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MODELLING OF FLUID-SOLID INTERACTION USING TWO STAND-ALONE CODES

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Abstract

A method is proposed for the modelling of fluid-solid interaction in applications where fluid forces dominate. Data are transferred between two stand-alone codes: a dedicated computational fluid dynamics (CFD) code capable of free surface modelling via the volume of fluid (VOF) approach and a physics engine code capable of predicting the movement of objects based on inputs of forces and moments. The method is weakly coupled, but has the advantage of accommodating a large number of independent objects which are allowed to touch or even overlap.

1 Introduction

South Africa has a number of major harbours along its coastline of nearly 3000 km and they play a vital role in its economy. Harbours and other coastal structures rely on breakwaters to protect them and therefore the study of breakwater structures and armour units (for example dolosse) are of importance in coastal engineering.

Traditionally, these studies involved the building of three-dimensional physical scale models of actual or planned breakwater structures with wave generators assisting in the study of the dynamic effects of the sea on these structures. Unfortunately, physical models are expensive and time-consuming to build and their accuracy is affected by the fact that not all physical processes scale down in the same way [1]. On the other hand, micro computers are continually becoming more powerful and affordable. This has led to an increased focus on the development and use of numerical prediction techniques in recent years.

A number of 3D numerical models of breakwater structures have been developed. Some treat the breakwaters as porous media [2], some study overtopping [3, 4] and others analyse the effect of turbulence on a single armour unit [5]. A recent study used a model containing a relatively large number of interlocking armour units [6].

This paper describes the development of a method that allows individual armour units to move relative to each other. Such a method can be used to study the robustness of a breakwater structure by identifying potential weak spots of a design where armour units might become dislodged under a given sea condition.

The research effort is part of a wide-ranging project aimed at developing analytical techniques for application to breakwater structural stability and the development of associated numerical simulation and modelling technology [1, 7, 8, 9, 10].

2 Research Scope

2.1 Problem Statement

A need was identified for a numerical analysis tool that could be used to study the robustness of breakwater structures. Robustness would be compromised in areas where individual armour units run the risk of becoming dislodged under certain sea conditions. The numerical tool therefore had to account for the interaction of armour units with each other and with sea water, and had to allow armour units to move relative to each other.

Fluid-structure interaction (FSI) is currently a popular field study in numerical modelling. As a result many research codes have been developed that focus on a variety of aspects and commercial CFD codes have started to implement features that deal with this phenomenon. The requirements for the numerical tool described in the previous paragraph are not catered for by available codes.

In the models, armour units must be free to move in all six degrees of freedom (so-called 6DOF motion) under the influence of gravity and fluid forces, unless they are constrained by their interaction with other armour units or with the domain boundaries (for example the rubble slope underneath). This requirement eliminates a number of candidate codes since many 6DOF codes require that a small gap always exists between objects. Although this limitation is often encountered when dealing with codes designed for the aero-space industry, it is likely that the initial implementation of 6DOF in general-purpose commercial CFD codes will also have this limitation [11].

Some codes model the interaction of free-moving objects with liquids using the VOF method, but usually limit the number of objects. A typical breakwater structure consists of hundreds if not thousands of interlocking units that must be accounted for without resulting in excessively long runtimes or unacceptably large meshes.

Codes that accommodate a large number of independently moving objects usually assume a simplified shape for the individual object, for example a sphere. More complex shapes can exist only as a number of these simple shapes clumped together. Typical armour units are geometrically complex (see figure 1) and the details are important. They may have seemingly insignificant grooves or protrusions that greatly enhance their interlocking ability. It would be difficult to retain such features when approximating the shape with a reasonable number of spheres clumped together. The numerical tool therefore had to be able to accommodate armour units with complex shapes.

While being numerous and complex in shape, armour units of the same type are identical. They are structurally rigid, eliminating the need to model their deformation under load. It is also reasonable to assume that the motion of the sea water dominates the movement of the armour units, not vice versa. All of these factors were considered in the design of the numerical tool.

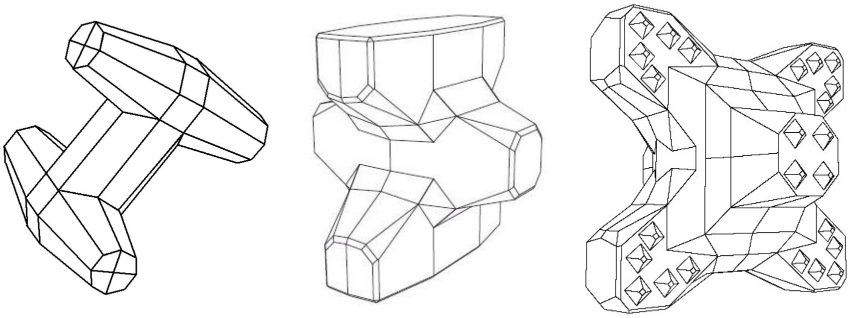

Figure 1: Typical armour unit shapes [12]

2.2 Codes Considered

In addition to the requirements set out in the previous section, resource and time constraints also existed that limited the options available when considering an appropriate strategy for developing the numerical tool.

It was not an option to write an in-house code for this purpose, since such a code would have to be written from scratch and would be technically too challenging to complete within time. The option of licensing appropriate commercial software was available and will be investigated in a further phase of the project, but the possibilities offered by commercial software already licensed and available freeware first had to be investigated.

The general-purpose, commercial software product StarCCM+ was licensed at the time and considered for use, and has already been used for the project [7, 8, 9]. It solves the mass (equation 1) and momentum (equation 2) conservation equations using the finite volume method.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = s_m \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j u_i - \tau_{ij}) = -\frac{\partial p}{\partial x_i} + s_i \tag{2}$$

t is time; x_i is a Cartesian coordinate (i = 1, 2, 3); u_i the absolute fluid velocity in the direction x_i; p is piezometric pressure; ρ is density; τ_{ij} is stress tensor components; s_m is a mass source term and s_i is momentum source components. Note that the equations are written in Cartesian tensor notation and that repeated subscripts denote summation.

Further specialisation of equation 1 and 2 is done depending on the flow problem under investigation, such as specification of a constitutive relation connecting the components of the stress tensor to the velocity gradients, application of time averaging, addition of mass fraction terms in fluid mixtures, etc.

The code was evaluated using a configuration where four fixed armour units are placed on a slope where they interact with waves (see figure 2). The configuration and wave properties were chosen arbitrarily.

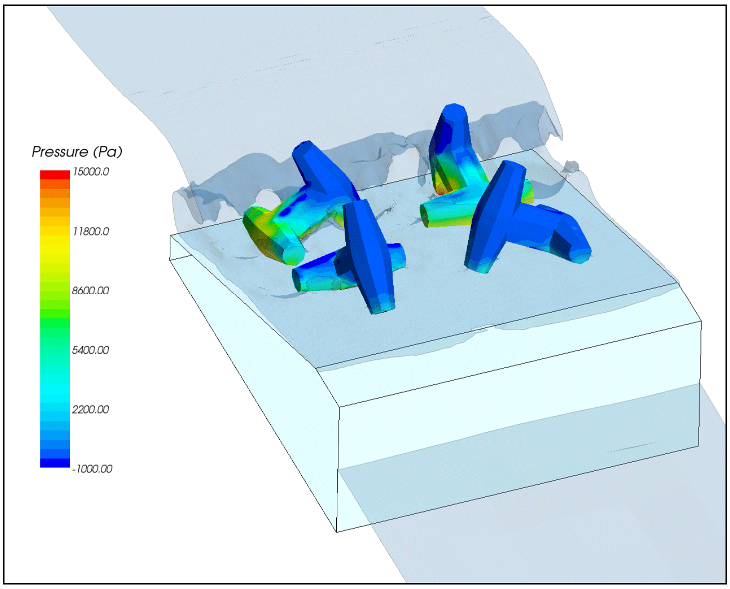

Figure 2: Configuration used to evaluate StarCCM+

The evaluation indicated that StarCCM+ offers a number of features that make it attractive as a numerical tool for the study of the robustness of breakwaters. These features include automated meshing, free surface modelling, wave modelling, process automation and parallelisation. The only remaining critical feature that StarCCM+ lacked at the time of the evaluation was the ability to do 6DOF modelling.

Consideration was given to the possibility of using two independent codes working in unison to satisfy the requirements set for the numerical tool. The first code would model the movement of fluid and its influence on the armour units and the second would determine how the armour units move under the influence of the fluid. If effective communication could be established between the codes, a two-code solution would be feasible.

StarCCM+ would be an excellent candidate as the first code. The second code would ideally be available for free or at a low cost and should be able to handle armour units with a complex shape. It should provide an interface for accepting force and moment data for each unit from the first code and an interface for providing its output: position data in terms of coordinates and rotations around coordinate axes. In addition, the second code should be able to handle a large number of independently moving objects that are allowed to touch and predict their movement in a physically realistic way.

A product called PhysX was identified as a candidate code, and has already been used for the project [1, 8, 9]. PhysX is a proprietary real-time physics engine owned by NVIDIA but is made available free of charge on Windows and Linux 32-bit platforms. It was assessed and accepted as a suitable ‘second code’. Figure 3 shows its prediction of the final resting positions of a number armour units packed using a specified method, confirming its ability to handle a relatively large number of complex shapes.

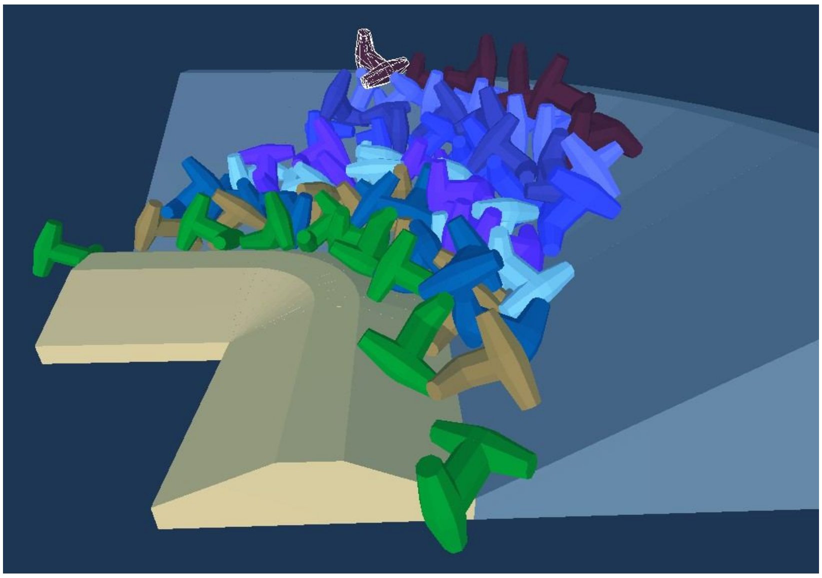

Figure 3: Predicted resting positions of armour units [8]

3 Code Integration

Integration of the two codes was done following the process described in figure 4.

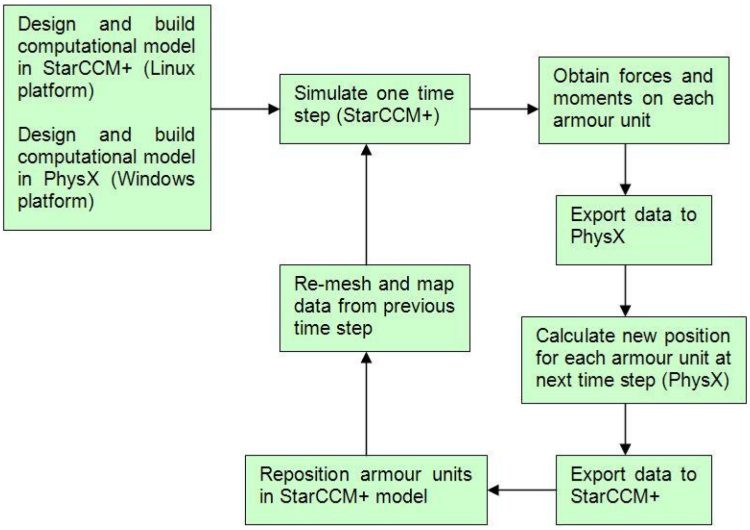

Figure 4: Integration process

StarCCM+ was licensed to run on 64-bit architecture under the Linux operating system, which made it impossible to run the free version of PhysX on the same platform. PhysX was therefore run on a Windows machine and data were transferred across operating systems using simple text format.

Since the codes ran independently of each other, a signalling mechanism was used to prevent both codes from executing simultaneously. Each code would poll a text file regularly and if it is found to contain the number 1, the code would execute. Once it is finished, it would write the number 0 to the file it polls and the number 1 to the text file being polled by the other code.

The fluid motion calculation at a given time step is decoupled from the rigid body motion at the same time step, which implies that large time steps would adversely affect accuracy. The coupling is also one way: fluid forces affect the motion of the rigid bodies but their movement does not yet affect the flow, apart from taking up different positions in space. That is because velocity data are not transferred to StarCCM+ yet (even though they can be obtained from PhysX).

4 Two Cube Simulation

A simple test case was designed consisting of two 1m cubes in a rectangular box. Cubes were chosen for their relatively simple shape (although they resemble Antifer cubes, an armour unit we have been modelling in other parts of the project [13]). Their density was relatively low (400 kg/m^3 compared to concrete at approximately 2300 kg/m^3) to ensure that they would move when hit by a collapsing column of water. Table 1 provides the values of the main model parameters.

Table 1: Model parameters of two cube simulation.

Parameter	Description
Number of blocks	2
Block dimensions	1m by 1m by 1m
Block density	400 kg/m^3
Placement of blocks	Symmetrically spaced halfway downstream, 1m apart.
Domain boundaries	25m by 5m by 5m
Water density	1 kg/m^3
Water column dimensions	3.75m by 2m by 5m
Number of cells in initial mesh	190976
Cell type used	Predominately hexahedral
Free surface model	VOF
Time step	0.002 seconds
Inner iterations	10 iterations per time step
Flow type	Laminar
Gravity	(0;-9.81,0) kg/ms^2

An initial simulation was run to ensure that the simulation parameters produced a stable solution. In the initial simulation the blocks remained stationary and the model was symmetrical around the xy-plane. It was expected to produce symmetrical forces, but minor asymmetries were observed and were ascribed to the relatively course mesh used [11]. Figure 5 depicts the values of F_x, the total force in the x-direction for each block and show the asymmetry as regions where the two lines do not lie on top of one another.

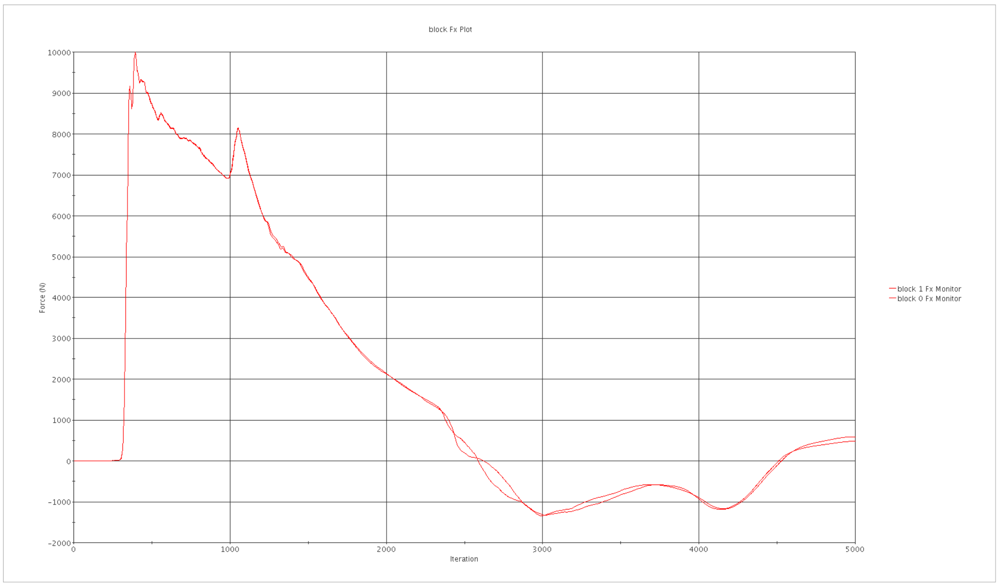

Figure 5: Minor asymmetries observed in the 2 cube simulation

The two cube simulation produced movement that appeared realistic: the cubes moved only when hit by the collapsing water column and their speed appeared to be of the same order as that of the surrounding fluid. Figure 6 shows the cubes' positions at four different times.

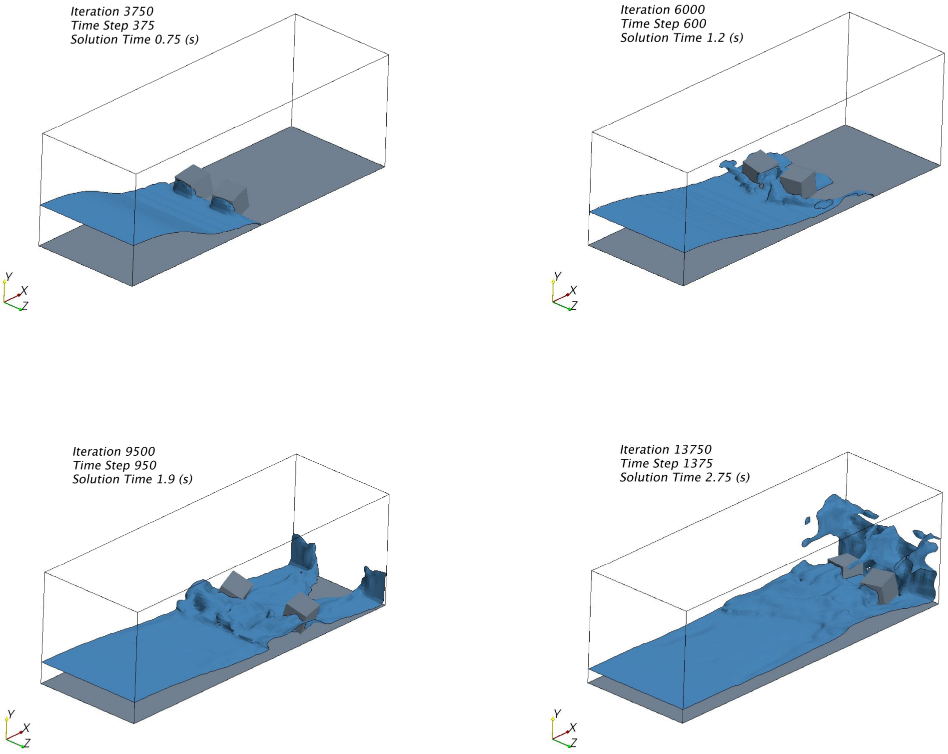

Figure 6: Movement observed in the 2 cube simulation

5 Six Cube Simulation

Another model was designed along similar lines but consisting of six cubes. The cubes were stacked with gaps of 0.25m between adjacent cubes and placed 5.625m downstream. The water column was 4.25m by 1.5m by 5m. All other parameters were kept the same as in Table 1.

The six cube simulation also produced movement that appeared realistic. The effect of buoyancy and momentum transfer from the water to the cubes was observed and the cubes also interacted with each other. Figure 7 shows the cubes' positions at four different times.

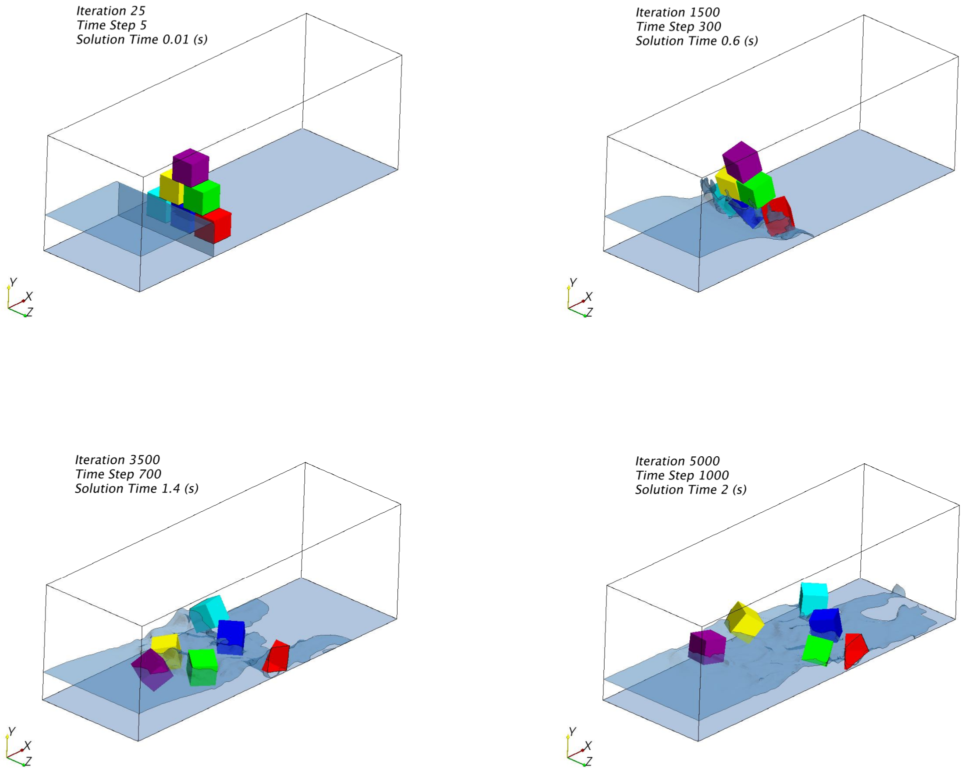

Figure 7: Movement observed in the 6 cube simulation

6 Validation

The two and six cube simulations proved that it was possible to use two stand-alone codes to model a number of independently moving objects that interact with a fluid and with each other. The accuracy with which the motion is modelled had not yet been considered.

The accuracy could be assessed by comparison with experimental data. That would require a series of experiments where the movement of cubes interacting with a fluid could be tracked in order to quantify their positions and orientations as a function of time. Simulations using a numerical model of the experiment would enable validation through comparison of the numerical and experimental data.

Such experiments were conducted using a 20m flume. Solitary waves were generated to interact with stacks of cubes placed on a platform. Their movement was tracked using fiducial target technology developed by CSIR [10]. Figure 8 shows some of the images obtained in the experiments. Processing the experimental data and their comparison with numerical data will form part of a future phase of the project. We are also calibrating the modelled waves against physical experiments [14].

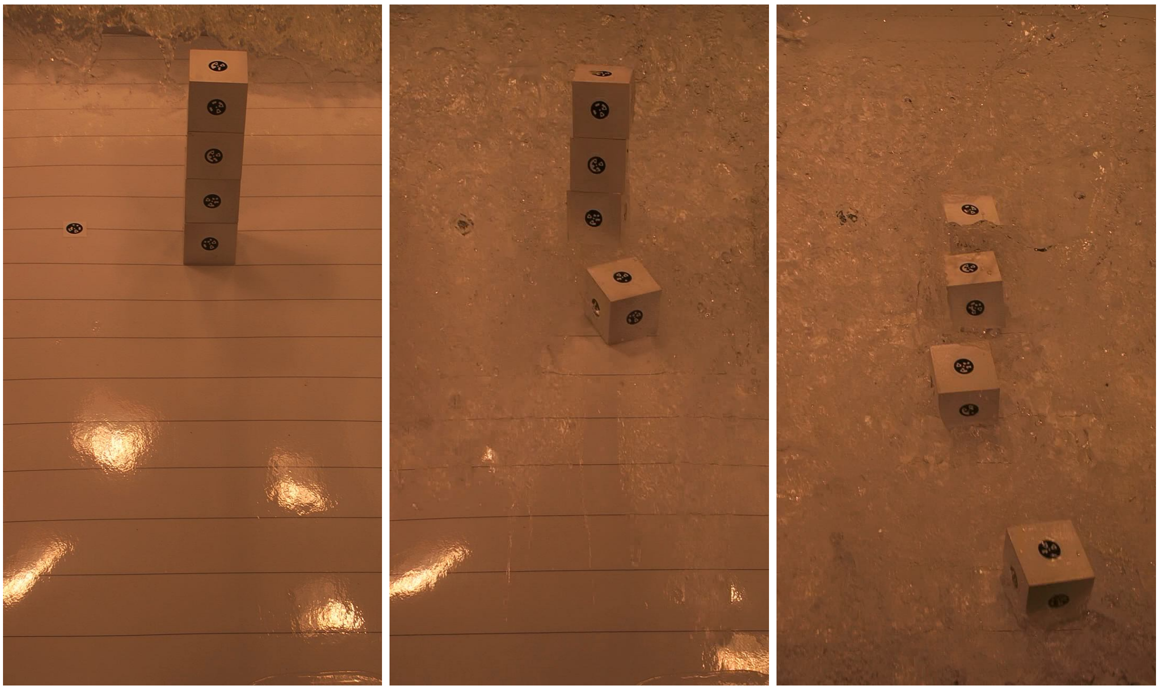

Figure 8: Four vertically stacked cubes interacting with a solitary wave

7 Conclusion

The initial aim of the work has been successfully achieved. It was shown that it is possible to use two stand-alone codes to model a number of independently moving objects that interact with a fluid and with each other. The movement of the objects appear to be realistic but proper validation is required by comparing predicted results with experimental data. Such a comparison could prompt further refinement of the numerical tool.

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