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On the simulation of highly nonlinear wave-breakwater interactions

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ABSTRACT: A numerical time domain simulation model has been developed to study the highly nonlinear interactions between waves and rubble mound breakwaters. In this model, a volume of fluid (VOF) technique is used to capture the violent free surface motion. The incompressible Euler/Navier-Stokes equations, written in an arbitrary Lagrangian-Eulerian (ALE) frame, are solved using projection schemes and a finite element method on unstructured grids. A general advancing front technique for filling space with arbitrary separated objects is developed to model the rubbles that are laid down on the sloped surface of the breakwater in a random way. Three case studies are performed to study the effects of rubbles and rubble types on the wave dissipation and wave overtopping.

KEY WORDS: Wave-body interaction; Rubble mound breakwaters; VOF; FEM; Overtopping; Grid generation.

1 INTRODUCTION

Rubble mound breakwaters are important coastal defense structures for harbor and shore protection. The principal function of a rubble mound breakwater is to protect a coastal area from excessive wave action. The dissipation of wave energy through absorbtion rather than reflection distinguishes rubble mound breakwaters from other types of fixed breakwater. It is of great practical engineering interest to model the highly nonlinear interactions between waves and rubble mound breakwaters and to investigate the effects of rubbles and rubble types on the wave dissipation and wave overtopping.

Until recently, the complex aspects of breakwater behavior were considered too challenging for detailed numerical simulations. This is especially the case for breakwaters consisting of rubble mounds composed of blocks of concrete or rocks in which water flows through complex paths with unsteady motion (Dentale, et al. [2]). Instead of creating a numerical flow domain in which rubble mound breakwaters are modeled on the basis of their real geometry, and simulating the hydrodynamic interactions of rubbles and flows, rubble mound breakwaters are approximated as homogeneous porous media (e.g., Sakakiyama and Kajima [19]; van Gent [4]; Liu et al. [11]; Isobe et al. [8]; Hsu et al. [6]; Hur and Mizutani [7]; Ting et al. [20]; Koutandos, et al. [10]; Karim et al [9]). In this study, the research effort is focused on finding a way to lay down the rubbles, such as stones or concrete blocks, on the given sloped surface of the breakwaters in a random way. Therefore, it is necessary to develop a technique that can fill a prescribed volume with arbitrary objects so that they are close but do not overlap in an automatic way. The technique used in the present study is based on the 'advancing front' or 'depositional' method (Löhner and Oňate [13-14]; Feng, et al. [4]). Starting from the surface, objects are added where empty space still exists. In contrast to the 'fill and expand' procedures (Sakaguchi and Murakami [18]), the objects are packed as close as required during introduction. Depending on how the objects are introduced, one can mimic gravitational or magnetic deposition, layer growing, or size-based growth. Furthermore, so-called radius growing can be achieved by first generating a coarse cloud of objects, and then growing more objects around each of these (Löhner and Oňate [14]). In this way, one can simulate granules or stones.

The proposed scheme allows for the direct generation of clouds of arbitrary objects with the same degree of flexibility as advanced unstructured mesh generators. The object size and the mean distance between objects (or, equivalently, the material density) is specified by means of background grids, sources and distance (size) attached to CAD-entities. In order not to generate objects outside the computational domain, we assume an initial triangulation of the surface that is compatible with the desired size of objects specified by the user. Moreover, we assume that the objects to be introduced are described by a coarse mesh of tetrahedra, and therefore have an external triangulation that is also compatible with the desired object size specified by the user. This is in contrast to the simplified method proposed in (Löhner and Oňate [14]), where the objects were described as a set of spheres. The penetration checks based on spheres proved unreliable for more complex objects, prompting the development of the technique described here. Starting from the boundary, i.e. the initial 'front' of faces, new objects are added, until no further objects can be introduced. In the same way as the advancing front technique for the generation of volume grids removes one face at a time to generate elements, the present scheme removes one face at a time, attempting to introduce as many objects as possible in its immediate neighborhood. This general advancing front technique to fill volumes with arbitrary objects has been used successfully to fill the given volumes with various objects (Löhner and Oňate, 2010[15]). In order to build the geometry model for studying the highly nonlinear interactions between waves and rubble mound breakwaters, this advancing front technique is used to lay down the cubes or tetrapods on the given sloped surface in a random way.

The interaction between waves and rubble mound breakwaters is a very complex and highly nonlinear free surface flow problem that involves overturning and breaking waves. As the objective of this study is to model the highly nonlinear free surface flows associated with the overturning and breaking wave phenomenon, one of the most promising interface-capturing methods -- volume-of-fluid (VOF) method (Hirt and Nichols[5]) is adopted in this study to capture the violent free surface motion. A single-phase VOF method is coupled with an unstructured grid based Euler/Navier-Stokes finite element solver to model highly nonlinear wave-body interactions. A steep regular wave is generated using a piston-type wave paddle (moving the left wall of the domain with a sinusoidal excitation). A fixed grid is used, which covers the space occupied by both the water and the air phases. An extrapolation algorithm is developed for obtaining the pressure and velocity in the air region. The surface nodes on the 'wave-maker plane' are moved according to the given sinusoidal excitation of the wave paddle. Approximately 30 layers of elements close to the 'wave-maker plane' are moved, and the Navier-Stokes/VOF equations are integrated using an arbitrary Lagrangian-Eulerian frame of reference. The compute code based on the present numerical model has been used to simulate the green water overtopping a fixed 2D deck, green water impact on fixed 3D bodies without and with a vertical wall on the deck, and green water impact on the deck and deckhouse of a moving FPSO model (Lu et al. [17]). Numerical results obtained using the present numerical model are compared with the experimental measurements for the aforementioned cases, and fairly good agreements are obtained. Therefore, the present numerical model can be used to model the violent free surface motion associated with the interaction of waves and rubble mound breakwaters.

2 NUMERICAL MODELING FOR THE HIGHLY NONLINEAR FREE SURFACE FLOW

Consider a breakwater shown in Fig. 1, where the wave is generated by the sinusoidal excitation of a piston paddle located at the left end of the computational domain. The y axis is vertical and points upward, the incoming wave propagates in positive x direction and is perpendicular to the breakwater, and the initial free surface is taken as the plane $y = 0$. Only half of the physical domain is considered in Fig. 1 as the computational domain due to the fact that the flow is symmetric about plane $z = 0$.

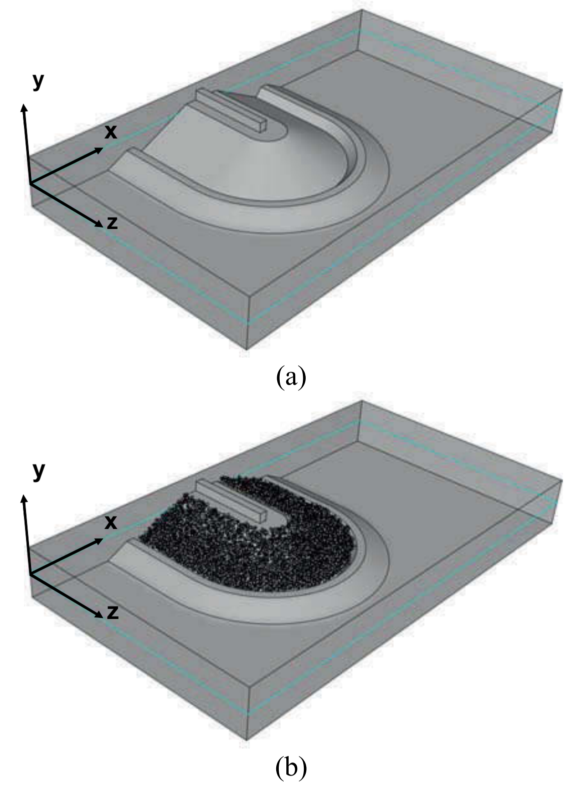


Fig. 1 Definition sketch of computational domain: (a) breakwater without rubble mound; (b) breakwater with rubble mound

The governing equations in the fluid dynamics model are the incompressible Navier-Stokes equations, which are written in an arbitrary Lagrangian-Eulerian (ALE) frame as follows,

$$\rho\, \boldsymbol{v}_{,t} + \rho\, \boldsymbol{v}_a \bullet \nabla \boldsymbol{v} + \nabla p = \nabla \bullet \mu\, \nabla \boldsymbol{v} + \rho\, \boldsymbol{g}, \qquad (1)$$

$$\nabla \bullet \boldsymbol{v} = 0. \qquad (2)$$

Here ρ denotes the density, $\boldsymbol{v}$ the velocity vector, p the pressure, μ the viscosity and $\boldsymbol{g}$ the gravity vector. The advective velocity is given by $\boldsymbol{v}_a = \boldsymbol{v} - \boldsymbol{w}$, where **w** is the mesh velocity. Both the air and water phases are considered incompressible, thus Eq. (2).

The water-air interface is described by a scalar equation of the form:

$$\Phi_{,t} + \boldsymbol{v}_a \bullet \nabla \Phi = 0. \qquad (3)$$

For the VOF technique used here, Φ represents the total density of the material in a cell/element or control volume.

The incompressible Navier-Stokes equations given by Eqs. (1) and (2) are solved using projection schemes. The main elements of the numerical schemes are as follows:

- Spatial discretization using unstructured grids (in order to allow for arbitrary geometries and adaptive refinement);
- Spatial approximation of unknowns with simple finite elements (in order to have a simple input/output and code structure);
- Temporal approximation using implicit integration of viscous terms and pressure (the interesting scales are the ones associated with advection);
- Temporal approximation using explicit integration of advective terms;
- Low-storage, iterative solvers for the resulting systems of equations (in order to solve large 3-D problems); and
- Steady results that are independent from the time step chosen (in order to have confidence in convergence studies).

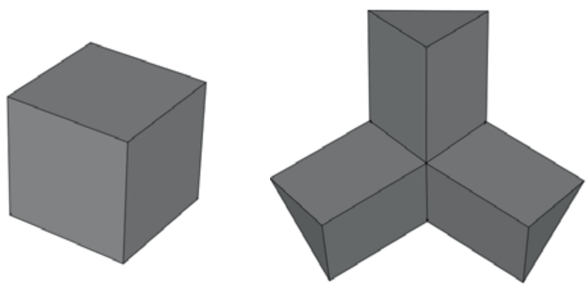
Recently, efforts have been devoted to integrate the advective terms in a more efficient way, either through multi-stepping or implicit iterative solvers (Löhner[12]; Löhner et al.[16]), and to develop a new preconditioned conjugate gradient technique for the solution of the pressure Poisson equation within an incompressible flow solver to reduce the number of iterations (Aubry, et al.[1]).

The computer code based on the numerical model described above has been used to simulate the green water overtopping a fixed 2D deck, green water impact on fixed 3D bodies without and with a vertical wall on the deck, and green water impact on the deck and deckhouse of a moving FPSO model (Lu et al.[17]). Numerical results obtained using the present numerical model are compared with the experimental measurements, and fairly good agreements are obtained. Therefore, the present numerical model can be used to model the violent free surface motion associated with the interaction of waves and rubble mound breakwaters.

3 SETUP OF RUBBLE MOUND BREAKWATERS

A general advancing front technique to fill volumes with arbitrary objects has been developed to lay down the stones or concrete blocks on the sloped surface of the rubble mound breakwaters in a random way. The input required consists of the specification of the desired object size and mean distance between objects in space and an initial triangulation of the surface. Each of the objects to be generated is given by a small tetrahedral mesh with an associated set of external faces. As with ordinary advancing front techniques for the generation of grids, one face at a time is removed and, if possible, surrounded by admissible new objects. This operation is repeated until no active faces are left.

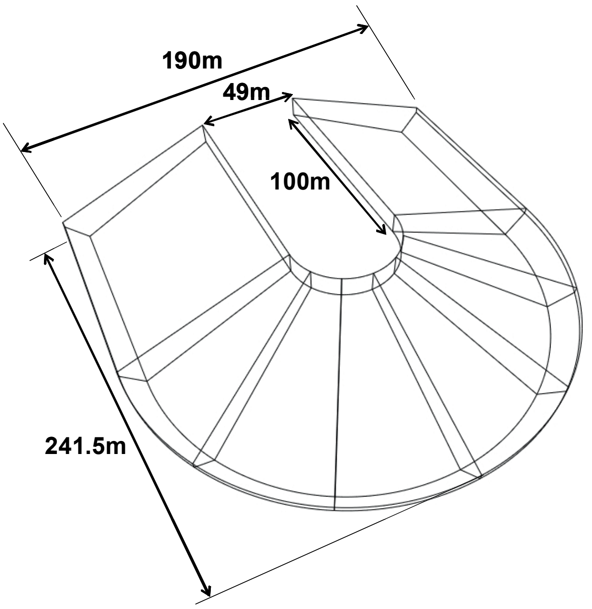
The details of the different techniques used to obtain maximum packing are discussed in author's previous work (Löhner and Oňate[15]). In the present study, two types of objects, cubes and tetrapods, shown in Fig. 2, are used to fill the sloped surface of the rubble mound breakwaters.



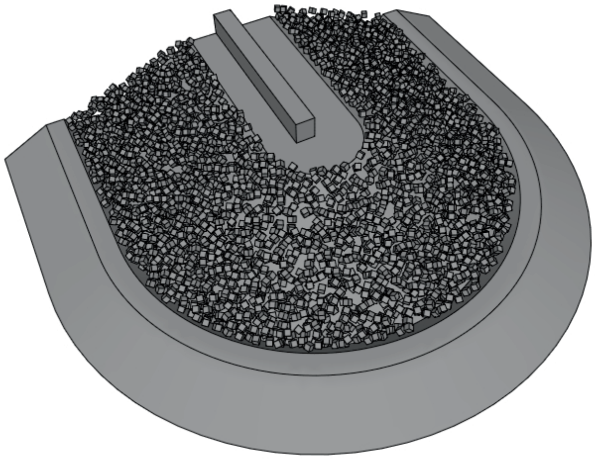
(a) (b)

Fig. 2 Two types of objects for the rubble mound breakwater: (a) cube; (b) tetrapod

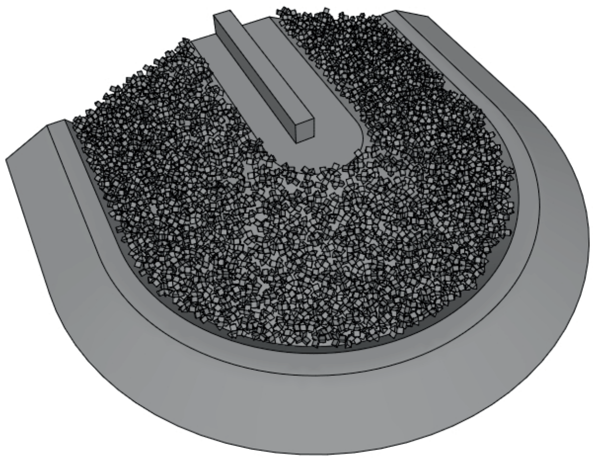
The sloped surface of the rubble mound breakwater and its main dimensions are shown in Fig. 3(a). The total length of the breakwater is approximately 283m, and the width 190m. Figs. 3(b) and 3(c) show the sloped surface of the rubble mound breakwater is filled with 2860 cubes and 1316 tetrapods, respectively.



(a)



(b)



(c)

Fig. 3 Half of the breakwater with or without the rubbles: (a) definition sketch; (b) filled with cubes; (c) filled with tetrapods

Each cube in Fig. 3(b) has a side length of 2.82m and a volume of 22.4m^3. Each tetrapod in Fig. 3(c) has a side length of 2.67m and a volume of 35.4 m^3. The total volume of the cubes used to fill the breakwater is approximately 64,064 m^3, and the total volume of tetrapods used to fill the breakwater is approximately 46,548 m^3.

4 SIMULATION EXAMPLES

Numerical simulations have been performed for three cases: (i) the breakwater without rubbles; (ii) the breakwater filled with cubes; and (iii) the breakwater filled with tetrapods. The definition sketch of the computational domain is shown in Fig. 1(a) for the breakwater without rubbles, and Fig. 1(b) with cubes or tetrapods. The computational domain has a length of 542m, and a width of 300m. The water depth is 30m. The incoming wave is generated using a piston-type wave paddle, i.e., by moving the left wall of the domain with a sinusoidal excitation. The period of excitation is T=15 s, and the stroke of excitation is 20m. The piston-type wave paddle generates a regular wave that roughly has a wave length L = 234.31m and wave height H = 16m. The computational domain is discretized approximately into 7,000,000 tetrahedral elements. The numerical simulations are performed on a SGI ALTIX 3700 machine at George Mason University that has 64 Itanium 2 Processors. The runs are performed with OpenMP using 16 processors. The computing time is approximately 14 hours for each case to simulate 10 wave periods (150 s).

Numerical simulations show that the rubbles on the sloped surface can dissipate the wave greatly. Fig. 4 shows the comparison of the horizontal wave impact force acting on the dike (upper structure on the breakwater) for three cases. One can observe from Fig. 4 that the horizontal impact wave forces are of the same order of magnitude for the breakwater filled with cubes and tetrapods. However, the wave impact force is nearly one order of magnitude larger in the case without stones.

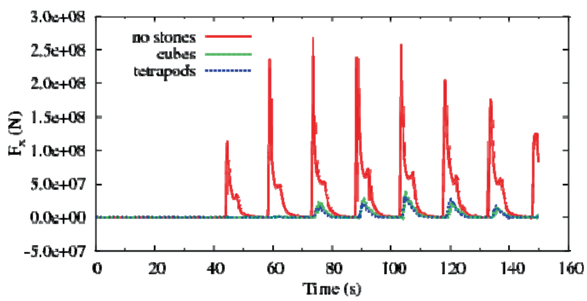


Fig. 4 Comparison of horizontal wave impact forces acting on the dike for the case without stones and filled with cubes and tetrapods

In order to further examine the impact wave force, the comparison of the horizontal wave impact forces for the breakwater filled with cubes and tetrapods is plotted again in Fig. 5 with different scale. This figure further demonstrates the fact that the wave impact forces are of the same order of magnitude for the breakwater filled with cubes and tetrapods.

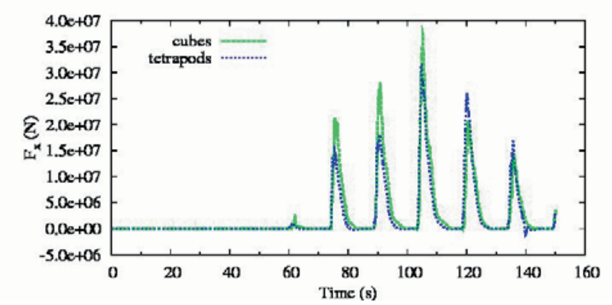


Fig. 5 Comparison of horizontal wave impact forces acting on the dike for the cases filled with cubes and tetrapods

The three-dimensional snapshots of the wave-breakwater interactions are shown in Fig. 6 for three cases, respectively, where the left column is for the case without stones, the middle column is for the case filled with cubes, and the right column is for the case filled with tetrapods. One can clearly observe that huge wave has been generated, including breaking waves and overtopping waves, in the case without stones. However, the wave fields look very similar in the case filled with cubes and the case filled with tetrapods, and no overtopping wave is generated. It should be noted that the total volume of tetrapods is much less than that of cubes (27% less). Therefore, one can save the material and achieve the same wave dissipation if the rubble mound breakwater is filled with tetrapods instead of cubes.

5 CONCLUSIONS

A numerical time domain simulation model has been developed to study the highly nonlinear interactions between waves and rubble mound breakwaters. A general advancing front technique for filling space with arbitrary separated objects is developed and used to model the rubbles, such as stones or concrete blocks, that are laid down on the sloped surface of the breakwater in a random way. The present space filling technique is very effective and efficient, which can be used to model the real geometry of the rubbles and setup the rubble mound breakwater automatically.

Three case studies are performed to study the effects of rubbles and rubble types on the wave dissipation and wave overtopping. Numerical results show that the wave impact force is nearly one order of magnitude larger for the case that the breakwater is not filled with stones. Therefore, the layers of stones offer an effective way of dissipating the waves. In addition, the stone geometry plays an important rule in dissipating the wave. Present numerical results show that the tetrapods are more effective than cubes.

Present numerical model and space filling technique can be used to analyze rubble mound breakwaters, which can provide useful information for practical designs.

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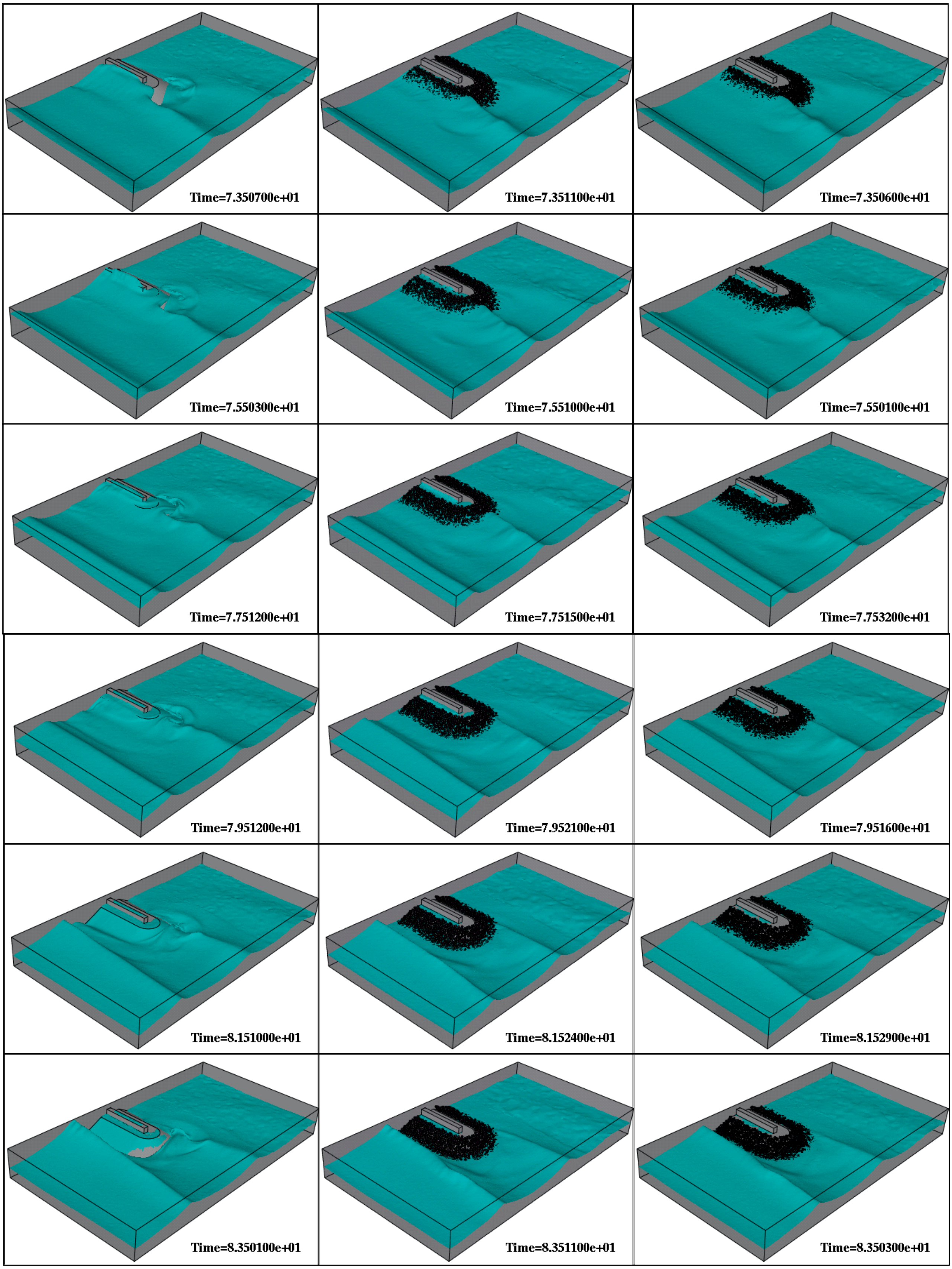

Fig. 6 Snapshots of wave-breakwater interactions (left column: without stones; middle column: filled with cubes; right column: filled with tetrapods)

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