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https://doi.org/10.53256/COSE_220201

Numerical study of Core-Loc™ breakwater stability under storm wave sea states using a fast wave proxy approach

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ABSTRACT

To meet the demands of practicing engineers for realistic-scale wave-breakwater interaction problems, the authors propose a new and fast "wave proxy" approach. In this approach, a rigid FDEM version – *SOLIDITY_R* – is employed to simulate structure-structure (e.g. armour unit) interaction. Hydrodynamic forces, form and skin drag, on units are calculated by the surface integral of fluid pressure at the local element level and by the Morison equation, respectively. Then these forces are integrated and applied to each unit along with contact and gravitational forces. The time series of pressures and velocities are obtained from a CFD wave tank (olaFlow/IH2VOF). In this paper, the authors illustrate the workflow of the wave proxy and some preliminary results showing the interaction between one hour long and 50/100 year return period storms with CORE-LOC™ breakwaters with different packing densities using the 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 mechanics 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 breakwaters under wave attack (Xiang et al., 2013, Latham et al., 2013).

For wave structure interaction (wave breaking on rubble mound structures, wave overtopping, wave reflection, etc.), one-way coupling models have been developed for rubble mounds with armour units fixed in place, or volume-averaged into homogeneous permeable layers (Liu et al., 1999). Most Numerical Wave Tanks (NWTs) aim to create, propagate and absorb wave energy realistically and to capture complex free surface configurations, including plunging waves. In recent years further wave simulation developments with parallelised commercial and open source codes such as FLOW3D (Dentale et al., 2009), CFX, Fluent and the increasingly popular OpenFOAM (Higuera et al., 2013, 2014) have indicated a modelling future fully capable of simulating turbulent waves interacting within the armour and porous layers of rubble mounds. Most recently, even the Lattice-Boltzmann method has been upgraded to simulate such physics (Xing et al., 2022). Other NWTs exist such as ones that use Lagrangian (particle-based) CFD models, which are meshless and can be more easily parallelized. These include Smooth Particle Hydrodynamics (SPH) (Gómez-Gesteira et al., 2010, Altomare et al., 2014,), and Moving Particle Semi-implicit (MPS) methods (Khayyer and Gotoh, 2010), or combine SPH with polyhedral DEM (Sarfaraz and Pak, 2018), to allow multi-material modeling (e.g. air-water boundaries) which are inherently simple to couple with moving solids.

The major challenge to model such complex systems is to include the interaction of energetic storm waves breaking on free complex solid structural elements, which interact with the other solid armour units. For the two-way modelling of wave structure interaction, a novel numerical model has been developed coupling FDEM with the generic multiphase CFD code Fluidity using 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 fully two-way coupled method is its high CPU cost, which hinders simulating a full breakwater system formed of thousands of units. After it is fully optimised and parallelised, it is expected that this coupled model will be able to simulate large-scale breakwater systems.

In order to carry out numerical tests that are useful in research and consultancy, the first task is to build a virtual breakwater in a computer environment with geometries representative of real armour units. However, accuracy limitations of surveyed data lead to inherent small but significant overlaps between solid bodies that cannot be used directly by the FDEM solver. Therefore, 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 for the user to set the particle/unit properties, e.g. centroid, orientation (can also be set randomly), initial velocity to deposit particles/units faster, etc. As mentioned earlier, the FDEM method is capable of simulating not only complex shapes but also deformable bodies. However, the main drawback of allowing deformability within units is the high CPU cost which hinders such a high fidelity FDEM model from simulating a full breakwater system formed of over a thousand units. Based on the deformable FDEM code Solidity_D, a rigid version of the FDEM code, Solidity _R was developed recently. The main difference between Solidity_D and Solidity_R is that Solidity_R only simulates rigid bodies and solid deformation (i.e. internal strain/stress) 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 constructing a realistic armour unit layer.

To meet the demands of practicing engineers to solve prototype-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 and the wave motion is treated as a periodically varying load. Hydrodynamic forces on individual units are calculated by integrating the fluid pressure obtained from 2D (IH2VOF) and 3D (olaFlow) 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 armour stone 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 a 24-hour running time when using 20 threads on a Linux workstation (Intel Xeon E5-2667 v3, 3.2GHz). The code is scalable to 100 threads using OpenMP on AMD EPYC 7742 64-Core Processor. We summarise all software used in this paper in table 1.

Table 1. Solid mechanics and CFD software used in this paper.

Software	Function
POSITIT	A tool for introducing particles into a computational domain. It can be used widely for industrial applications, e.g., armour unit placements and creation of realistic armour layers, particle depositing tool, etc.
Solidity_D	Fully deformable FDEM code to simulate complex shapes of deformable bodies. Capable of simulating internal strains/ stresses. Its main drawback is the high CPU cost.
Solidity_R	A rigid version of the FDEM code to simulate rigid solids only. Solidity_R is much faster than Solidity_D and requires a much smaller CPU cost.
IH2VOF	Computational Fluid Dynamics solver to simulate wave and structure interactions in 2D. Coastal structures are described using a porous media approach.
olaFlow	Computational Fluid Dynamics solver based on OpenFOAM to simulate wave and structure interactions in 2D and 3D. Coastal structures can be described using a direct (solid) approach (3D) or a porous media approach (2D/3D).

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.

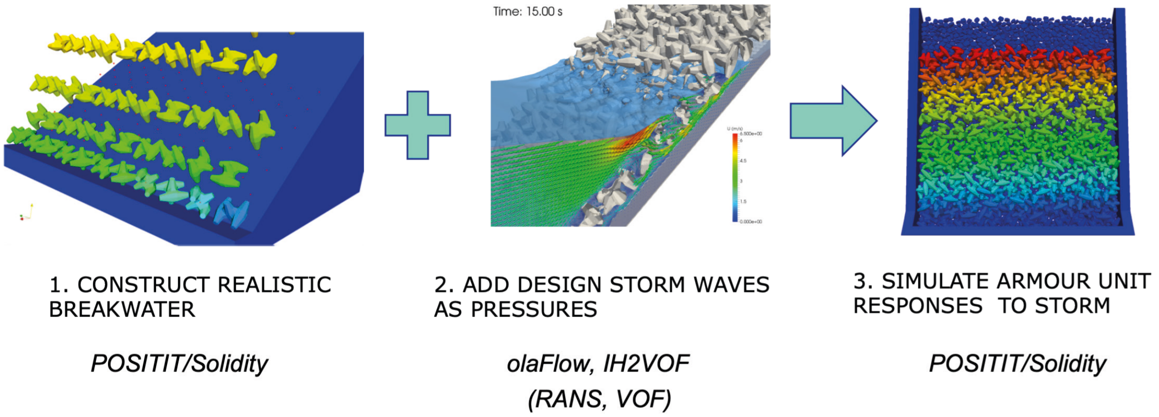

Figure 1. Workflow of the Virtual Breakwater Wave Proxy Simulation Tools

2 VIRTUAL BREAKWATER WAVE PROXY SIMULATION TOOLS

Previous research by Applied Modelling & Computation Group (AMCG) in Imperial College London 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 the 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 the 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 realistic results observed were an improvement on vibrations affecting all units, but the simplified representation of velocities in the armour layer led to motions that lacked some of the expected behaviour observed 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 (Latham, et al, 2015):

1. the solids' modelling code with recently enhanced capability, coupled POSITIT/*Solidity_R*, is used to construct a realistic breakwater;
2. both 2D (IH2VOF) and 3D (olaFlow) NWTs are used to generate a one-hour storm for both a 50 and a 100 year return period storm on the breakwater geometry;
3. storm forcing is applied to armour units to simulate the displacements.

2.1 Construct realistic virtual breakwater

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 the 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 first 3D FDEM code was developed by Xiang and Munjiza (Xiang, et al., 2009) and was named as Y3D and released in 2009. Since 2009, the code efficiency was enhanced with optimisation and parallelisation in 2016, the current name 'Solidity' was adopted for the Imperial College team's FDEM platform. 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 overlapping volume in order to be distributed among the surrounding nodes.

POSITIT/Solidity_R allows the user to choose any particle shape, 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 applied to generate an armour unit layer of 242 8m^3 CORE-LOC™ 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 the maximum contact force between unit and unit or unit and rock is also analysed (see Figure 2a). Figure 3b also shows that the 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 referenced to the structure slope is used to show the orientation distribution of the nose axes of the placed unit.

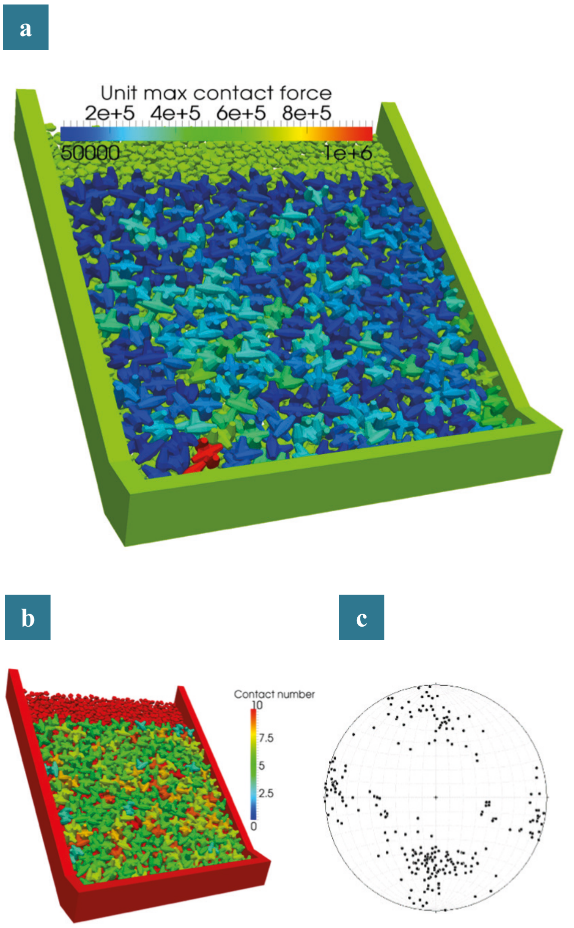

Figure 2. FDEM placement of armour layers including useful analysis tools: (a) a snapshot of an armour layer of 242 CORE-LOC™ units, the color represents each unit'smaximum contact force; (b) the contact number of each unit is defined as the number of contacts each unit makes with its neighbours; (c) stereographic plot of unit nose axis dip angle and dip azimuth with reference to the average slope plane and breakwater trunk axis.

2.2 Wave modelling

Both 2D (IH2VOF, Lara et al., 2008) and 3D (olaFlow, Higuera, 2017) CFD models were used in the test programme (Table 2) to simulate the wave action on the newly-built structure. As 3D runtimes are excessive for full storm durations, olaFlow was used to evaluate the 3D effects and validate the 2D simulations, which are faster. In the 3D simulations a solitary wave and regular waves were tested. While the armour layer was explicitly captured, the underlayer was too complex to model. Therefore, it was represented as a homogeneous porous medium with porosity = 0.5 and D_{50} = 1.0 m and nonlinear frictional losses (Darcy-Forchheimer coefficients α and β, see Table 2) based on Higuera et al. (2014). olaFlow produces the pressure-time (p-t) history and flow velocity field around the units in 3D.

The solitary wave test in Series 1 was repeated for the 2D model in Series 2. Using 2D modelling requires that the armour layer is represented by the Darcy-Forchheimer model. Therefore, the optimal values for the α_1 & β_1 coefficients were chosen based on the ability to reproduce the time series of 3D pressures averaged in the y-direction (the coordinate system is defined in Fig. 3 top right) among 20 2D tests with different parameters. Having obtained the friction parameters for the 2D model, the next task was to evaluate the variations in pressure-time histories that are observed due to the 3D variability. Therefore, Series 3 was 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 given in our previous paper (Latham et. al. 2015). This simulation with H = 6.5m, T_p = 10s, h=12m, and a real simulation time of 65s was completed in 5 days using 96 processors.

Table 2. Test Programme – Calibrations (Series 1-3) and Wave Proxy (Series 4)

Series		Waves	Void Structure of Armour Layer	Void Structure of Underlayer
1	3D: olaFlow	Solitary wave	Explicitly Captured	Porous media α & β Forchheimer
2	2D: IH2VOF	Solitary Wave Calibration	Porous media α1 & β1 Forchheimer	Porous media α & β Forchheimer
3	3D: olaFlow	Regular Waves For y-Variability	Explicitly Captured	Porous media α & β Forchheimer
4	2D: IH2VOF	Entire Sea State For Wave Proxy	Porous media α1 & β1 Forchheimer	Porous media α & β Forchheimer

OlaFlow provides pressure, velocity and fluid content (air/water content with the Volume Of Fluid technique) for some 4000 surface elements for each of the 242 units, sampled every 0.05s. The highly resolved 3D results are compressed into a 2D (xx-zz, 5m x 37.5m) slice of breakwater which consists of 100 x 750 square grid elements, each one being extruded into a long thin voxel of 44.5 m of 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 and velocity histories acting on the surface of that individual mesh element is recorded in the corresponding voxel. As indicated in the red box (Fig.3, bottom), there will be numerous (m-point) concrete surfaces per voxel, 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.

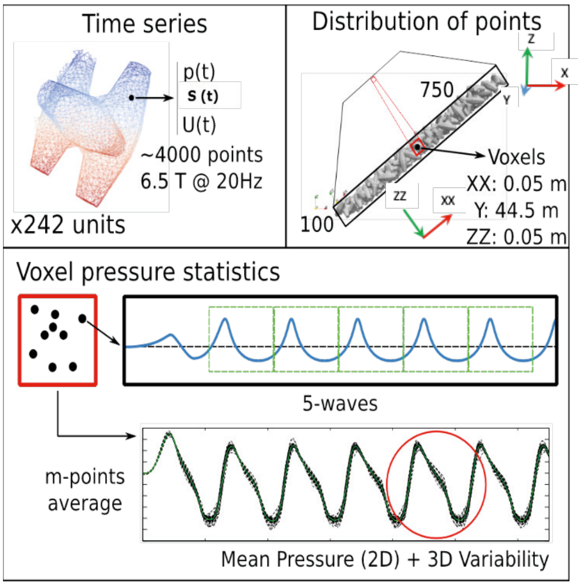

Figure 3. Methodology for capturing 3D pressure-time histories and synthesising variability statistics.

In short, the distribution varies differently in crests 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 (Series 4) are thus translated into 3D using variability statistics that were obtained from regular wave calibrations. The large file representing a storm history (pressures and velocities) is then compressed into netCDF with the input format required by the solids' Wave Proxy code. Further details of the method will be described in detail in a future paper.

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 hydrodynamic forces, on each unit. More information about these forces is available in published papers (Xiang, et al., 2009, Xiang et al., 2013; Latham et al., 2014).

To obtain the time varying hydrodynamic forces, *which comprise the form drag and viscous drag forces*, within *Solidity,* an exact linear interpolation in time and space from the netCDF file 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 and are, therefore, significantly larger than viscous drag forces. Hydrodynamic viscous forces arise from integrating the viscous stresses. However, since obtaining a detailed boundary layer flow description requires significantly larger computational efforts, in this work the viscous forces are approximated with the semi-empirical Morison equation:

$$F = \rho V \dot{u} + \rho C_a V(\dot{u} - \dot{v}) + 1/2 \rho C_d A(u - v)\left|u - v\right| \qquad (1)$$

where is the fluid density, V is the volume of the body, Ca is the added mass coefficient, Cd is the drag coefficient, u is the fluid velocity, v is the solid velocity (equal to zero in the CFD

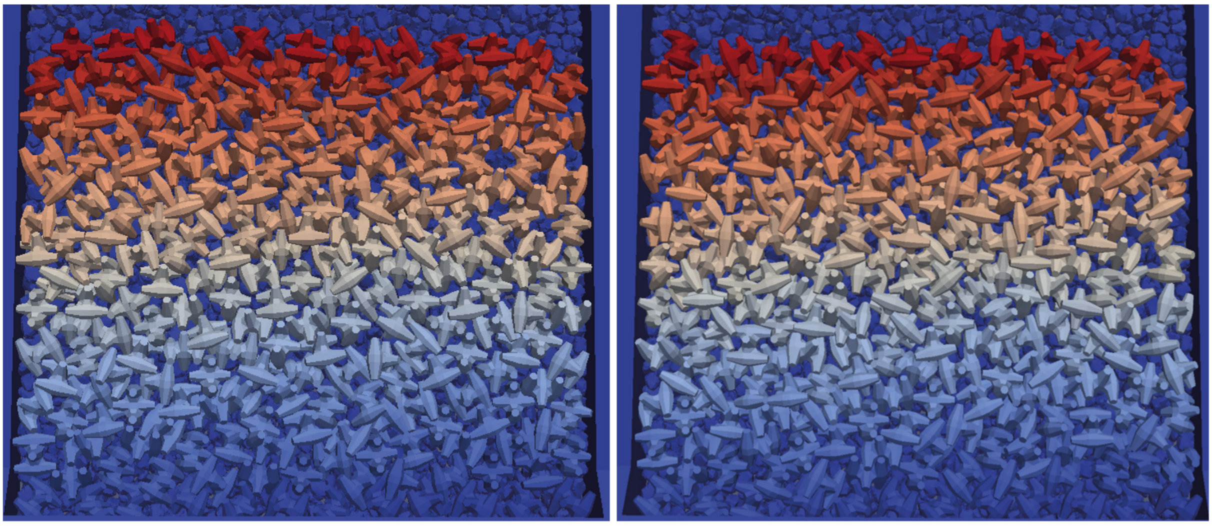

Figure 4. Concrete armour unit layers with different packing density, placed on rock underlayer; Color represents the index of each unit, from 1-242. Left: loose pack with packing density of 0.603, Right: tight pack with designed packing density of 0.625.

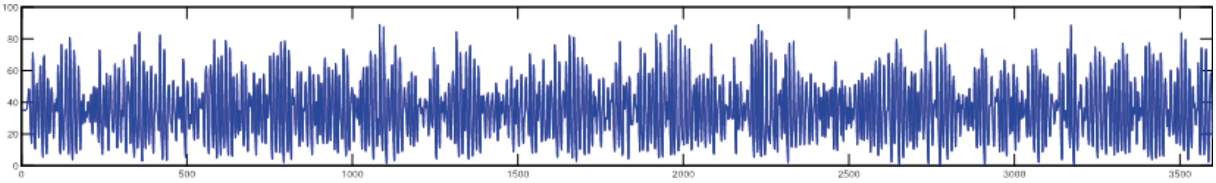

Figure 5. 100 year design storm to be simulated with the Wave Proxy: presented as pressure (kPa) versus time (s) at a permanently submerged cell inside the armour layer near the centre of the model.

code). In this study, we only consider the drag force F_D which is the third term on the right hand side of the Morison equation. We recognise the importance of the inertia term of the Morison's equation. We have in fact implemented this term and have obtained interesting results which suggest that in certain cases the inertial force can exceed the drag force magnitude. However, this effect is not that predictable, especially if units move. Inertia force can even be acting in opposite directions to drag force. Until we can thoroughly investigate the fuller complexity of both terms, we make the assumption that the drag term generally is the dominating term for stability prediction (Eq. 2). Similarly, simplifying the real pressure distribution leading to the hydrodynamic force may mask wave slamming and impulsive forces, which may be of importance locally despite their short duration. In the near future, we will implement the inertia force calculation and evaluate the effect of it along more localized effects on the stability of the breakwater.

$$F_D = 1/2 \rho C_d A(u-v)\left|u-v\right| \qquad 2$$

The hydrodynamic 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, 1 hour irregular wave sea states for the design storm (50- and 100-year return periods) are simulated with IH2VOF, but any other NWT able to simulate porous media flow and store the pressures and velocities in the required format could also be applied.

3 RESULTS AND DISCUSSIONS

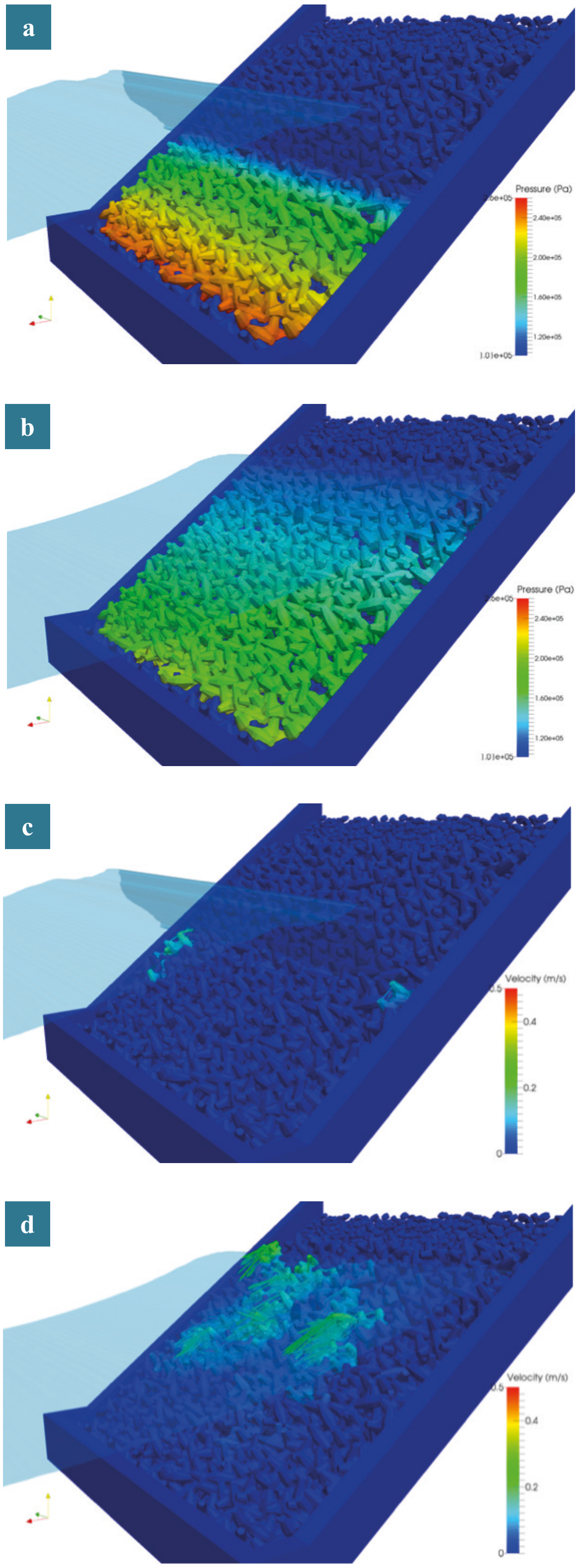

Figure 6. Total water pressure on CORE-LOC™ armour units (a,b), Velocities during wave run-up and (c) run-down (d).

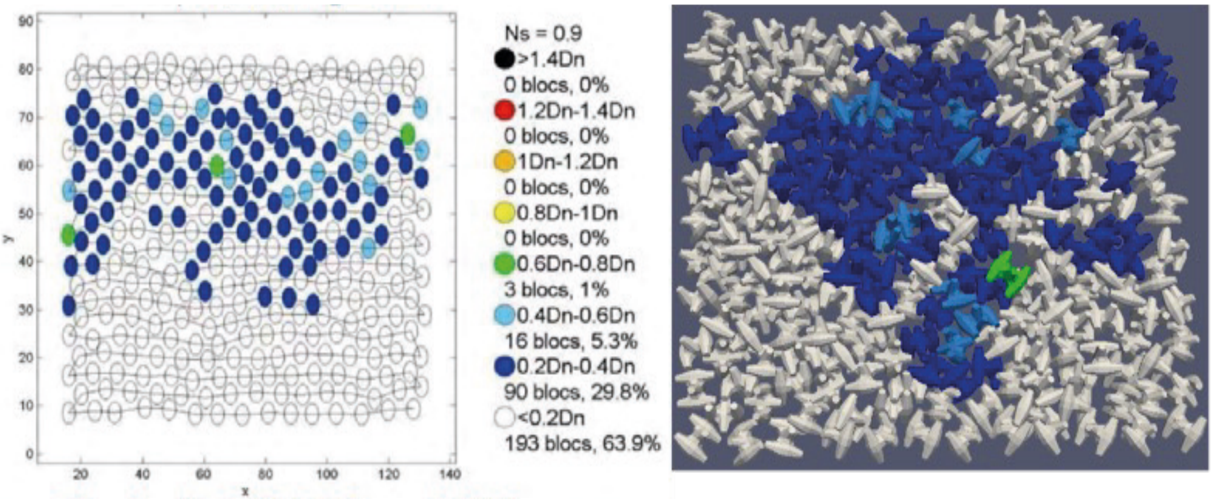

Figure 7. Numerical wave tank simulation of armour movement on a tightly packed CORE-LOC™ structure (PD 0.625). Comparison of total displacement vectors after one-hour 50 year recurrence interval storm; left: experiment results from CHL's report, right: numerical results of wave proxy.

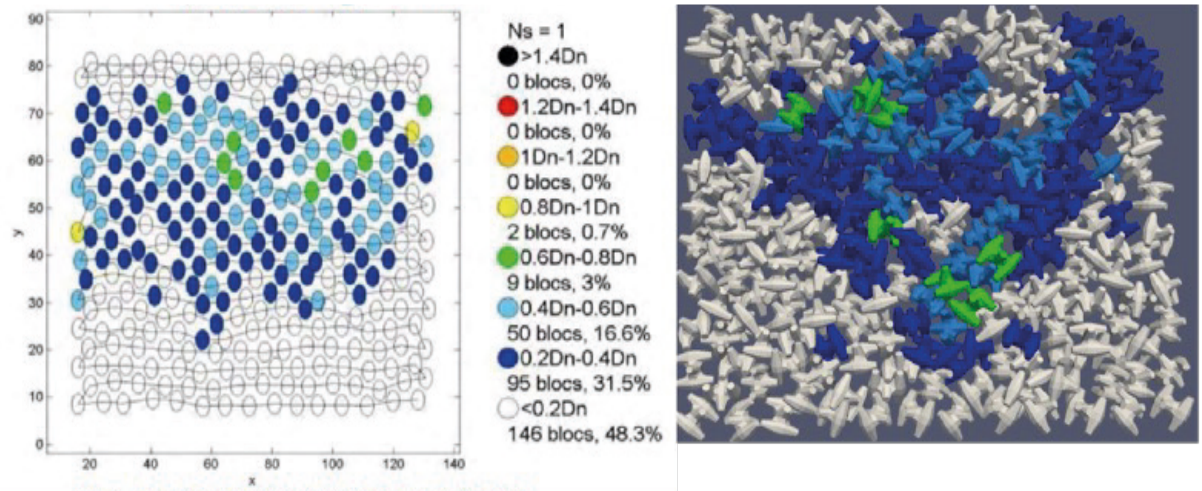

Figure 8. Numerical wave tank simulation of armour movement on a tightly packed CORE-LOC™ structure (PD 0.625). Comparison of total displacement vectors after one-hour 100 year recurrence interval storm; left: experiment results from CHL's report, right: numerical results of wave proxy.

For this work, a 45m wide, 28m high numerical section 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 Coastal and Hydraulics Laboratory - US Army Corps of Engineers (CHL) recommendations, two armour unit layers with different packing density, 0.603 and 0.625, were built (see Figure 4). In CHL's report, the centroid of each armour unit and packing density of the armour layers before and after the storm are provided. However, the orientation and the contact forces are unknown. Therefore, it is very difficult to match the displacements of each armour unit. Instead, general patterns are discussed next.

3.1 Wave structure interaction

A sea state roughly equivalent to a 100-year design storm for the 5m³ 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 from IH2VOF 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. Displacement velocities of CORE-LOC™ armour units during regular wave action are 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 phase.

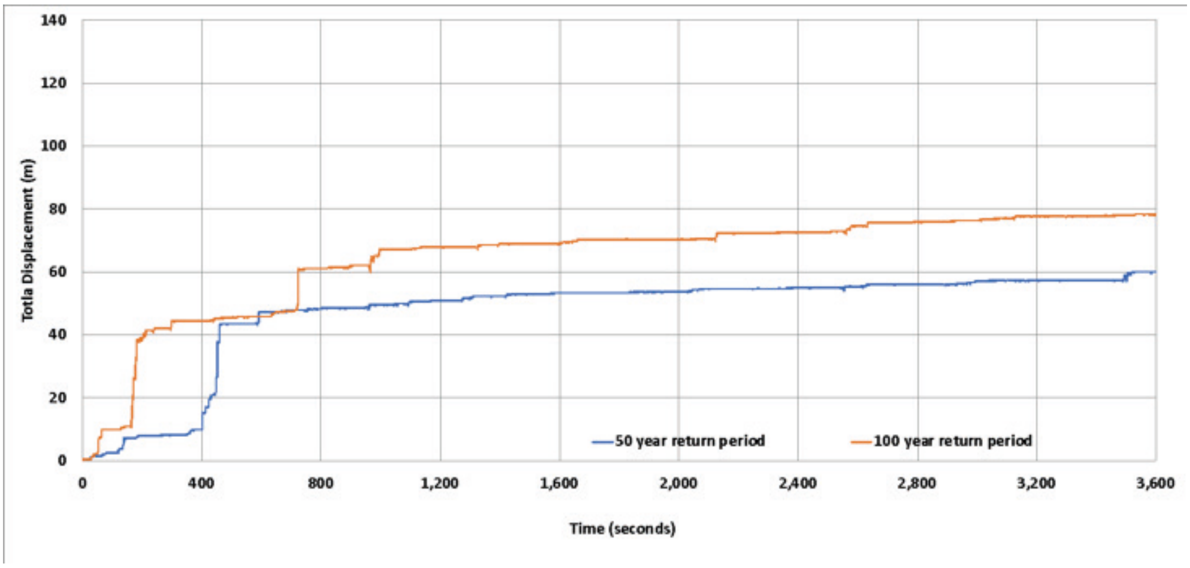

Figure 9. Evolution of the total displacement of all CORE-LOC™ units in a tightly packed structure (PD 0.625) with time.

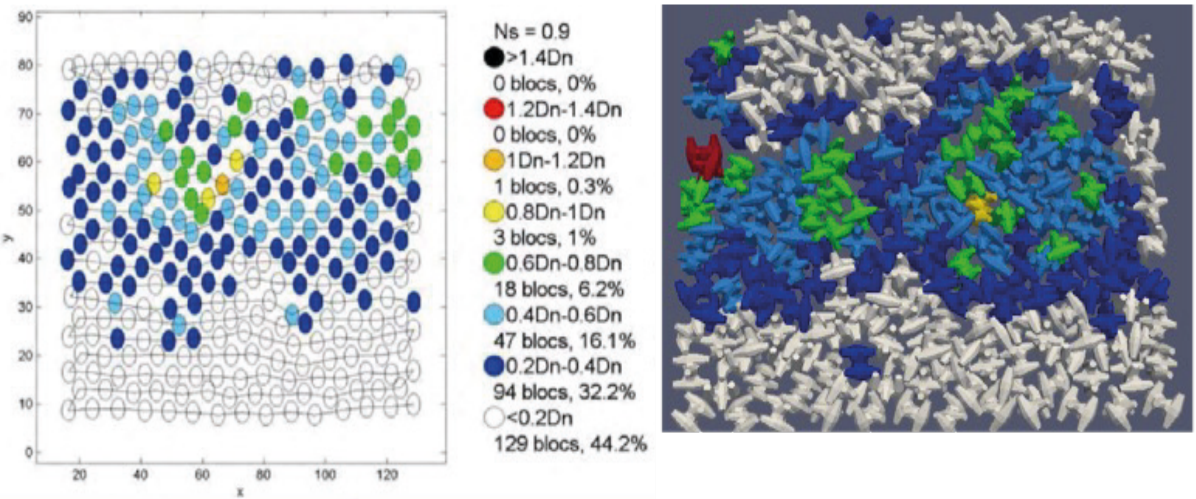

Figure 10. Numerical wave tank simulation of armour movement on a loosely packed CORE-LOC™ structure (PD 0.603). Comparison of total displacement vectors after one-hour 50 year recurrence interval storm; left: experiment results from CHL's report, right: numerical results of wave proxy.

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 the 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 0.6-0.8 Dn for 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 the 50 year return-period sea state, the structure is unstable in the beginning of

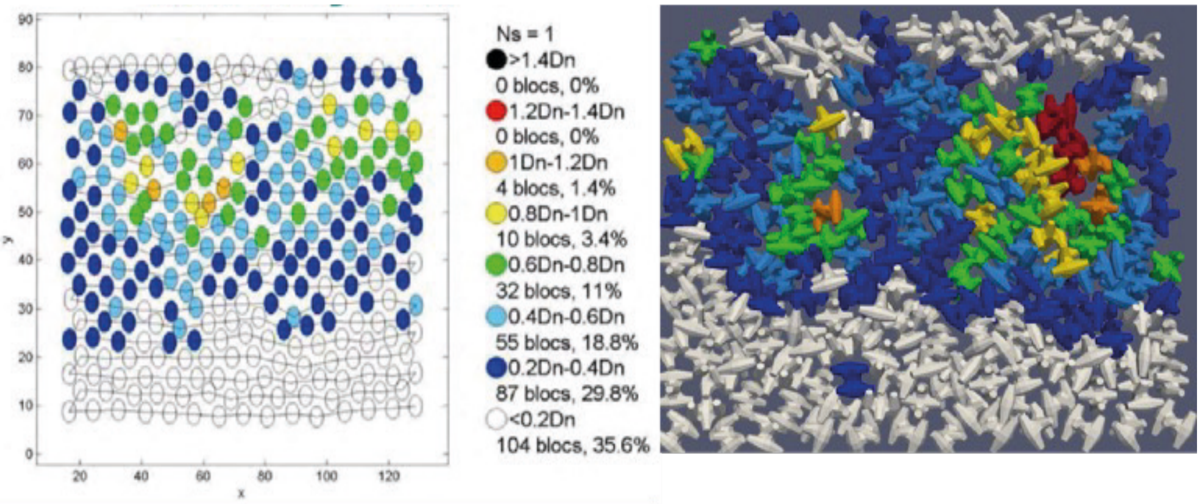

Figure 11. Numerical wave tank simulation of armour movement on a loosely packed CORE-LOC™ structure (PD 0.603). Comparison of total displacement vectors after one-hour 100 year recurrence interval storm; left: experiment results from CHL's report, right: numerical results of wave proxy.

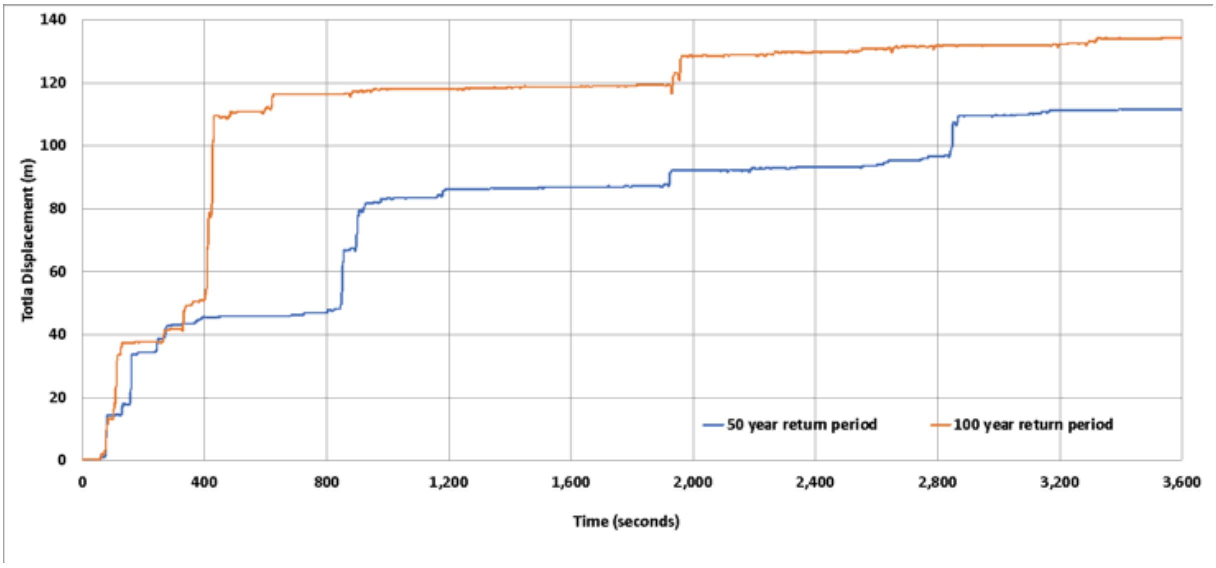

Figure 12. Evolution of the total displacement of all CORE-LOC™ units in a loosely packed structure (PD 0.603) against time.

the storm, but is quickly stabilised after 600s. A similar behaviour is found for the structure under the 100 year return-period sea state. It is worth mentioning that the structures are newly-built and not shaken by the waves. The structure has the ability to change the positions of units and adapt to the designed wave conditions after the impact of the first 100-150 waves (mean period of ~12s).

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 design value (0.624), it is understandable that nearly 50% of the CORE-LOC™ units have moved above 0.2-0.4 Dn, the maximum displacement is in the range of 1.2 -1.4 Dn for 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 average displacement after 2800 seconds. The evolution of displacement over the storm appears on average to follow a power law form but expressed in terms of major event steps.

Given that the sea states are simulated using CFD prior to FDEM, there exists the potential to examine which wave group events lead to significant simultaneous multiple movements of units and also the subsequent rocking behaviour that is often observed and that can have important structural implications.

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 wave action loads derived from CFD modelling with the IH2VOF and olaFlow models, coupled to the FDEM solver *SOLIDITY_R* via the wave proxy. The inertia forces, although assumed here to be of secondary importance compared to the form drag forces, may also prove to be key for the hydrodynamic interaction and for realistic armour damage assessment. Therefore, further research will focus on evaluating both the role of the inertia force together with the most optimal and realistic drag coefficient used with the Morison equation approach. This future work will include validation with directly measured forces on CORE-LOC™ units through experimental work performed at the University of Ottawa, Canada.

ACKNOWLEDGEMENTS

The authors are grateful for the substantial early financial support and expertise of Artelia Group and Baird Associates and to the EPSRC (grants EP/H030123/1, EP/K503733/1) for sponsoring this research.

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