CFD SIMULATION OF A TSUNAMI IMPACTING A COASTAL CITY INCLUDING NUMEROUS BUILDINGS

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Tsunami, Macro-roughness modelling, Validation.

ABSTRACT

This work has been performed within the framework of the national project Tandem (2014-2017), with the aim to improve knowledge about tsunami risk on the French coasts. In this project Principia works especially on the validation of the in-house EOLE CFD software for the simulation of tsunamis. The code solves 3D multi-phase flows on multi-blocks structured meshes coupled with a free surface tracking VOF model. Many validations have been carried out on academic test cases of wave generation, propagation, run-up and submersion. A focus has been especially done on the "macro-roughness" modelling, namely the influence of buildings of significant size on the tsunami wave propagation.
Two different approaches for the "macro-roughness" modelling have been studied and compared, the classical projected boundary method, where only the building's walls are discretized and its influence on the flow is taken into account by the no slip boundary condition applied on these walls, and the immersed boundary method, where a solid color function assigns the solid/fluid ratio in each cell of the mesh. Due to their different nature, both methods present specific advantages and drawbacks (meshing set-up and topological constraint, accuracy, CPU time). Comparisons are carried out between the two macro-roughness models, and with a test case for which data issued from an experience on a city at a 1/50 scale are available.

1. INTRODUCTION

This work has been performed by a French national consortium within the framework of the national project Tandem (2014-2017), with the aim to improve knowledge about tsunami risk on French coasts.
One of the main project focuses is especially the qualification of CFD models on various tsunami test cases for covering the mains stage of tsunami life, generation, propagation, run-up and submersion. Into that frame, simulations of tsunami coastal impact have been carried out with the CFD multiphase EOLE code developed by Principia, for which examples of validations on tsunami academic test cases can be found in [1].
One of the challenging topics is the "macro-roughness" modelling to account for the complex geometry and the potentially large number of buildings present in the coastal area.

Two different approaches for the "macro-roughness" modelling have been studied and compared with the EOLE code:

- Projected boundary method : boundaries of mesh blocks are projected on geometrical boundaries. So the boundary condition is applied at exactly block cell faces.
- Immersed boundary method : geometrical boundaries are immersed within mesh blocks. The boundary condition is then applied at block cells close to the immersed geometrical boundaries.

The immersed VOS (Volume of Solid) method is a simplified immersed boundary method developed and integrated in the EOLE CFD code, and more particularly using a specific coupling with the VOF (Volume Of Fluid) to allow interactions of the liquid free surface (VOF function) with the solid (buildings/sea bottom/coast) VOS function.
Comparisons of projection and VOS methods for macro roughness modelling have been done on a test case dedicated to the study of a tsunami impacting an urban area [2].

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2. DESCRIPTION OF THE MODEL

2.1 Brief presentation of the EOLE solver

The EOLE code developed by Principia since 1990 is a multi-phase URANS model solving the equations on structured curvilinear multi-blocks meshes (possibly moving and deforming). It is based on a pseudo-compressibility technique using a dual time stepping and a second order finite volume scheme for spatial discretization (Guignard et al., 2001). The motion of the interface between the different phases is simulated from an implicit VOF model avoiding any CFL constraint and thus allowing globally large time steps. The transport of the VOF function (actually the displacement of the interface) may be ensured by a classical Eulerian equation or by an improved Eulerian-Lagrangian method developed by Principia, especially for complex wave breaking problem [1], [2], [3].
The code is fully parallelized and uses MPI/OMP libraries.

2.2 Macro-roughness modelling

In the first classical "projected boundary method", only the building's walls are discretized (no meshing of the inner solid volume) and its influence on the flow is accounted from the no slip boundary condition applied on these walls. Generally very accurate meshes are issued from this technic but sometimes it may present possible drawbacks: long time for the meshing set-up if there is a lot of buildings, big meshes and then large CPU time, topological difficulty of meshing when strong bathymetry gradients are present (even if using non-matching boundaries conditions between blocks).

For these reasons a second macro-roughness "immersed boundary method" has been developed. It introduces a VOS color function which assigns the solid/fluid ratio in each cell of the mesh and then allows to represent the buildings in the mesh directly from the topography file. The methodology consists in first building a simplified mesh without topological constraints and then integrating the buildings from the VOS field which is totally independent from this preliminary mesh.

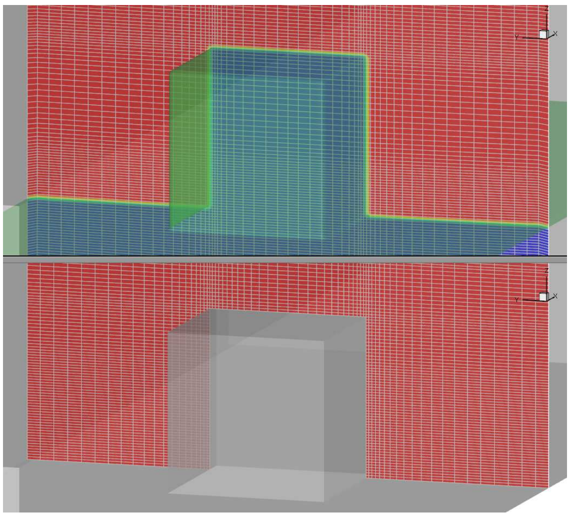

Figure 1: Schematic representation of both methods for building representation –"immersed boundary –VOS model" (top) and "projection method" (bottom).

In this immersed boundary method the VOS values vary from 1 in the solid to 0 in the fluid. In partial VOS cells (0<VOS<1) boundary conditions are applied. As example for a given partial VOS cell (cell in red on figure 2) the boundary conditions are deduced from the extrapolation of variables from neighbouring cells (orange cells on the same figure): slip or no slip conditions for velocity and extrapolation of all the other variables.

For no-slip conditions, the velocity of solid cells and partial cells is set to zero. For slip conditions, an average velocity is estimated at partial cells based on neighbouring fluid cells, then only the velocity compoenent being tangential to the geometrical boundary is unchanged, the normal component equals the opposite of the estimated average normal component so that fluxes through the walls are null.

The simplicity of this boundary treatment allows not deterioring calculation time. However, the physical representation of the geometrical immersed boundary may be significantly dependent on the mesh discretisation accuracy. Besides, because such a method does not ensure local mass conservation at the geometrical boundary, a numerical correction is applied on the whole set of partial cells to maintain mass conservation at block level.

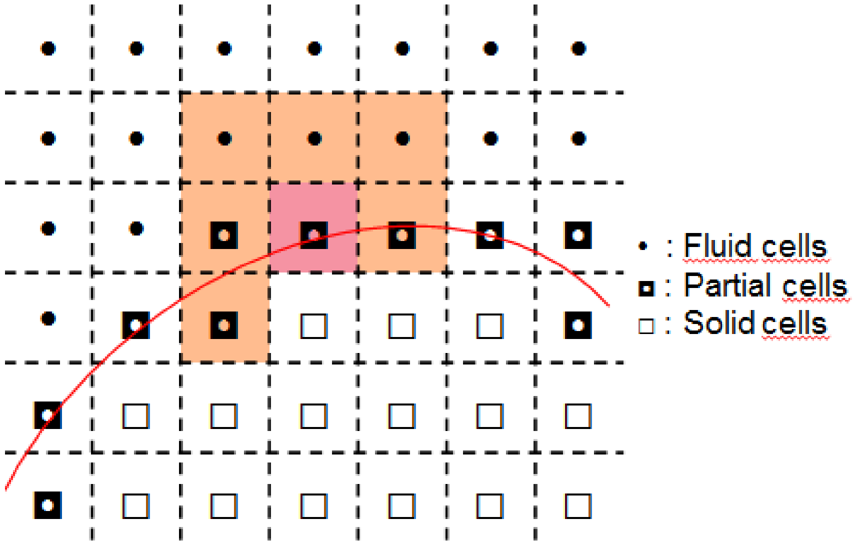

Figure 2: Identification of the solid, fluid and partial cells according to the solid boundary (red line) – Boundary condition for a given cell (in red) are obtained from extrapolation of the fields in the neighbouring cells (in orange).

Specific criteria must be ensured when the liquid free surface (given by the VOF method) enters in contact with the solid (given by the VOS method), meaning for cells coupling VOF and VOS partial values simultaneously. The criteria are:

- $VOF+VOS \leq 1$
- available liquid volume = (1-VOS) * $Volume_{cell}$
- free surface if: $0 < \frac{VOF}{1-VOS} < 1$

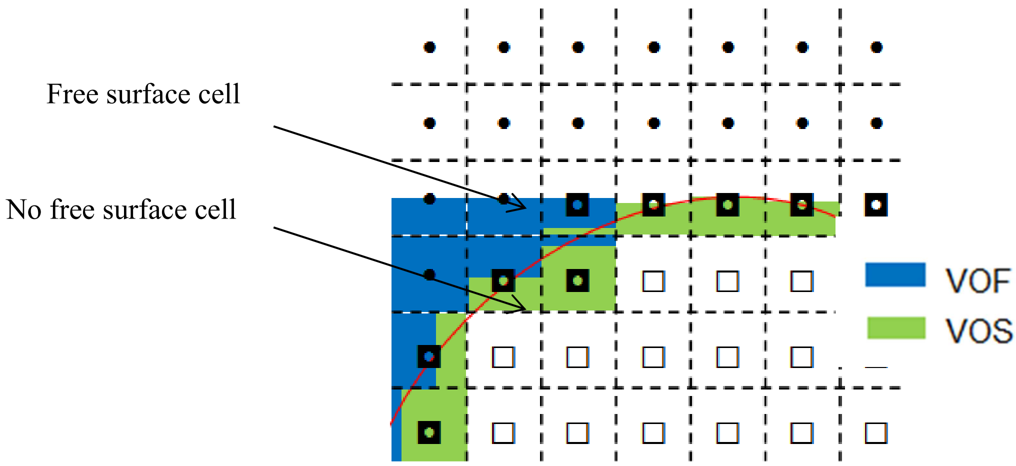

Figure 3: Coupling solid VOS (green) and fluid VOF (blue)

4. TEST CASE: IMPACT OF A TSUNAMI ON A COASTAL CITY

This experimental case has been done in the Oregon State University basin (PARK et al., 2013). A complex topography has been realized including a seawall and a lot of buildings (about one hundred), inspired of the real city of Seaside (Oregon) at a 1/50 scale. The dimensions of the basin are 49m long, 26.5m wide and 2.1m depth offshore. The experiment consisted in generating a solitary wave (0.2m, 10s) with a piston-type wavemaker which was designed to correspond to the estimated tsunami wave height for the "500 years" CSZ (Cascadia Subduction Zone) tsunami. More than thirty sensors (elevations, velocity) were placed mostly in the city at different positions between buildings (figure 4).
The different macro roughness models have been compared on this coastal geometry.
For the projection method a curvilinear multiblock mesh of the model is built with more particularly local refinements in the city, for all fluid areas between buildings. Because of its intrinsic nature these local refinements are projected in the entire mesh according to topological constraint (if considering matching boundaries between blocks). Then the number of cells reaches 9M.
In the VOS method, as previously said, a homogeneous mesh is built without considering the buildings and so without topological constraint. Buildings are introduces next using the VOS field.
Due to the fact that there is no meshing of the buildings, the main advantages of the VOS model are an important reduction of the size (5M in this case) and the complexity of the mesh regarding the classical projection method, and thus a saving time of the meshing set-up and CPU time.

Figure 5 shows pictures of the meshes issued from both methods.

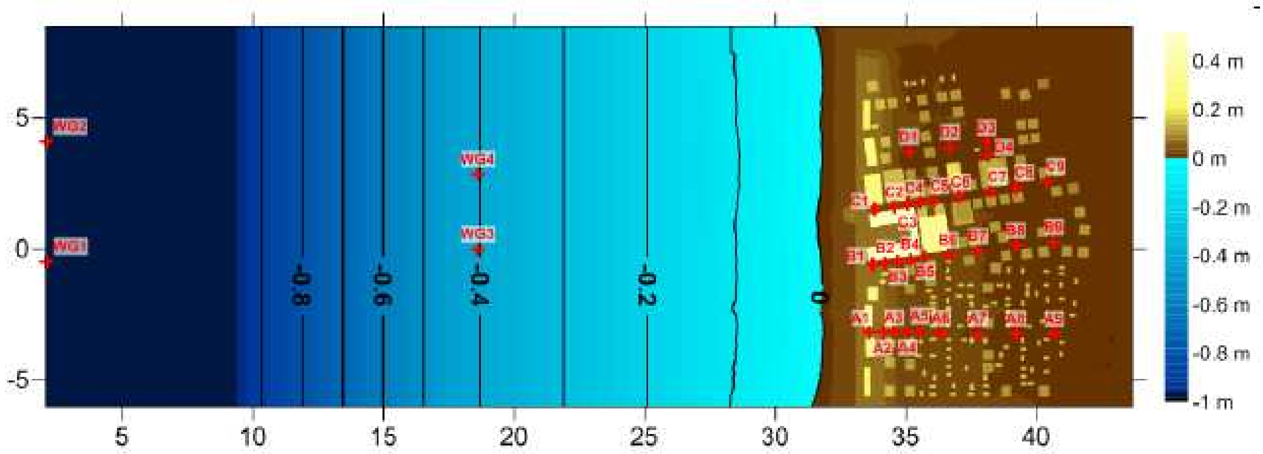

Figure 4: Experimental model of the city and positions of the sensors.

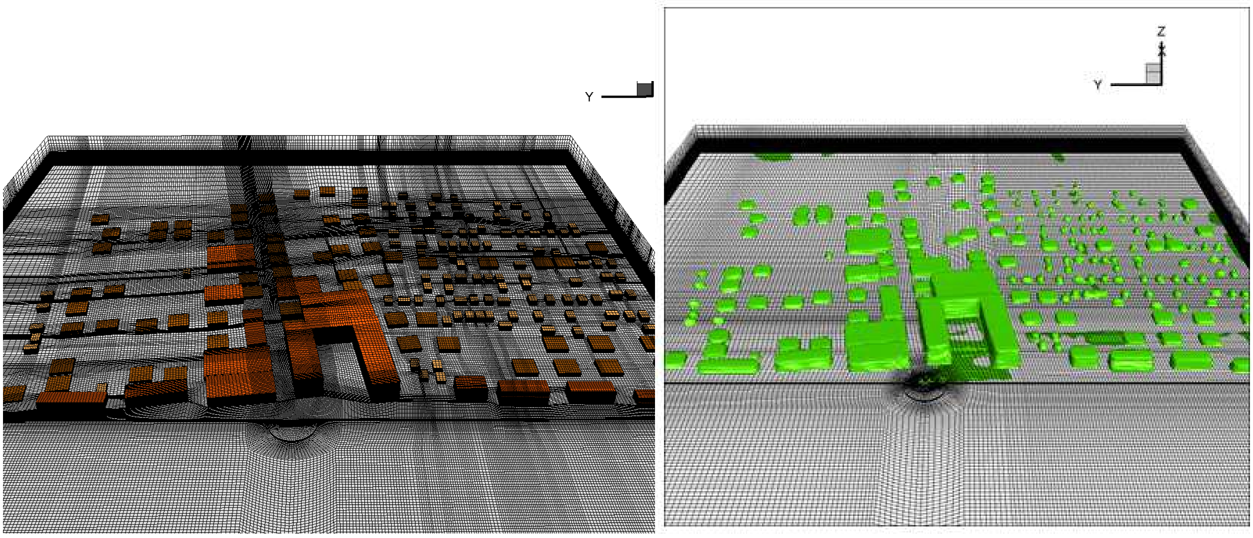

Figure 5: Meshing of the urban city test-case: projection method on the left (9M cells) and VOS method on the right (5M cells)

The first computation is done using the projection method. Figure 6 shows snapshots of the offshore wave propagation, the wave breaking when arriving close to the coast and the tsunami impact against the buildings of the city. Red and blue colors express respectively the positive wave propagation velocity (Umax≈1ms/s) and the reflecting wave velocity (Umin≈-0.5ms/s) around level 0 (in white).

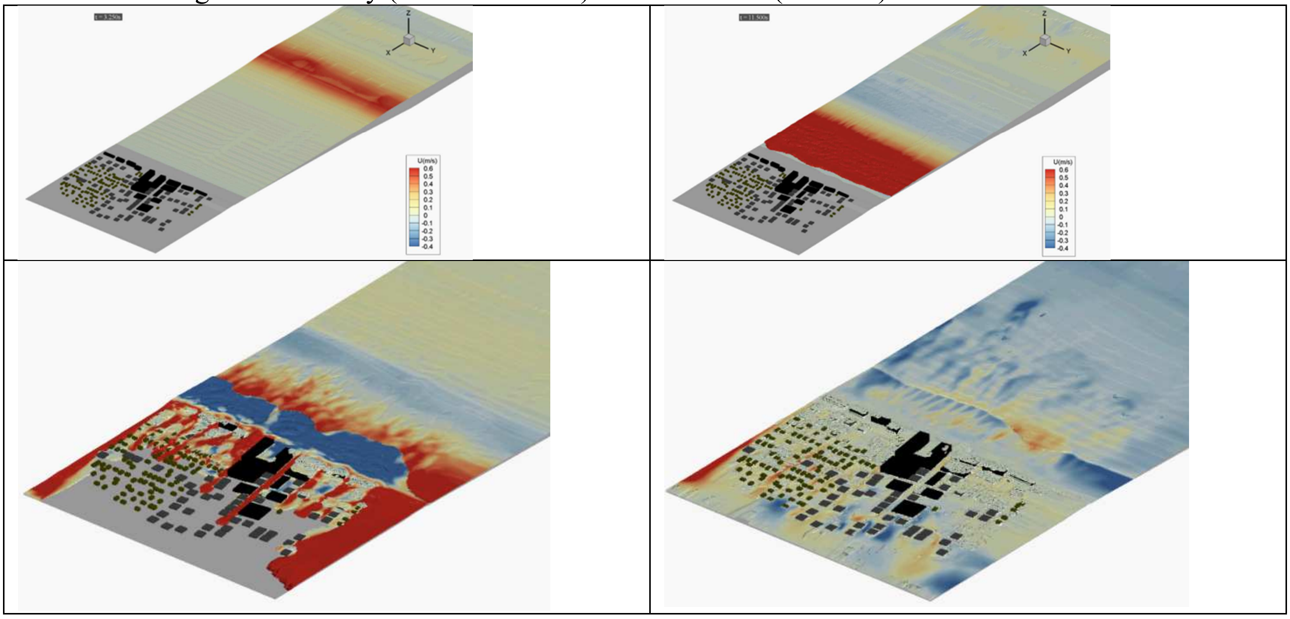

Figure 6: Simulation with EOLE of a tsunami impacting a coastal city (t=3s, t=12s, t=18s, t=34s respectively from top to bottom and left to right) – projection method.

Comparisons between the two meshing methods are done at the beginning of the flooding process (figure 7) at the early impact of the waves on the buildings. A picture of experiment is shown at the same time. On the whole both models issue very comparable results and manage to correctly represent the flooding according to the layout of the city, as well as the reflecting wave by the buildings.
This result put into evidence the performance of the VOS method which allows working on a very much simpler model without apparently affecting the overall accuracy.

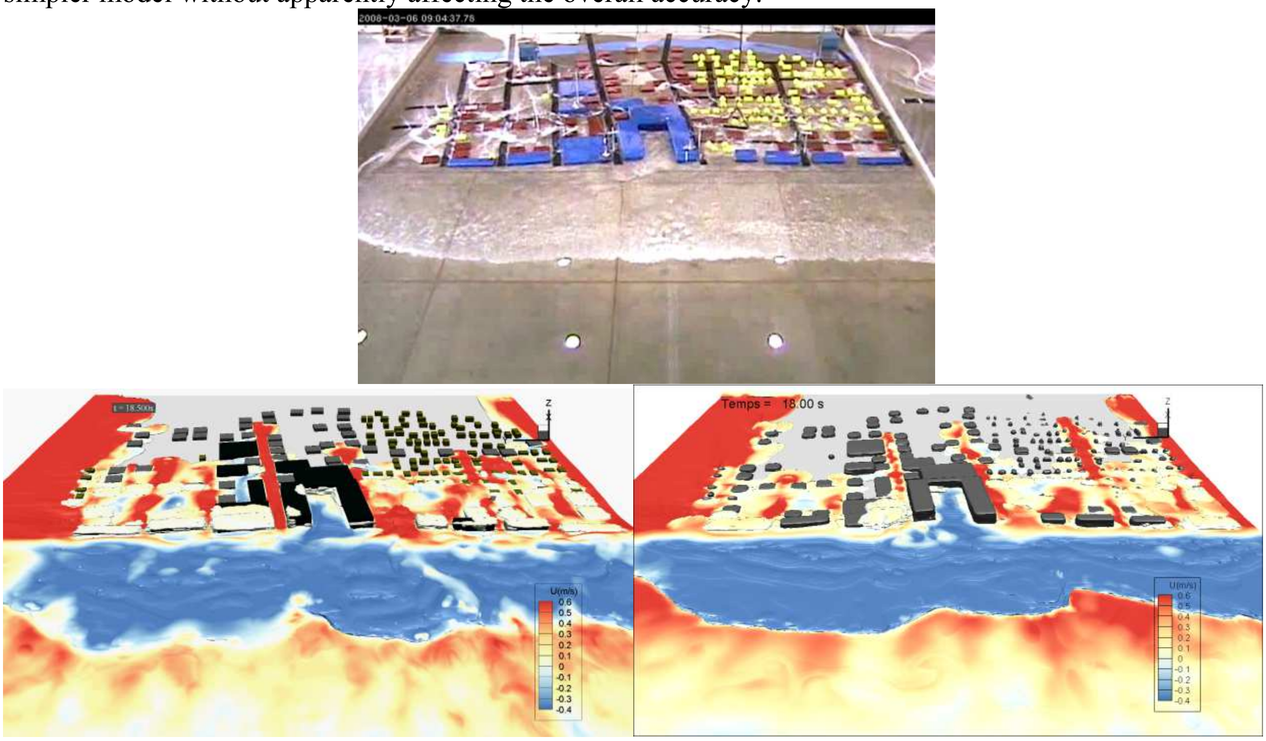

Figure 7: Example of comparison of the flooding at a given instant - experiment (top) – simulations on the bottom with projection method on the left and VOS method on the right

Accuracy of both models is confirmed regarding more quantitative comparisons of elevation time series on a sample of sensors (see example on figures 8 and 9). On the whole numerical results of elevation are satisfactory in amplitude as well as in phasing whatever the position of the probes. Even for the further inland area (A9 and C9 probes) for which the run-up amplitude is expected to be the weaker (maximal amplitude of only ~5 cm), the numerical models allow to capture the small wave elevation amplitudes.

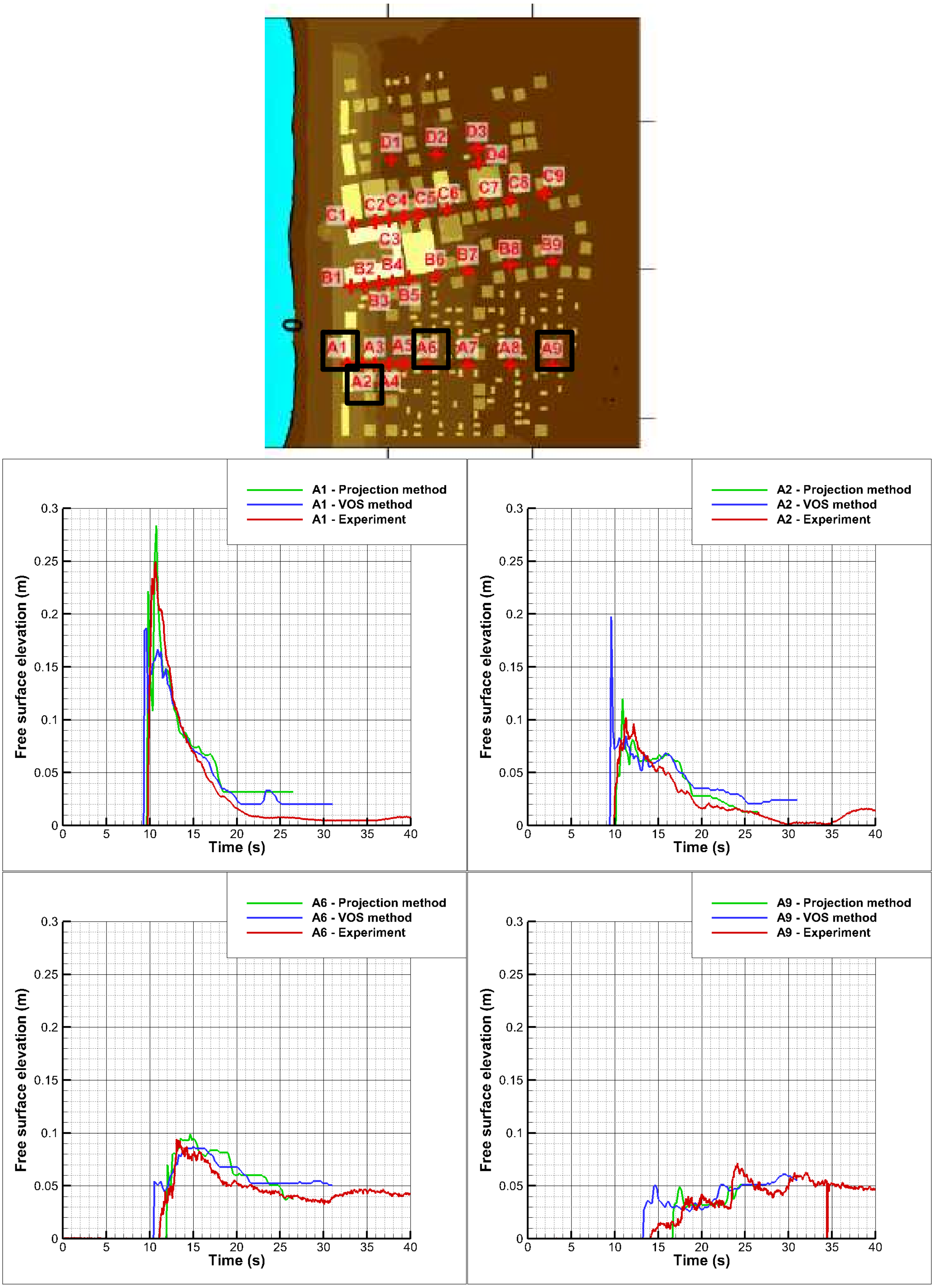

Figure 8: Wave elevations - comparisons experiments / projection method / VOS method on different probes A
VOS method in blue, projection method in green, experiments in red

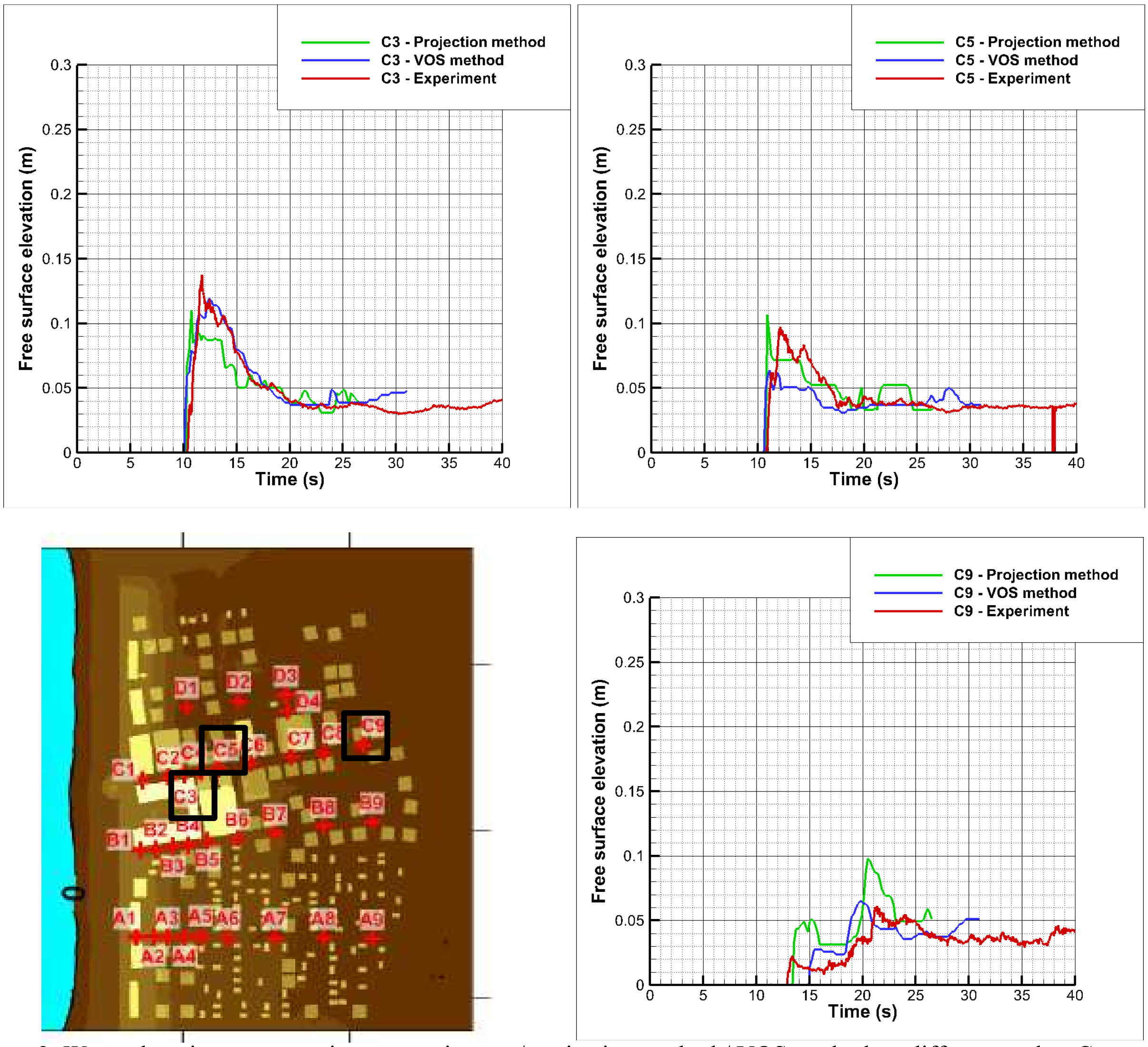

Figure 9: Wave elevations - comparisons experiments / projection method / VOS method on different probes C VOS method in blue, projection method in green, experiments in red

Figure 10 shows the wave velocity on different probes A, from the most nearshore one (A1) to the further inland one (A9). On the whole both numerical models allow obtaining correct velocity of the flow, especially a slight speed increase at probe A6 due to a local ducting effect. Note some difficulties for the numerical models to manage the reverse flow put into evidence in the experiment (probes A1 and A9) but the corresponding velocity to capture remains very low ~0.2 m/s.

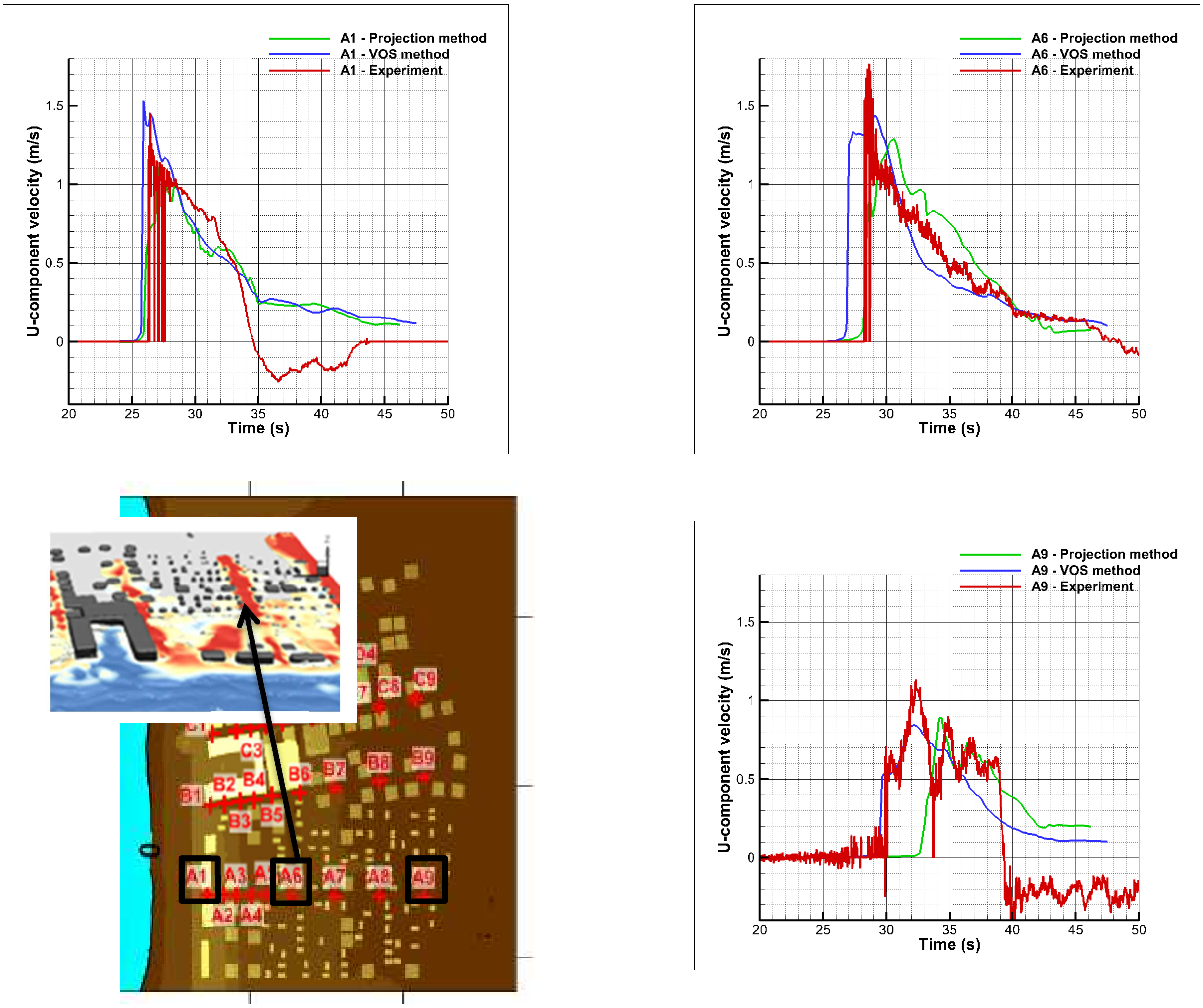

Figure 10: Velocity - comparisons experiments / projection method / VOS method different on probes A
VOS method in blue, projection method in green, experiments in red

5. CONCLUSIONS

When modelling a city composed of a large number of buildings the projected boundary method projection method allows a very accurate representation of buildings but may not necessarily issue better results regarding the VOS method which allows a much more easily meshing set-up and a significant reduction of CPU time.
Furthermore the VOS method presents other potential interests. It is well-adapted for a bathymetry with strong gradients and it also allows a possible time varying VOS field (computed from a fluid/structure coupling) meaning the ability to simulate for example the collapse of buildings and breakwaters, or the motion of debris in the flow.
The drawback is a possible lack of accuracy if the mesh on which the VOS field is built, is too coarse; so resulting in a bad description of the geometry (bathymetry / topography / buildings).

Further investigations will be addressed about hydrodynamics loads (applied on buildings) for which projection method remains intrinsically better with especially an easier control of boundary layer modelling. The accuracy of the VOS method on this matter still needs to be checked.
Another axe of investigation concerns the coupling of the two methods, using more particularly the projection method only where high precision is needed for hydrodynamic loads (close to breakwaters for example).

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