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A Fast and Effective Wave Proxy Approach for Wave-Structure Interaction in Rubble Mound Structures

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Abstract: To meet the demands of practicing engineers for realistic-scale engineering problems, the authors propose a new and fast wave proxy approach for wave-structure interaction. In this approach, a rigid FDEM version - SOLIDITY_R is employed to simulate structure-structure (e.g. armour unit) interaction. Hydraulic forces on units are calculated by the surface integral of fluid pressure at the local element level. Then these forces are integrated and applied to each unit. For the time history of water pressure imposed on the breakwater and armour units, the approach can accept velocity data from any sources, e.g. derived from theory, measured from experiments, even from a CFD wave simulator. For example, a wave generator (IHFOAM/IH2VOF) was used to generate a one-hour 50/100 year return period storm and the storm forcing was applied to armour the units. In this paper, the authors illustrate the workflow of the wave proxy and some preliminary results showing the hydraulic flow and wave action loads coupled to our FDEM solver, SOLIDITY_R, via the wave proxy.

Keywords: wave proxy, wave-structure interaction (WSI), Combined Finite-Discrete Element Method (FDEM), rubble mound structure

1 Introduction

One of the main challenges for engineers designing coastal structures, such as breakwaters, is to ensure that individual armour units will maintain stability both under construction conditions and under wave loading during the design storm event. Over the past decade, solid numerical models used to design rubble mound structures have been developed and significantly improved. The finite-discrete element method (FDEM) which combines the multi-body particle interaction and motion modelling (i.e. Discrete Element Method, DEM) with the ability to model internal deformation of arbitrary shapes (Finite Element Method, FEM) has been successfully applied to assess the behaviour of breakwater models under wave attack (Xiang, et al., 2013, Latham, et al., 2013).

For wave structure interaction (wave breaking on beaches/rubble mound structures, wave overtopping, wave reflection, etc.), one-way coupling models have been developed that fix the armour units in place, or volume-average the rubble mound geometry into simplified homogeneous permeable layers (Lara, et al., 2008). Most Numerical Wave Tank (NWT) models aim to create, propagate and absorb wave energy realistically and to capture energetic free surfaces with plunging wave jets. In recent years further wave simulation developments with parallelised commercial codes such as FLOW3D (Dentale et al., 2009), CFX, Fluent and the increasingly popular wave modelling applications of OpenFOAM, (Higuera et al., 2013, 2014) have indicated a modelling future with turbulent waves interacting within the armour layer and within generalised porous media of rubble mounds. Other numerical wave tank models exist such as ones which use Lagrangian particle-based CFD models which can be more easily parallelized. They apply Smooth Particle Hydrodynamics (SPH) (Gómez-Gesteira, M., et al., 2010, Altomare et al., 2014), and Moving Particle Semi-implicit (MPS) methods (Khayyer, A. and Gotoh, H. 2010) to allow multi-material modeling (e.g. air-water boundaries) which are inherently simple to couple with moving solids. However, the major challenge
to model such complex systems is to include the interaction of energetic storm waves breaking on free complex solid structures and devices as well as the interaction between the solid armour unit geometries. For two-way modelling of wave structure interaction, a novel numerical model has been developed that couples FDEM with the generic multiphase CFD code Fluidity for arbitrary unstructured finite element meshes, (Xiang et al., 2013, Vire, et al., 2013). This coupled model has the capability of simulating not only the interactions between waves and the emerged and submerged breakwater but also the structure-structure interaction. However, the main drawback of this method is its high CPU cost, which hinders simulating a full breakwater system formed of thousands of units. However, after it is fully optimised and parallelised, it is expected that this coupled model will be able to simulate large scale breakwater system.

In order to carry out numerical tests, the first task is to build a virtual breakwater in a computer environment with geometries representative of real armour units. However, due to accuracy limitations, surveyed data cannot be used directly by the FDEM solver. A powerful and fully automated numerical placement protocol, POSITIT, was developed for the purpose of constructing virtual breakwaters. POSITIT is a generic code that has many features of a pre-processor but combines these capabilities with some of the fast mechanics of the DEM code. POSITIT has various functions, e.g. user-defined particle/unit centroid, user-defined or random particle/unit orientation, user-defined initial velocity applied to all particles/units to deposit particles/units faster, etc. As mentioned earlier, FDEM method is capable of simulating not only complex shapes but also deformable bodies. However, the main drawback is high CPU cost which hinders FDEM from simulating a full breakwater system formed of over a thousand units. Based on the full deformable FDEM code Solidity_D, a rigid version of FDEM code, Solidity_R was developed recently. The main difference between Solidity_D and Solidity_R is Solidity_R only simulates rigid bodies and solid deformation is neglected. The time step of Solidity_R is related to the whole particle/unit body. In contrast, the time step of Solidity_D is related to the smallest element in the particle/unit meshes. Therefore, Solidity_R is much faster than Solidity_D, e.g. if a CORE-LOC™ unit is formed of ~2500 elements, Solidity_R is about 50 times faster than Solidity_D. Coupled POSITIT/Solidity_R is capable of simulating a realistic armour unit layer.

To meet the demands of practicing engineers to solve realistic-scale engineering problems, Xiang et al. (2013) published a new and computationally effective wave proxy approach for wave-structure interaction: the rigid FEM version - SOLIDITY_R is hence employed to simulate structure-structure (e.g. armour unit) interaction in which the wave motion is treated as a periodically varying load. Hydraulic forces on individual units are calculated by integrating the fluid pressure over the surface of each individual element. Then, these calculated forces are integrated and applied to each unit. As the model treats armour units and rocks as rigid bodies and since the rigid FDEM version – SOLIDITY_R has been optimised and parallelised using OpenMP, the authors can simulate a one-hour storm acting on a structure with over 3500 underlayer rocks and 242 individual armour units within 24-hour CPU time when using 20 threads on a Linux workstation (Intel Xeon E5-2667 v3, 3.2GHz).

In this paper, the authors briefly describe a new improved wave proxy method and preliminary results showing the stochastic nature of armour unit movements in response to irregular wave action and the inevitable irregularities in the initial unit layer construction. The challenge that is addressed in the current study is to apply appropriate hydrodynamic boundary conditions to individual units during wave action, and to determine the response of the armour units under this loading.

2 Virtual Breakwater Wave Proxy Simulation Tools

Previous research by AMCG has highlighted the use of FDEM simulation to create realistic breakwater armour unit systems and to examine some of their statistical properties likely to have a bearing on armour stability (Latham et al., 2013; Anastasaki et al., 2015). However, although the solid skeleton of units that were numerically placed were subjected to vibrational disturbances, a wave-like oscillatory forcing was considered a more relevant disturbance to apply to the solid armour unit granular model. A highly simplified one-way coupling concept based on use of water particle velocities was introduced to compute oscillatory wave-induced drag forces on each unit (Xiang et al., 2013; Latham et al., 2014). The realism observed was an improvement on vibrations affecting all units, but through lack of a good representation of velocities in the armour layer, the type of motion
observed lacked some of the expected behaviour seen in laboratory studies. In this paper, the authors briefly describe a new wave proxy method to simulate the stochastic nature of armour unit movements in response to irregular wave action and the inevitable irregularities in the initial unit layer construction. The workflow is shown in Figure 1:

1. the solids modelling code with recently enhanced capability, Solidity, is used to construct a realistic breakwater;
2. both 2D (IH2VOF) and 3D (IHFOAM) wave generators are used to generate a one-hour storm for both a 50 and a 100 year return period storm;
3. storm forcing is applied to armour units.

![Workflow of the Virtual Breakwater Wave Proxy Simulation Tools](image)

Fig. 1. Workflow of the Virtual Breakwater Wave Proxy Simulation Tools

### 2.1 Construct realistic virtual breakwater

![FDEM placement of armour layers including useful analysis tools](image)

(a) a snapshot of an armour layer of 242 CORE-LOC™ units, color represents each unit’s maximum contact force; (b) contact number of each unit is defined as the number of contacts each unit makes with its neighbors; (c) stereographic plot of unit nose axis dip angle and dip azimuth with reference to the average slope plane and breakwater trunk axis.

POSITIT is a new tool for introducing particles into a computational domain. In this paper, the authors briefly outline how it has been used in the context of armour unit placements and creation of realistic armour layers. The code is designed to be a versatile i.e. generic depositing tool, which can be used widely for industrial applications such as in particle technology. The program is designed to be
compatible with a FDEM solver. The 3D FDEM code (Y3D) which was developed by Xiang and Munjiza in 2009 (Xiang, et al., 2009) has great potential to be applied in the field of coastal structures. In FDEM, a penalty function method is employed to calculate the normal contact force when the two particles are in contact. The penalty function method in its classical form assumes that two particles penetrate each other. The elemental contact force is directly related to the overlapping volume of the finite element in contact. The distributed contact force approach takes into account the shape and the size of the overlap volume in order to be distributed among the surrounding nodes.

POSITIT/ Solidity_R allows the user to choose any shape of particle, e.g. any rock or armour unit shape, and to position their centres with a user-defined grid file in a predefined container geometry (e.g. rough underlayer with walls, see Figure 2). The particles begin to pile up mechanically as they are caught in the container. At the end of the run, if the particles have come to rest, the particles are touching and in static force equilibrium. A post-process analysis code was developed to analyse existing packs in terms of unit maximum contact force, contact number and stereographic plot. POSITIT/Solidity_R are applied to generate an armour unit layer of 242 8m$^3$ CORE-LOC$^{TM}$ units (21 rows, 11 of which have 12 units and 10 of which have 11 units) on a rough underlayer with 3436 rocks (see Figure 2). The maximum unit contact force by choosing maximum contact force between unit and unit or unit and rock are also analysed (see Figure 2a). Figure 3b also shows contact number has a wide variation with the number of contacts between neighbouring units or rocks ranging from 2 to 10. In Figure 2c, a stereographic plot is used to show the orientation distribution of the nose axes of the placed unit.

2.2 Wave modelling

Both 2D (IH2VOF) and 3D (IHFOAM) CFD models were used in the test programme (Table 1) as 3D runtimes are excessive for full storm durations whereas 2D runs are faster. In the IHFOAM simulations of both the solitary wave and regular wave in 3D, the underlayer was represented by a homogeneous porous medium with nonlinear frictional losses represented by Forchheimer coefficients $\alpha$ and $\beta$ (see Table 1) considered optimal for representing underlayer of porosity $= 0.5$ and $D_{50} = 1.0$ m. IHFOAM produces the pressure-time (p-t) history and flow velocity field in 3D. The results for the regular waves with $H = 6.5m$, $T = 10s$, SWL=12m with a real time simulated of 65s were achieved with a run time of 5 days using 96 processors. Solitary wave tests in Series 1 were repeated for the 2D case in Series 2. The mean pressure-time history in the y-direction from 3D simulation is taken as the calibration target. Using 2D modelling where the armour layer is represented as a porous medium, a range of Forchheimer coefficients were tested for the solitary wave interaction and from a series of 20 tests. The optimal values for the $\alpha_1$ & $\beta_1$ coefficients were chosen based on the ability to reproduce the average 3D pressures in the y-direction (coordinate system is defined in Fig. 3 top right). The structural parameters for any 2D wave history WSI modelling were thus obtained, the next task being to construct the variations in pressure-time histories that are observed due to the variability will exist parallel to the trunk. A further 3D test (Series 3) was therefore run for regular waves with the express purpose of characterizing the variability about the mean pressure-time response as a function of location along the trunk and phase in the wave cycle. The detailed calibration procedure is in our previous paper (Latham et. al. 2015).

<table>
<thead>
<tr>
<th>Series</th>
<th>Waves</th>
<th>Void Structure of Armour Layer</th>
<th>Void Structure of Underlayer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3D: IHFOAM Solitary wave</td>
<td>Explicitly Captured</td>
<td>Porous media $\alpha$ &amp; $\beta$ Forchheimer</td>
</tr>
<tr>
<td>2</td>
<td>2D: IH2VOF Solitary Wave</td>
<td>Porous media</td>
<td>Porous media</td>
</tr>
<tr>
<td>3</td>
<td>3D: IHFOAM Regular Waves</td>
<td>$\alpha$, $\beta$ Forchheimer</td>
<td>Porous media</td>
</tr>
<tr>
<td>4</td>
<td>2D: IH2VOF Entire Sea State</td>
<td>Explicitly Captured</td>
<td>$\alpha$ &amp; $\beta$ Forchheimer</td>
</tr>
</tbody>
</table>

Tab. 1 Test Programme – Calibrations (Series 1-3) and Wave Proxy (Series 4)
The 2D (xx-zz) slice of breakwater 5m x 37.5m with highly resolved pressure-time history consists of 100 x 750 square grid elements, each one being extruded into a long thin voxel of 44.5 m length in the y-direction parallel to the trunk (Fig. 3, top right). Each occasion that a solid surface mesh element is encountered within the voxel, the p-t history acting on the surface of that individual mesh element is recorded. IHFOAM provides pressure, velocity and free-surface elevation for some 4000 surface elements for each of the 242 units, sampled every 0.05s. As indicated in the red box (Fig.3, bottom), there will be numerous (m-point) concrete surfaces with p-t wave action histories, typically m~20. Plotting m-point averages for the p-t history acting on concrete surfaces for one voxel allows the variability about the mean to be analysed. In short, the distribution varies differently in crest and troughs and is different above and below the means. However, each of these four variabilities can be characterised according to four sets of best-fit weibull distribution coefficients. This pressure variability can then be added back to the measured 2D p-t history and distributed with random sampling to populate unique p-t histories to all cells in the 3D volumetric computational domain. The added variability is weighted to allow for the case of irregular wave trains but is determined uniquely for each different unit and is also controlled to be in accordance with whichever of the four weibull distributions is appropriate - depending on whether the wave is in a crest or trough part of the cycle. 2D storm sea states measured at the structure are thus translated into 3D using variability statistics that were obtained from regular wave calibrations. The large file representing a storm history is then compressed into netCDF with format required for input to the solids Wave Proxy code. Further details of the method will be described in a future paper.

![Fig. 3 Methodology for capturing 3D pressure-time history and synthesising variability statistics.](image)

2.3 Simulation of armour unit responses to storm sea states

The solids code, Solidity, (which applies a rigid body FDEM solver with a contact force model) computes \( f_c + f_b + f_i + f_h \) which are respectively the contact, body, inertia and hydraulic forces, on each unit. To obtain the time varying hydraulic forces within Solidity, an exact linear interpolation from IH2VOF cells to Solidity surface element meshes is performed. Surface pressures on each unit are then integrated by the Wave Proxy code to give “form drag” forces which include buoyancy effects. The form drag forces are computed and updated every 0.1s, as forcing source terms. The resultant forces and unit motions are obtained for the duration of the wave forcing inputs applied. For this
work, a 1 hour random wave sea state for the design storm is considered. For the time-history of the water pressure imposed on the breakwater, velocity data from any sources can be used, e.g. derived from theory, experimentally-measured, even the output from a CFD wave simulator. For example, a wave generator (olaFlow/IH2VOF) is used to create one-hour, 50-year and 100-year return period, storms and then apply it to the armour units. To compute the inertia and drag forces on armour units, the semi-empirical Morison equation is used in this work.

3 Results and discussions

For this work, a 45m wide, 28m high numerical panel of a breakwater structure with 242 units in 20 rows of 5m$^3$ Core-Loc units were placed on a 4H:3V slope with a typical toe and underlayer. Using the CHL recommendations, two armour unit layers with different packing density, 0.603 and 0.625, were built (see Figure 4).

![Concrete armour unit layers with different packing density, placed on rock underlayer; Color represents the index of each unit, from 1-242. Left: loose pack with packing density of 0.603, Right: tight pack with designed packing density of 0.625.](image)

3.1 Wave structure interaction

A sea state roughly equivalent to a 100-year design storm for the 5m$^3$ Core-Loc structure was modelled with the wave proxy. The 100 year design storm was characterised by $H_s = 7m$ and $T_p = 11$ seconds and was simulated for a duration of 60 minutes. The pressure time history for a permanently submerged cell, from which the water surface elevation arriving at the structure can be deduced, is shown in Figure 5. The influence of the 100 year storm wave action on a loosely packed structure is shown in Figure 6. The total pressure (shown in Figure 6a and Figure 6b) includes hydrostatic and non-hydrostatic pressures, thus the pressure varies to the depth of the units in the armour unit layer. Velocities of Core-Loc armour units during regular wave action is shown in Figure 6c, and velocities during run-down are shown in Figure 6d. It clearly shows that the units are dragged down the slope during the wave run-down.

![100 year design storm to be simulated with the Wave Proxy: presented as pressure (kPa) versus time (s) at a permanently submerged cell inside the armour layer near the centre of the model.](image)
3.2 Effect of pack density of the breakwater armour layer

3.2.1 Tightly packed structure, Packing density (PD)=0.625

Figures 7-9 show the behaviour of tightly packed structure under 50 and 100 year return period sea states. The packing density, 0.625, is slightly higher than the design value (0.624) indicated for 5m³ Core-Loc (CLI online document). The structure is fairly stable, and the maximum displacement is in the range of 0.6 Dn-0.8 Dn under both sea states. The results are in good agreement with CHL’s report (Figures 7,8). The numerical method calculates not only the displacement distribution but also the total displacement which is cumulative in any direction for all Core-Loc units. Figure 9 shows the evolution of the total displacement in the tightly packed Core-Loc structure with time. Under 50 year return period sea state the structure is unstable in the beginning of the storm, but quickly is stabilised after 600s. The similar behaviour is found for the structure under 100 year return period sea state. This is because the structure has the ability to change the positions of units and adapt to the designed wave conditions after impact of first 100-150 waves.
Fig. 8  Numerical wave tank simulation of armour movement on a tightly packed Core-Loc structure (PD 0.625). Comparison of total displacement vectors after one-hour 100 year recurrence interval storm; left: experiment results from CHL’s report, right: numerical results of wave proxy.

Fig. 9  Evolution of the total displacement of all Core-Loc units in a tightly packed structure (PD 0.625) with time

3.2.2  Loosely packed structure, Packing density (PD=0.603)

Figures 10-12 show the behaviour of a loosely packed structure (PD=0.603) under 50/100 year return period sea states. As the packing density is well below the designed value (0.624), it is understandable that nearly 50% of the Core-Loc units have moved above 0.2-0.4Dn, the maximum displacement is in the range of 1.2Dn-1.4Dn under both sea states. The results also qualitatively agree with CHL’s report. It is also found that under the 50 year return period sea state the structure still has a big jump in total displacement after 2800 seconds. It is worth to run more tests for another 50 year return period sea state which lasts more than one hour.

4  Conclusions

In this paper, a new and fast wave proxy approach for wave-structure interaction is presented. The workflow of the wave proxy is illustrated. These preliminary results show the hydraulic flow and wave action loads coupled to our FDEM solver, SOLIDITY \( \hat{R} \), via the wave proxy. Further research enabling the most optimal and realistic coefficients for use with the Morison equation approach for hydraulic force interaction will include directly measured forces on Core-Loc units through experimental work at the University of Ottawa, Canada.
Fig. 10. Numerical wave tank simulation of armour movement on a loosely packed Core-Loc structure (PD 0.603). Comparison of total displacement vectors after one-hour 50 year recurrence interval storm; left: experiment results from CHL’s report, right: numerical results of wave proxy.

Fig. 11. Numerical wave tank simulation of armour movement on a loosely packed Core-Loc structure (PD 0.603). Comparison of total displacement vectors after one-hour 100 year recurrence interval storm; left: experiment results from CHL’s report, right: numerical results of wave proxy.

Fig. 12. Evolution of the total displacement of all Core-Loc units in a loosely packed structure (PD 0.603) against time.
Acknowledgments

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