the Introduction section, the WCSPH mixture model is briefly described. Section 3 contains the model validation by analytical solution, experimental data and other numerical results. Section 4 presents the results and discussions of the predicted wave-induced currents through a permeable reef under various changing porosity conditions. Finally, the main conclusions are summarized.

#### WCSPH mixture model for porous flow

#### Governing equations for WCSPH mixture model

Based on the standard two-phase mixture theory as can be found in Drew (1983) and Shi et al (2019), the continuity and momentum equations for the fluid phase in Eulerian form can be expressed as

 

 

where ** and  are the intrinsic fluid density and pressure,  is the volume fraction of fluid phase and is usually named as the porosity of porous media,  and  denote the intrinsic fluid velocity components and the indices *i*, *j* = 1, 2, 3 represent the coordinate directions. The viscous stress tensor  is written as

 

where  refers to the kinematic viscosity of water. Following Khayyer et al. (2018b), the body force  is composed of gravity, buoyancy and the resistance force:

 

in which the last term on the right hand side of the equation represents the resistance force acting on the porous flow by the solid skeleton. The equations for the solid phase are not required here as the solid skeleton of porous media is fixed in the present model.

The Favre-averaged continuity and momentum equations can be written as the following forms:

 

 

where – indicates a filtered value and ~ is a Favre-averaged value, with .

 

in which  is the turbulence eddy viscosity determined using Large Eddy Simulation (LES) technique both inside and outside the porous media based on Smagorinsky model:

 

where =0.1 is the Smagorinsky constant, the filter width is set as  following Maruyama (2008),  is the particle spacing,  is the rate-of-strain tensor.

Eqs. and can be rewritten in Lagrangian form to facilitate SPH discretization:

 

 

in which the notations for filtering and Favre averaging are dropped for simplicity.

Following Shi et al. (2019), the fluid pressure is explicitly solved by the following equation of state:

 

where  is the reference density,  is the artificial sound speed and its value must be at least ten times larger than the maximum fluid velocity to satisfy the weakly compressible fluid hypothesis (Monaghan, 1994).

It's worth emphasizing that the solid skeleton is assumed to rigid and fixed fully, and the permeability and porosity of porous media are then constant in time and space after the finishing of the initial setup. In addition, the present model is theoretically incapable of the simulation of unsaturated porous media flow due to the ignoring of the air phase in the adopted mixture theory. Moreover, the model cannot obtain the precise pore pressure because of the using of equivalent continuum porous media assumptions.

#### Resistance force induced by porous media

The last term in the right hand of Eq. represents the resistance force acted on the porous flow by the fixed solid skeleton of porous media and is usually expressed as

 

where  and  are the linear and nonlinear resistance coefficients, respectively. The inertial resistance, which is negligible in comparison with the linear and nonlinear resistance terms (Van Gent, 1994), is excluded in this formulation. Despite considerable research effort, the two resistance coefficients can only be determined empirically and there is still no general agreement on their appropriate values at the present stage (Wen et al., 2018b). In this model,  and  are estimated by the following expressions according to:

 

 

 

where  is the volume fraction of solid phase and  is the mean diameter of porous material.

Fig. 1 shows the relationships between the porosity of porous media and the resistance coefficients. It can be seen that  and  decrease with the increase in both the porosity  and the mean diameter of porous material . Eqs. - are obtained from the N-S equations for the fluid flow in a granular porous medium by Du Plessis (1994) based on the assume that the medium is rigid and stationary, and the porosity is the continuous function of position. These resistance formulae have some distinct advantages compared with others. The first one is that the empirical coefficients  and depend only on  and . The second advantage is that the flow inside and outside the porous media can be simultaneously described using a set of uniform governing equations, since  when, which means that the resistance force induced by the fixed solid skeleton of porous media vanishes automatically when fluid particles move into the pure fluid zone from the porous zone. Good agreements with the corresponding experimental data have been obtained by Ren et al. (2016) and Wen et al. (2018b) by simulating wave interaction with 2D and 3D permeable structures using these resistance forms.

#### Discretization of governing equations

Following the standard SPH discretions, the divergence of velocity, pressure and viscosity for particle *a* can be expressed as

 

 

 

where  is the number of fluid particles within the influence domain of particle *a*, ,  and  are the mass, volume and density associated with the neighboring particle *b*;  is the kernel function derivative and is written as:

 

where *h* is the smoothing length which refers to the influence domain of a kernel function. The quantic kernel function developed by Wendland (1995) is adopted in the present model:

 

where *q*=*r*/*h*, *r* represents the distance between fluid particles.

In the present SPH mixture model, the fluid and solid phases are independently discretized by fluid and solid particles. Each solid particle has two additional variables except its location: the solid volume fraction  and the particle volume . The two variables are constant since the porous media is taken as fixed in space and time. Following Peng et al. (2017) and Khayyer et al. (2018b), considering a saturated condition without the presence of air phase within the porous domain, the fluid volume fraction for the fluid particle *a* can be evaluated by

 

where *M* refers to the number of solid particles within the influence domain of particle *a*,  and  is the fluid volume fraction of particle *a* and the solid volume fraction of particle *b*. Based on Eq. , we have

 

Finally, the discretized governing equations of the SPH mixture model for porous flow are obtained as:

 

 

in which the original kernel function derivative is replaced by the normalized kernel function derivative  to correct the disabled normalization and symmetry conditions for all the SPH particles.  is written as

 

where  is the tensor product,  are the distance between the particles *a* and *b*.

The last term in the right hand of Eq. refers to the additional diffusive term to suppress the unphysical pressure oscillation and can be written as

 

 where  controls the intensity of the diffusive and is set as 0.1 following Marrone et al. (2011). The SPH discretized formulation of this diffusive term can be written as

 

in which  is the modified density of the fluid particle *b* to conserve the total volume of the fluid system and following Wen et al. (2018c), it is written as

 

#### Boundary conditions

#### Interface boundary condition for different media

Previous studies (Akbari and Namin, 2013; Ren et al. 2016) have shown that in the Lagrangian framework the fluid particles move across the interface continuously and there is no need to impose the continuity conditions of velocity and stress at the interface of different media as long as the seepage resistance force acting on the fluid particles through the interface changes continuously. In the present SPH mixture model, the permeable structure is discretized by solid particles with the spacing of 0.2*d*50. Each solid particle carries the information of particle location, particle volume and solid volume fraction (*ns*).

At each time step, the fluid volume fraction of each fluid particle is updated by a SPH interpolation algorithm with a searching radius of *rs* over the adjacent solid particles as presented in Eq. . Fig. 2 shows a schematic diagram of water seeping through a porous structure. It can be seen that for the fluid particle located far away from the porous structure, there is no solid particle in its searching domain and then its fluid volume fraction calculated by Eq. is *nf* = 1.0. For the fluid particle located in the porous structure, its searching domain is fully filled with solid particles and its fluid volume fraction is *nf* = 1.0-*ns*. Between the two zones, a transition zone of 2*rs* thickness, where part of the searching domain of fluid particle is filled with solid particles, is formulated. In the transition zone, the fluid volume fraction of fluid particle is continuously changed from 1.0 to 1.0-*ns*. By this way the interface matching conditions can be automatically fulfilled. A sensitivity test for the thickness of the transition zone is conducted and it is found that the optimal value is obtained when the thickness is set as *d*50, namely *rs*= *d*50/2, which is consistent with the conclusions of Kaviany (2012) and Ren et al. (2016).

#### Other boundary conditions

The solid boundary is discrete as two layers of SPH particles, the pressure of boundary particle is updated using the improved dynamic boundary conditions, which is originally proposed by Crespo et al. (2007) and further improved by Ren et al. (2014) to mitigate the nonphysical high-frequency pressure oscillations near the solid boundaries. The inflow and outflow boundaries are modeled by the periodic boundary condition. By this mean, the fluid particle going out from the fluid domain is injected into the inlet and the computational domain can be seen as a continuous zone, which is analogous to the experimental idea of recirculating flume (Wen et al. 2018a). Following Wen and Ren (2018) and Liu et al. (2015), wave generating and absorbing are realized by a momentum source wavemaker and a sponge layer.

#### Verification of the WCSPH model

#### Darcy seepage flow in a U-tube with permeable soil

Based on the assumption of Darcy seepage conditions, the evolution of water level difference  between the two sides of the U-tube can be calculated as

 

where  is the initial water level difference, *t* represents time, *L* is the seepage path length, and  is the hydraulic conductivity and can be written as , where  is the dynamic viscosity of water and the permeability of uniform soil  is calculated as

 

For the stratified soil in the horizontal direction, if the permeability of each layer has been determined, the average permeability can be calculated as (Murthy, 2002)

 

where *N* is the number of the soil layers,  and  are the thickness and the permeability of the *i*th layer soil, respectively. If  and  are the continuous functions of the soil depth, Eq. can be further rewritten as the following integrated form

 

where  represents the total soil thickness.

In this section, the mixture model is firstly verified by modeling Darcy seepage flow in a U-tube with permeable soil body. The numerical setup of the computational domain is given in Fig. 3. The initial water level difference is  m, the total depth of soil is  m and the seepage path length is  m. Water will flow from left to right through the permeable soil under gravity and the balanced water level in the two sides of U-tube will finally be obtained. Three simulations are performed with varying hydraulic conductivity and the corresponding computational conditions are displayed in Tab. 1. For case A, a uniform distribution of porosity is set as . For case B, the soil is divided into three equal layers () with the porosity of 0.3, 0.4 and 0.5 from bottom to top, respectively. For case C, the porosity of soil is set as a linearly continuous function of the soil depth: .

Following Khayyer et al. (2018b), the initial particle spacing is set as 5.0 cm, the turbulent model and the nonlinear resistance force term in momentum equation are disabled. Fig. 4 shows the particle distributions together with the pressure field for the three tested cases. The solid phase particles are erased in this figure in order to display the fluid particle distribution and the corresponding pressure field more clearly. Smoothing and continuous pressure fields at the interfaces between the free and porous flow regions are obtained for all cases, which indicates the present interface treatment method is effective. Fig. 5 displays the time series of the variations of the water level differences for the three cases. The markers and lines represent the numerical and analytical solutions, respectively. Good agreements between the analytical and numerical results indicate the Darcy seepage flow both in the homogeneous and inhomogeneous media can be well simulated by the present model.

#### Wave damping along a permeable seabed

The developed model is further verified by modeling wave damping along the permeable seabed. The numerical setup of the computational domain is given in Fig. 6 and the corresponding parameters are listed in Tab. 2. Savage and Fairchild’s ([1953](#_ENREF_20)) and [Sawaragi and Deguchi’s (1992](#_ENREF_21)) experimental data are adopted, which represent small and large permeability conditions, respectively.

To test the sensitivity of particle spacing, three tests with the relative particle spacing of =0.141, 0.282 and 0.423 are carried out.  represents the ratio of the initial particle spacing to the incident wave height. Fig. 7 shows the particle distributions and the corresponding pressure fields with different particle spacings. As it can be seen in this figure, smoothing pressure field and uniform particle distributions are obtained for all the tests. Fig. 8 displays the comparisons of wave height attenuation along the permeable seabed with different particle spacings. As observed in this figure, the predicted results have reasonably agreements with the experimental data when =0.141 and 0.282, and an obvious discrepancy occurs for the test with =0.423. In order to estimate quantitatively the errors between the numerical and experimental results, the corresponding root mean squared errors (RMSEs) are calculated by , where  and  are the relative wave height obtained from numerical model and physical test, respectively. The calculated RMSEs are 0.009, 0.011 and 0.027 when =0.141, 0.282 and 0.423, which indicates the computational results are approximately convergent when 0.282 although the RMSE decreases slightly as the increase of particle spacing.

Fig. 9 presents the comparisons of the present model results with the corresponding experimental data and Ren et al.’s (2016) SPH porous model results. The relative particle spacing =0.282 is adopted here considering the computational efficiency. As it can be seen, reasonable agreements can be obtained by both models but the present model can better reproduce wave damping along the permeable seabed than Ren et al.’s (2016) model, especially for the small permeability condition (case B). The reason for this is believed to be due to the inaccuracy as the result of the adoption of apparent density and the use of variable kernel smoothing length for fluid particle in Ren et al.’s (2016) porous model. In fact, trial results for this case using Ren et al.’s (2016) model show that numerical instability will occur, when the porosity of porous media is less than 0.15.

#### Wave transformation over a permeable platform reef

In this section, wave transformation over a permeable platform reef is simulated to test the robustness of the model. Firstly, the corresponding physical model tests are carried out in the nonlinear wave flume of the state key laboratory of coastal and offshore engineering, Dalian university of technology, China. As shown in Fig. 10, the flume of 60.0 m× 4.0 m× 2.5 m is longitudinally separated into two sections with widths of 1.0 m and 3.0 m by a waterproof plate, which helps to decrease the reflection of the model structure. The narrower section is used as the working channel and can be seen as a 2D wave flume. The wider section is used as the tidal channel, by which the water body carried by wave-induced current over the reef-flat can return freely to the open water region.

An idealized platform reef model is built in the working flume. The model is consisted of a steep reef-face of 1:1 slope and a horizontal reef-flat of 8.6 m long. Both the permeable and impermeable reef models are tested. For the impermeable reef, the reef-flat is 1.8 m high, and the reef surface is finished smoothly without any friction resistance. For the permeable reef, the solid reef-flat is 1.7 m high, and a permeable layer of 0.1 m thickness is placed over the solid reef which is made of gravels with different median diameters and fixed by a thin wire netting. The water surface elevations at 15 gauging points and the flow velocity at three gauging points are tested. The capacitance-type wave gauges (WEG-600, Japan) and the high-resolution acoustic Velocimeters (Vectrino Profiler, Norway) are used to measure the water surface elevation and flow velocity. The measurement accuracy is ± 0.1 mm for water surface elevations and ±0.5% for flow velocity in theory. The Velocimeters are fixed on the lateral wall of the flume, and the probe sensors of the Velocimeters are placed at the elevation of 0.5 times of the static water level over the reef-flat. The origin of coordinates is set at the reef-toe, the relative positions of wave and velocity gauges are displayed in Fig. 10 and their coordinates are shown in Tab. 3.

The numerical model setup is displayed in Fig. 11 and the flume length is adjusted based on the incident wavelength. The left and right boundaries of the wave flume are set as the inflow and outflow boundaries, and modeled by the periodic boundary conditions without any boundary particle. The target wave is generated by a momentum source wave maker of 1.0*L* width, and is absorbed by two artificial sponge layers of 0.5*L*-1.5*L* width placing at the two ends of the flume as shown in Fig. 11. In this figure, *L* represents the incident wavelength. As the water caused by wave-induced current moving into the lagoon region cannot move back to the open water region for the common vertical 2D model, an unphysical setup of the mean water level usually occurs. To overcome this issue, a circuit channel is installed below the two sponge layers. With the same role of the wider section of the wave flume used in physical model tests, the circuit channel acts as the tidal channel in the actual ocean environment. The free exchange of the water body is achieved under the action of a pressure gradient between the lagoon and the open water region. Therefore, the numerical model setup can be roughly identical with the physical model setup in 2D sense. Following Wen et al. (2018a), the circuit channel of 0.2*d* high is adopted through a series of calibration tests in the present simulations.

In this section, the mean diameter is *d*50=3.2 cm, the porosity is *nf* = 0.42, the thickness of the porous layer is *ds*=0.1 m, the wave height is *H*0=0.2 m, the wave period is *T*=2.0 s, and the initial water depth over the reef-flat is *hr*=0.0 m and 0.1 m. Considering the computational accuracy and efficiency of numerical model, the initial particle spacing is set as 2.0 cm and then results in a relative particle spacing of =10.0 following Wen and Ren (2018), who have test the effect of particle spacing to the performance of SPH model for simulating wave transformation over an impermeable fringing reef with the same wave height, water depth and reef topography used in this study. They found that the numerical results in terms of wave height and wave setup with a relative particle spacing of =10.0 had reasonably agreements with the experimental data. The simulation time is 50.0 s for all the cases simulated. The code is performed on Intel(R) Core(TM) i7-8700K CPU with a clock speed of 3.7 GHz and 16.0 GB RAM. For a typical case with nearly 96,000 particles, the computational time is about 14 hours.

#### Free surface elevation

Fig. 12 shows the comparisons of the free surface elevations over the permeable reef between the numerical predicted results and the experimental data. The corresponding RMSEs of the free surface elevations are displayed in Tab. 4. The initial water depth on the reef-flat is set as 0.1 m in this case. Following Wen et al. (2018a), a circuit channel of 0.2*d* thickness is installed beneath the sponge layer to avoid the unphysical wave setup occurring over the reef-flat. As seen from Fig. 12 and Tab. 4, good agreements are obtained as expected between the predicted results and the experimental data, the maximum RMSE of the free surface elevations is not more than 0.083. That means the water discharge through the circuit channel is approximately equal to that through the return channel of the laboratory flume, and the thickness of the present circuit channel is suitable.

It is also can be seen from Fig. 12 that as wave propagates along the porous reef, wave nonlinearity is quite obvious near the reef-rim at WG.7 and subsequently wave breaking occurs with substantial wave energy dissipation on the reef-flat. The steep asymmetric bore-like wave, which is reformed after wave breaking, propagates through the entire reef-flat and then moves into the lagoon.

#### Flow velocity

Fig. 13 shows the comparisons of the flow velocity over the permeable reef between the numerical predicted results and the experimental data. The velocity gauging points are set at the middle of the initial water level over the reef-flat and their coordinates are shown in Tab. 3. The flow velocity is non-dimensionalised by the local shallow water wave celerity . As seen from this figure, a notable divergence can be observed between the numerical and experimental results. The RMSEs are 0.106, 0.074, 0.100 for the measured points V.1, V.2 and V.3.

The differences between the numerical and experimental results are believed to mainly come from the noise of the experimental signals. In the physical model tests, the measured data often contain oscillating components of high frequency, probably due to the influence of the rugged bottom boundary or other unknown disturbances. The experimental data shown in this paper are the results after these high frequency oscillating components have been filtered out. In addition, as the probe sensors of the Velocimeters have a diameter of 5.0 cm and they are placed at the elevation of 5.0 cm above the bottom for the case in Fig. 13, the rugged bottom may cause a complex three dimensional flow field which cannot be captured using the present 2D model. Although a divergence phenomenon occurs for the time series of the numerical and experimental flow velocity, the relative error of the average velocity between the numerical and experimental results is in the range of 9.2%, which indicates the experimental flow velocity can be seen as a reference for validating the proposed SPH model.

#### Wave height and wave setup

The distributions of wave height and wave setup over the permeable reef at high tide (*hr*=0.1 m) and low tide (*hr*=0.0 m) are displayed in Fig. 14, where the corresponding experimental data are also given as a reference. As seen in Fig. 14, the predicted wave height and wave setup compare reasonably with the experimental results. It indicates the complex wave transformation process over the permeable platform reef can be well simulated by the present SPH mixture model.

As shown in Fig. 14 (a), a partial standing wave pattern can be clearly observed in the front of the reef-face. More wave energy is reflected into the open sea at low tide than that at high tide. Wave breaking occurs near the reef-rim and wave height tempestuously decreases along the permeable reef-flat. Similar with the impermeable reef, as the water depth over the reef-flat increases, wave height increases, whereas wave setup decreases. The maximum wave setup is about 0.1*H*0 at high tide, which is smaller than that at low tide as shown in Fig. 14 (b) under the present conditions.

#### Wave-induced current on the permeable platform reef

Together with wave setup, wave-induced current is generated and flows over the platform reef-flat to balance the radiation stress gradient caused by wave breaking. The wave-induced current is significantly influenced by reef permeability, which is generally related to the reef porosity, the porous layer thickness, the distribution type of reef porosity, and the mean diameter of porous material. From Fig. 1, it can be seen that the effect of the mean diameter of porous material is relatively weak and can be well represented by a typical value. In this section, the effects of the homogeneous permeable reef body with different porosity values and permeable layer thickness are analyzed. This is followed by a parametric study of the wave-induced current on the inhomogeneous permeable reef body with different distribution types of porosity. The setup of numerical model follows Section 3.3 as shown in Fig. 11. The initial water depth over the reef-flat is *hr*=0.1 m, the mean diameter is *d*50=3.2 cm, the wave height is *H*0=0.2 m and the wave period is *T*=2.0 s for all cases tested in the present section.

#### Effect of porosity value

In this paper, wave-induced current is approximated by averaging the instantaneous flow velocity during five wave periods. The current velocity is calculated by, where  is the instantaneous velocity of fluid particle in the horizontal direction. The spatial distributions of wave-induced current over the platform reef-flat with different reef porosity are displayed in Fig. 15. The corresponding impermeable reef results are also given as a reference. The porous layer thickness is set as *ds*=0.1 m for the permeable reefs in the present subsection.

As shown in Fig. 15, the maximal current velocity occurs near the mean water level for all the tests. The mean water level is the sum of the initial water level and wave setup. The maximal current velocities increase as the reef porosity decreases. The current velocities on the impermeable reef are much larger than that on the permeable reefs, especially for the current velocities near the bottom. For the impermeable reef, the vertical distributions of wave-induced current on the front half of the reef-flat (*x*=3.7 m-7.3 m) is very different from that on the latter half of the reef-flat (*x*=7.9 m-10.0 m). The current velocity on the front part of the reef gently increases from the reef bottom to the mean water level. However, the current velocity on the reef-flat close to the lagoon is almost constant from the bottom to the mean water level, the possible reasons are that the influence of the bore-like wave on the current is weak on the latter half part of the reef-flat and there is very little resistance on the current by the reef bottom because of the smooth surface.

For the permeable reefs, the current velocity continuously decreases from the mean water level to the reef bottom over the reef-flat and further decreases along the vertical direction within the permeable reef body. Due to the seepage resistance induced by the reef skeleton, the current velocity on the permeable reef is much smaller than that on the solid reef, especially near the reef bottom. A large part of wave and current energy is dissipated at the reef surface and within the permeable reef body. From Fig. 15, it also can be observed that the current velocity within the porous layer is much smaller than that over the reef-flat

Fig. 16 and Fig. 17 give the instantaneous velocity fields and the normalized turbulence eddy viscosity () fields around the coral reef with different porosity when wave crest and trough approach the reef-rim. As seen in Fig. 16, wave near the reef-rim begins to collapse and the water body with a large onshore velocity interacts with the water body of the previous wave with an offshore velocity. As observed in Fig. 17, the reformed bore-like wave propagates over the reef-flat and a slight offshore flow appears around the reef-rim. For the impermeable reef, the turbulence energy concentrates in the wave breaking zone and near the reef surface. For the permeable reef, except the wave breaking zone, the vicinity of the interface between the free and porous zones is the main zone of the turbulence energy distributions. From the two figures, it also can be observed that a weak flow exists within the permeable layer below the wave crest. The flow velocity in the permeable layer increases as the reef porosity increases and its direction is same as that over the reef-flat.

Fig. 18 gives the time series of the water volume through the reef-flat section at *x*=10.0 m with different porosity conditions. The water volume through the section *x*=10.0 m is calculated as following:

 

As displayed in Fig. 18, more water volume moves through the reef-flat for a smaller reef porosity and the water volume reaches the maximal value as excepted when the reef body is impermeable (*nf*=0.0).

#### Effect of porous layer thickness

The effect of the porous layer thickness of reef body on wave-induced current is studied and the porosity is set as *nf* = 0.55 in the present subsection. The spatial distributions of wave-induced current over the reef-flat with the porous layer thickness of *ds*=0.1 m, 0.2 m and 0.3 m are displayed in Fig. 19. As presented in this figure, the maximal current velocity occurs around the mean water level for all the tests with different porous layer thickness. The current velocities decrease as the reef porous layer thickness increases. The current velocity gently decreases from the mean water level to the reef bottom over the reef-flat and further decreases along the vertical direction within the porous reef body. As seen in Fig. 20, in the permeable reef body, a weak offshore current close to the open sea and a weak onshore current near the lagoon can be observed, although the current velocity within the porous reef body is much smaller than that over the reef-flat due to the seepage resistance induced by reef skeleton.

Fig. 21 and Fig. 22 give the instantaneous velocity fields around the reef-flat with different porous layer thickness when wave crest and trough approach the reef-rim. As can be observed in the two figures, similar to the instantaneous velocity fields with different reef porosity displayed in the previous subsection, wave collapses and mixes with the offshore remaining water body of the previous wave in the front of reef-flat when wave crest approaches the reef-rim, the bore-like wave continues to propagate along the reef-flat and a weak backflow occurs near the reef-rim when wave trough approaches the reef-rim. The flow velocity within the porous layer is much smaller than that over the reef-flat due to energy dissipation induced by the seepage resistance of reef skeleton.

Fig. 23 gives the time series of the water volume through the reef-flat section of *x*=10.0 m for different porous layer thickness. As shown in this figure, the water volume moving through the reef-flat decreases as the reef porous layer thickness increases, which indicates that more wave energy is dissipated within the reef body with a thicker porous layer.

#### Effect of porosity distribution types

It is well recognized that the permeable layer of coral reef has a wide range of porosity values in space. The porosity value is low at the bottom, where internal cavities have been infilled with detrital material of assorted sizes, and it is much higher at the top due to the branching of coral framework (Cabioch et al., 2010). In this section, a parametric study is performed involving three porosity distribution types: constant, linear and nonlinear distribution, respectively. The porous layer thickness is set as *ds*=0.2 m for all the tests. Fig. 24 gives the vertical distributions of porosity along the permeable reef body. *dc*=0.0 m and *dc*=0.2 m are located at the bottom and top of the permeable reef body, respectively. For the constant distribution type, the porosity is set as  in the whole permeable zone. For the linear distribution type, the porosity increases from 0.0 to 0.6 by the linear function of . For the nonlinear distribution type, the porosity increases from 0.0 to 0.9 by the quadratic function of . It should be noted that the total pore volume at any section () is equal in all the three porosity distribution types.

Fig. 25 displays the spatial distributions of wave-induced current at the selected sections for the different distribution types of porosity. As it can be seen in this figure, the differences of wave-induced currents for the different distribution types of porosity are clearly visible, although they are not as pronounced as those for the different porosity and permeable layer thickness cases. In the free fluid zone over the reef-flat, the intensity of wave-induced current is strongest for the constant distribution type and weakest for the nonlinear distribution type. However, in the porous fluid zone within the permeable reef body, the intensity of wave-induced current is strongest for the nonlinear distribution type due to the larger porosity close to the top of the permeable reef body. Although these results are physically plausible, further verifications are required by either laboratory or field data.

#### Conclusions

A general WCSPH model for turbulent flow motions inside and outside a permeable structure is developed with the governing equations being formulated in terms of the intrinsic velocity and fluid density instead of the apparent quantities. The model is capable of simulating fluid flow interaction with both homogeneous and inhomogeneous permeable structures.

The model validation results indicate that the developed mixture model can well reproduce the complex processes of wave interaction with permeable structure. *The turbulent effect is taken into account* instability problem associated with Ren et al.’s (2016) SPH porous model using the apparent velocity and fluid density when the porosity is small.

The model enables for the first time the prediction of the spatial distributions of wave-induced current over a reef-flat and within its permeable body under different reef permeability conditions. It is found that the intensity of wave-induced current over the reef-flat increases with decreasing reef porosity and reef porous layer thickness. The effect of the distribution type of porosity on wave-induced current is also obvious, the intensity of wave-induced current for the selected nonlinear distribution type is weakest over the reef-flat but is strongest within the permeable reef body. For the permeable reef, the current velocity continuously decreases from the mean water level to the reef bottom over the reef-flat and further decreases along the vertical direction within the permeable reef body. It is different from the impermeable reef, for which the current velocity is almost constant in the latter half of the reef-flat close to the lagoon due to the neglection of reef permeability. Although the flow velocity within the reef porous layer is much smaller than that over the reef-flat, a discernable current moving to the deep-water area can be observed at the two ends of the porous reef body.

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**Figure captions**

Fig. 1 Relationships between the porosity of porous media and the resistance coefficients.

Fig. 2 Fluid particles pass through the interface between the permeable structure and the free flow region.

Fig. 3 Setup for Darcy seepage through soil in a U-tube.

Fig. 4 Sketch of fluid particle distributions together with pressure filed for Case A, B and C at *t*=75.0 s.

Fig. 5 Evolution of water level difference in time for Case A, B and C.

Fig. 6 Sketch of model setup for wave damping along the porous bed.

Fig. 7 Sketch of fluid particle distributions together with pressure filed for Case A with different particle spacing,

Fig. 8 Comparisons of the free surface elevations with different particle spacing,  is the ratio of the initial particle spacing to the incident wave height.

Fig. 9 Comparisons of the free surface elevations along the porous seabed.

Fig. 10 Experimental setup of wave transformation over a permeable platform reef.

Fig. 11 Numerical setup of wave transformation over a permeable platform reef.

Fig. 12 Comparisons of wave surface elevations over the permeable reef (*hr*=0.1 m).

Fig. 13 Comparisons of flow velocity over the permeable reef (*hr*=0.1 m).

Fig. 14 Comparisons of wave height and wave setup distributions with experimental data.

Fig. 15 Spatial distributions of wave-induced current over the reef-flat for different reef porosity values.

Fig. 16 Instantaneous velocity fields and normalized turbulence eddy viscosity () fields around the coral reef with different porosity values when wave crests approach the reef-rim. (a) *nf*=0.0, (b) *nf*=0.42, (c) *nf*=0.55.

Fig. 17 Instantaneous velocity fields and normalized turbulence eddy viscosity () fields around the coral reef with different porosity values when wave troughs approach the reef-rim. (a) *nf*=0.0, (b) *nf*=0.42, (c) *nf*=0.55.

Fig. 18 Time series of the water volume through the reef-flat section (*x*=10.0 m) under different porosity conditions.

Fig. 19 Spatial distributions of wave-induced current at selected sections for different porous layer thickness *ds*.

Fig. 20 Distributions of wave-induced current within the reef body for different porous layer thickness *ds*.

Fig. 21 Instantaneous velocity fields around the coral reef with different porous layer thickness *ds* when wave crests approach the reef-rim. (a) *ds*=0.1 m, (b) *ds*=0.2 m, (c) *ds*=0.3 m.

Fig. 22 Instantaneous velocity fields around the coral reef with different porous layer thickness *ds* when wave troughs approach the reef-rim. (a) *ds*=0.1 m, (b) *ds*=0.2 m, (c) *ds*=0.3 m.

Fig. 23 Time series of the water volume through the reef-flat section (*x*=10.0 m) under different porous layer thickness conditions.

Fig. 24 Vertical distributions of porosity value along the permeable reef body.

Fig. 25 Spatial distributions of wave-induced current at selected sections for different porosity distribution types.

**Table captions**

Tab. 1 Computational conditions for Darcy seepage flow in a U-Tube.

Tab. 2 Parameter values for wave damping along the permeable seabed.

Tab. 3 Coordinates of wave gauges and velocity gauges.

Tab. 4 RMSEs for water surface elevations.

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