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Numerical Modelling of Landslide-Generated Tsunamis with OpenFOAM®: a New Approach

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Abstract: In this paper we present a new method for numerically modelling landslide-generated tsunamis in OpenFOAM® by using a new approach based on the Overset mesh technique. This technique, which is based on the use of two (or more) numerical domains, is new in the coastal engineering field and appears to be extremely powerful to model the interaction between a moving body and one or more fluids. Indeed, the accurate resolution around the moving body (i.e. body-fitted approach), guaranteed by this method, offers a great advantage to study the momentum exchange between the body and the water. Furthermore, in order to overcome a drawback of the Overset mesh implementation we modelled the solid boundaries, along which the landslide body moves, as a porous media with a very low permeability. The new approach has been preliminarily, and successfully, validated through the numerical reproduction of past experiments for landslide-generated tsunamis triggered by a solid and impermeable wedge at a sloping coast.

Keywords: Tsunamis, Landslide, Overset, OpenFOAM®, Numerical modelling

1 Introduction

Impulsive waves (i.e. tsunamis) can be generated by sudden displacements of volumes of water induced by earthquakes, landslides, volcanic eruptions, impacts of asteroids and gradients of atmospheric pressure (Løvholt et al., 2015). Among these triggering mechanisms, landslides assume a relevant role, especially as far as confined geometries are considered (e.g. bays, reservoirs, lakes, islands, etc.). This paper deals with landslides-generated tsunamis in proximity of the coast, for which interest has risen in the last years due to some devastating events, such as those in Lituya Bay in 1958 (Alaska, Fritz et al., 2009, left panel of Figure 1), in the Vajont Valley in 1963 (Italy, Panizzo et al., 2005), in Papua New Guinea in 1998 (Synolakis et al., 2002), in Stromboli in 2002 (Italy, Tinti et al., 2005, right panel of Figure 1), in Haiti in 2010 (Fritz et al., 2012) and recently in Indonesia in 2018.
The physical process at hand is generally characterized by smaller length and time scales than those of tsunamis generated by earthquakes. The triggering mechanism, i.e. the landslide, can be classified as subaerial, partially submerged or completely submerged, depending on the initial landslide position (Di Risio et al., 2011; McFall & Fritz, 2016). When the landslide occurs directly at the water body boundaries, impulsive waves both radiate seaward and propagate alongshore. Since the tsunamis generation is likely to occur in shallow water regions, the interaction between the waves and the sloping sea bottom plays immediately a relevant role. The waves can be refracted by the interaction with the bottom, and trapping mechanisms, like those typical of edge waves, can occur (Romano et al., 2013; Bellotti & Romano, 2017). The complex interaction that exists between the generation and

the propagation mechanisms is therefore to be carefully considered for a proper understanding of the generated waves features and, consequently, for developing effective Tsunamis Early Warning Systems (TEWS) that work in real-time (Cecioni et al., 2011).

Fig. 1. Left panel: pictures of the effects of the tsunamis occurred in 1958 at Lituya Bay (Alaska, USA). Right panel: landslide at the Sciara del Fuoco, Stromboli Island (South Thyrrenian Sea, Italy).

The landslide-generated tsunamis has been deeply studied by the scientific community by exploiting experimental, analytical and numerical modelling. As far as the numerical modelling is considered, a multitude of approaches has been adopted during the recent years. Eulerian and Lagrangian frameworks with three grid types (structured, unstructured, and meshless) have been used for tsunamis simulations (see Yavari-Ramshe & Ataie-Ashtiani, 2016 for a detailed review on the topic).

Important achievements have been reached so far, but still large gaps in the knowledge of the involved phenomena have to be filled. The new tools offered by the Computational Fluid Dynamics (CFD) methods can provide a valuable assistance for shedding light on the unresolved aspects. In particular, the CFD modelling of the so-called "near-field" appears to be crucial as far as tsunamis generated by landslides are considered. Indeed, a detailed modelling of the momentum exchange between the landslide and the water body is important for a deep understanding of the tsunamis generation and propagation mechanisms, even considering the small amount of time that usually is available for spreading the alarm during such catastrophic events.

In this paper we present a new method for numerically modelling tsunamis generated by solid and impermeable landslides with OpenFOAM® (v1812) by using a new approach based on the Overset mesh technique. The Overset mesh method is new in the coastal engineering field. To the knowledge of the authors, this technique has been successfully used to model the dynamics of floating bodies under the effects of waves and currents (e.g. Di Paolo et al., 2018) and other hydrodynamics problems (Chen et al., 2019). The Overset mesh is based on the use of two (or more) domains. The outer one (i.e. background domain) allows the motion of one, or more, inner domain (i.e. floating domain) that contains a solid body. The mutual exchange of information between the two domains is guaranteed by interpolation. The great advantage that this approach offers, if compared with other methods available to simulate the interaction between a moving body and one or more fluids in OpenFOAM® (e.g. immersed boundary method, etc.), is that the resolution around the moving body is extremely accurate (i.e. body-fitted approach) and furthermore, which is even more important, it remains constant throughout the simulation. This aspect is extremely useful when the momentum exchange between the landslide and the water body is investigated.

Furthermore, the modelling of the solid boundaries along which the landslide moves is another point of novelty of the present approach. The numerical reproduction of a body which is moving close to an impermeable surface is not allowed by using the Overset mesh method because of the interpolation procedure, on which the implementation is based. Indeed, few computational cells are needed between the body and the domain's edges. In order to overcome this drawback of the method, we modelled the solid boundaries, along which the landslide body moves, as a porous media with a very low permeability by using the VARANS approach proposed by del Jesus et al. (2012), Lara et al. (2012) and Losada et al. (2016). Moreover, in order to validate, as well as to show the features of the proposed approach, we present the numerical reproduction of the experimental benchmark described by Liu et al. (2005) for landslide-generated tsunamis triggered by a solid and impermeable wedge at a sloping coast.

The paper is structured as follows. After this introduction, the description of the new technique is provided in Section 2. In Section 3 the validation procedure of the presented method as well as the discussion of the features of the technique are provided. Finally, concluding remarks and ongoing research close the paper.

2 Numerical model

The new approach for numerically modelling tsunamis generated by solid and impermeable landslides, described in this paper, has been developed on the OpenFOAM® platform (Jasak et al., 1996). IHFOAM (Higuera et al., 2013a, b), based on interFoam of OpenFOAM®, includes wave boundary conditions and porous media solvers for coastal and offshore engineering applications and can solve both three dimensional Reynolds-Averaged Navier-Stokes equations (RANS) and Volume-Averaged Reynolds-Averaged Navier-Stokes equations (VARANS) for two phase flows.

In the present work both RANS and VARANS equations have been used, and solved, coupled to the VOF equation and to the Overset mesh method. In this section the base equations as well as a description of the proposed method are presented.

This section is organized as follows: first the RANS as well as the VARANS equations are briefly described, then an overview of the Overset mesh method is presented, finally the new approach for landslide-generated tsunamis is presented.

2.1 RANS equations

The Reynolds-Averaged Navier-Stokes equations (RANS) are based on the Reynolds decomposition, that identifies an average and a fluctuating component. These equations are represented by the mass and momentum conservation equations, coupled to the VOF equation as follows:

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) - \nabla \cdot (\mu_{eff} \nabla \mathbf{U}) = \nabla \cdot p^* - \mathbf{g} \cdot \mathbf{X} \nabla \rho + \nabla \mathbf{U} \cdot \nabla \mu_{eff} + \sigma k \nabla \alpha \tag{2}$$

$$\frac{\partial \alpha_1}{\partial t} + \nabla \cdot \mathbf{U}\alpha_1 + \nabla \cdot \mathbf{U}_c \alpha_1 (1 - \alpha_1) = 0 \tag{3}$$

where $\boldsymbol{U}$ is the velocity field, p is the pseudo-dynamic pressure, $\boldsymbol{g}$ is the acceleration of gravity; $\boldsymbol{X}$ is the position vector, σ is the surface tension coefficient, k is the curvature of the interface and is calculated as follows: $k = \nabla \cdot \nabla \cdot \alpha_1 \,/\, |\nabla \cdot \alpha_1|$, and α_1 is the volume fraction. Finally μ_{eff} is the efficient dynamic viscosity, which takes into account the molecular dynamic viscosity plus the turbulent effects: $\mu_{eff} = \mu + \rho\, \nu_{turb}$,and ν_{turb} is the turbulent kinetic viscosity, and it is given by the turbulence model. $|\boldsymbol{U_c}| = \min[c_\alpha\, |\boldsymbol{U}|, \max(|\boldsymbol{U}|)]$. By default, c takes the value of 1, but it can be larger to enhance the compression of the interface. The readers are referred to Higuera et al. (2013a) for an exhaustive description of all the terms.

The solver supports several turbulence models (e.g. two equation models (k-epsilon, k-omega, k-omega-SST) and LES), but in this study only k-epsilon model has been considered.

2.2 VARANS equations

Volume-Averaged Reynolds-Averaged Navier-Stokes equations (VARANS) are currently an efficient method to characterize three-dimensional wave-induced flows within porous structures. For the sake of shortness only a brief description is given here. A more detailed description on the topic can be found in Losada et al., (2016). The original VARANS equations, proposed by del Jesus et al. (2012)

and Lara et al (2012), including the conservation of mass, the conservation of momentum and the VOF function, have been adapted to OpenFOAM® by Higuera et al (2014a, b). We refer to Higuera et al. (2014a) for further details on the VARANS equations.

2.3 Overset mesh method

In this subsection a brief description of the Overset mesh technique is provided. To the knowledge of the authors, there are very few works that applied this promising technique for coastal and offshore engineering applications. This technique has been mainly used to simulate the dynamics of floating objects and the so-called "water entry problem" (e.g. Windt et al., 2018, Ma et al., 2018). More recently, Di Paolo et al. (2018) applied this mesh technique to simulate the dynamics of floating bodies under the effects of waves and currents, while Chen et al. (2019) have applied the Overset mesh method to reproduce a numerical wave tank for modelling realistic free-surface hydrodynamic problems (water entry problem, dynamics of floating objects, etc.).

The Overset mesh method is based on the use of two (or more) domains. The outer one (i.e. background domain) allows the motion of one, or more, inner domain (i.e. floating domain) that contains a solid body. The mutual exchange of information between the two domains is guaranteed by interpolation. Therefore, the two domains, which overlap each other, can be used to simulate different features of the hydrodynamics problem at hand. In Figure 2 a sketch depicting the features of the method is shown.

Conversely to other techniques (e.g. immersed boundary method or moving mesh), this method offers the great advantage that the resolution around the moving body is extremely accurate (i.e. body-fitted approach) and remains constant throughout the simulation. Thus, the strength of the Overset mesh method lies in its ability to represent complex geometries whilst maintaining a good quality mesh, especially for large amplitude body motions (Ma et al., 2018, Chen et al., 2019). This aspect is extremely important as far as the momentum exchange between a solid body and the water is investigated.

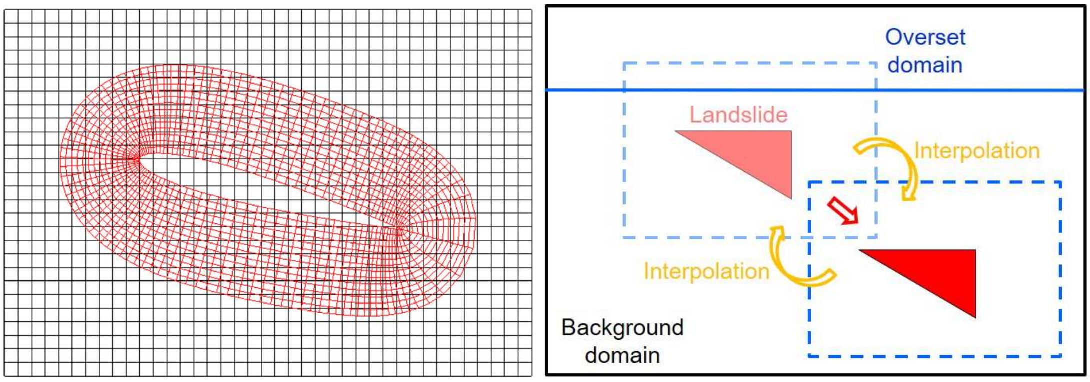

Fig. 2. Left panel: sketch (adapted from Celeritas Simulation Technology, 2011) of the backround domain (black lines) and the floating one (red lines). Right panel: sketch of the Overset mesh method.

2.4 The new approach for landslide-generated tsunamis

All the features described in the Subsections 2.1, 2.2 and 2.3 have been coupled together for setting up a numerical tool able to model tsunamis generated by solid and impermeable landslides at a sloping coast. Indeed, although the Overset mesh method seems to be suitable to address this task, the numerical modelling of a body, which is moving in contact with a solid and impermeable boundary (i.e. the sloping coast), is not possible because of the interpolation, on which the implementation is based. As early mentioned, few computational cells are needed between the body and the domain's boundaries, as shown in the left panel of Figure 3.

Obviously, this drawback of the Overset mesh method does not affect the hydrodynamics modelling of floating bodies that are placed in the inner part of the numerical domain (i.e. "far" from the domain's boundaries), as shown in the works cited before. Nevertheless, as far as landslide-generated tsunamis occurring at a sloping coast are considered, this approach is no longer an option. The momentum transfer, between the landslide and the water, takes place during the sliding of the body along the inclined surface.

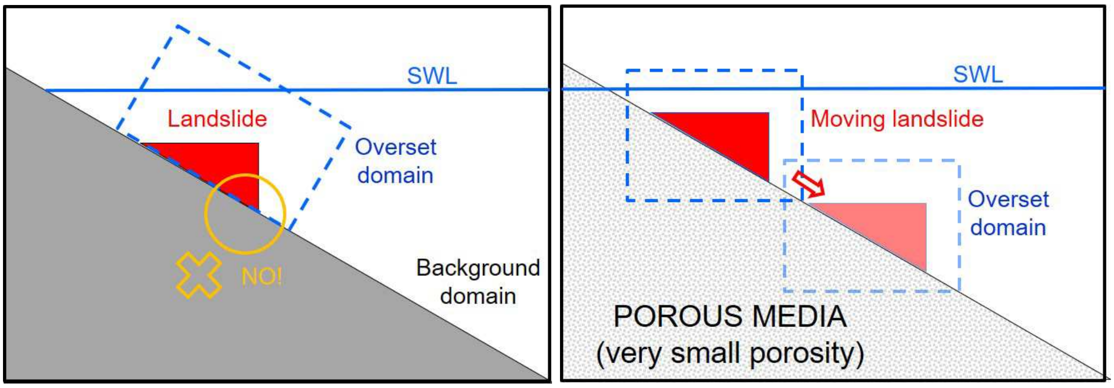

Fig. 3. Left panel: sketch of the current limitation of the Overset mesh method. Right panel: sketch of the proposed approach (i.e. sloping coast simulated as a porous media characterized by very low permeability).

In order to overcome this requirement of the Overset mesh method we used a new approach to model the sloping coast along which the landslide moves. We modeled the sloping coast as a porous media characterized by a very low permeability in order to simulate an impermeable surface, as shown in the right panel of Figure 3. Therefore, the sea bottom is not modeled as a solid boundary, instead it is just a part of the background domain in which a different set of equations (i.e. the VARANS equations valid for porous media flow) are solved. This approach allows the floating domain that contains the landslide to move through the background one and, consequently, the body to move in touch with the sloping coast. Obviously, a preliminary tuning of the numerical parameters, that characterize the porous media flow, is necessary to represent the sloping coast as an impermeable surface.

3 Results and discussions

In order to validate the proposed approach, and to show the features of the numerical tool, we reproduced numerically the experiments described by Liu et al. (2005), valid for landslide-generated tsunamis triggered by a solid and impermeable wedge at a sloping coast. The validation procedure is shown in this section, which is organized as follows: firstly, a description of the validation case as well as a discussion of the landslide's law of motion are introduced, then, the description of the numerical setup is presented and, finally, the comparison between the experimental and numerical results is shown.

3.1 Description of the validation case

A brief description of the experiments carried out by Liu et al. (2005) is given here, nevertheless the reader is referred to their paper for a more detailed description. The experiments have been carried out in a wave tank at the Oregon State University. The wave tank is 104.0m long, 3.7m wide and 4.6 m deep. A plane slope (1 vertical, 2 horizontal) was located near one end of the tank and a dissipating beach at the other end. For all experiments, the water depth in the wave tank was about 2.44m. Liu et al. (2005) used several geometries (a wedge and a hemisphere) to represent the landslide; in this paper only the wedge has been considered for the numerical modelling.

The wedge-shaped slide has the following dimensions: a length of b=91.44 cm, a front face a =45.72 cm high and a width of w=65.25 cm. Different initial slide positions have been used during the experiments (ranging from subaerial to submerged). It is worth noticing that in the present paper only submerged landslides have been modeled (i.e. initial position of the landslide below the still water level). The slides move down the slope by gravity rolling on specially designed shaped wheels. Figure 4 (left panel) shows a definition sketch of the experimental setup as well as the nomenclature of the parameters used by Liu et al. (2005). The vertical distance between the still water level and the landslide is D, accordingly with the nomenclature used shown in the left panel of Figure 4. The spatial coordinate x, is measured seaward from the intersection of the SWL with the slope.

Wave features have been measured by deploying several instruments: both runup wave gauges and wave gauges have been used to record the runup time series and the free surface elevation time series respectively. An example of three free surface elevation time series, measured along the centerline of the landslide (x = 1.7967, 2.1807, 2.5648 m respectively), for a test with submerged landslide (D/b=-0.33), is shown in the right panel of Figure 4 (note that both the panels of Figure 4 have been adapted from the original paper of Liu et al., 2005). It is worth to highlight that the results of the experimental test shown in the right panel of Figure 4 have been used as the validation case for the numerical approach described in the present paper.

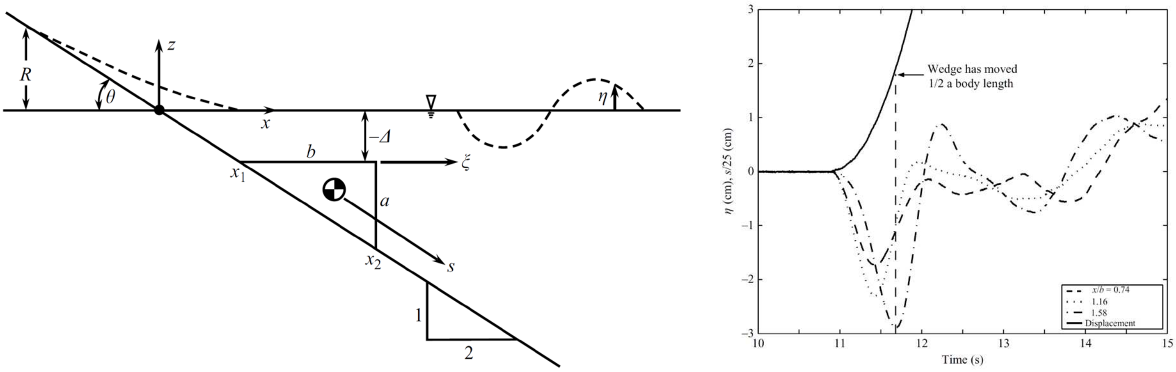

Fig. 4. Left panel: sketch of experimental setup (Figure 4 from the Liu et al., 2005). Right panel: free surface elevation time series and landslide's law of motion for one configuration (Figure 5 from the Liu et al., 2005).

3.2 Landslide's law of motion

In this subsection the discussion of the landslide's motion is provided. As far as landslide-generated tsunamis are considered, then the proper description of the landslide kinematic is a crucial aspect, especially when the goal is to model numerically such a phenomenon. To date the numerical reproduction of the landslide kinematic, although if a simple geometry and a rigid and impermeable landslide is considered, is not an easy task. The physical phenomena governing the triggering mechanisms and the evolution of a landslide (submerged or subaerial) are far to be included in most of the numerical hydrodynamics codes.

On the other hand, the governing equation of landslide motion has been widely used in past researches (e.g. Romano et al., 2016a, b) and, at least in the case of submerged landslides, analytical solutions are available (e.g., Pelinovsky and Poplavsky, 1996; Watts, 1998). Therefore, in this paper we used the analytical solution provided by Pelinovsky & Poplavsky (1996), and later by Watts (1998), to reproduce the movement of the landslide. Note that the same technique has been applied by Liu et al. (2005) to validate their numerical model, based on the large-eddy-simulation (LES) approach.

The equation of motion of a sliding solid body obtained by Pelinovsky & Poplavsky (1996), and later by Watts (1997), reads as follows:

$$(m + C_m m_0)\frac{d^2 s}{dt^2} = (m - m_0)g(\sin\alpha - C_n\cos\alpha) - \frac{1}{2}C_d\rho A\left(\frac{ds}{dt}\right)^2 \tag{4}$$

where m is the landslide mass, s is the landslide displacements, t is the elapsed time, g is the gravity acceleration, α is the incline slope angle, C_n is the Columbic friction coefficient, C_m is the added mass coefficient, m_0 is the displaced water mass, A is the main cross section of the moving landslide (i.e., perpendicular to the direction of motion), and ρ is the water density and C_d is the global drag coefficient.

In the case of submerged landslides, the theoretical solution of (4) is (e.g., Watts, 1998):

$$s(t) = \frac{u_t^2}{a_0}\log\left[\cosh\left(\frac{a_0 t}{u_t}\right)\right] \tag{5}$$

where a_0 is the initial acceleration and u_t is the terminal velocity that can easily calculated as follows:

$$a_0 = \frac{(m - m_0)g(\sin\alpha - C_n\cos\alpha)}{m + C_m m_0} \tag{6}$$

$$u_t^2 = \frac{2(m - m_0)g(\sin\alpha - C_n\cos\alpha)}{C_d\rho A} \tag{7}$$

once the hydrodynamics coefficients have been estimated. In the left panel of Figure 5 it is shown the comparison between the analytical solution, used in this paper, and the experimental landslide's law of motion as from one of the experiments carried out by Liu et al. (2005) that has been used for the validation of the new approach (see Figure 4, right panel). In Figure 5 the red line refers to the analytical solution, while the black markers refer to the experimental data. Furthermore, the right panel of the figure shows the velocity of the body as obtained by the (4).

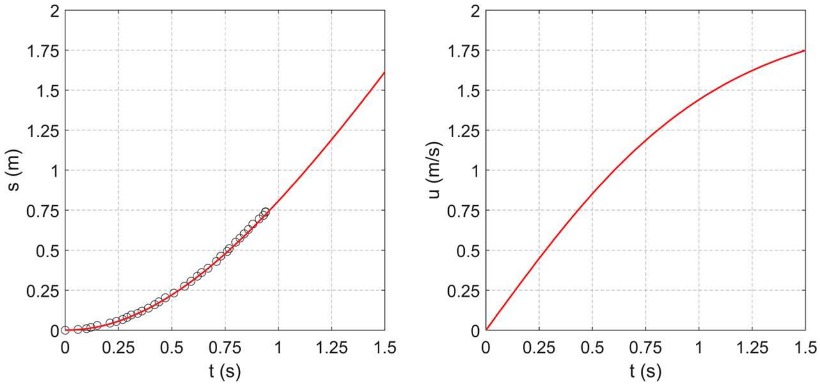

Fig. 5. Left panel: analytical (red line) and experimental (black markers) landslide law of motion. Right panel: analytical velocity time series of the landslide.

3.3 Numerical setup

A numerical wave tank has been designed in order to reproduce the experiments described in Liu et al. (2005). The numerical domain is represented in Figure 6. Accordingly to the Overset mesh method a background domain and a floating one, containing the impermeable body (i.e. the landslide), have been defined. The background domain is 6.5 m long, 3.7 m wide and 4.0 m high, while the floating one is 1.3 m long, 1.1 m wide and 0.9 m high. Different mesh setups have been tested to assess the influence of the mesh resolution on the results. The chosen mesh for the background domain is characterized by a cell resolution of 0.025 m along x and y directions and 0.014 m along z direction. In the floating domain the mesh is characterized by the same cell resolution of the background one, nevertheless it is worth to highlight that the body-fitted approach ensures a much more detailed mesh resolution around the object (i.e. cell size in the order of few mm), which is placed in the center of the floating domain.

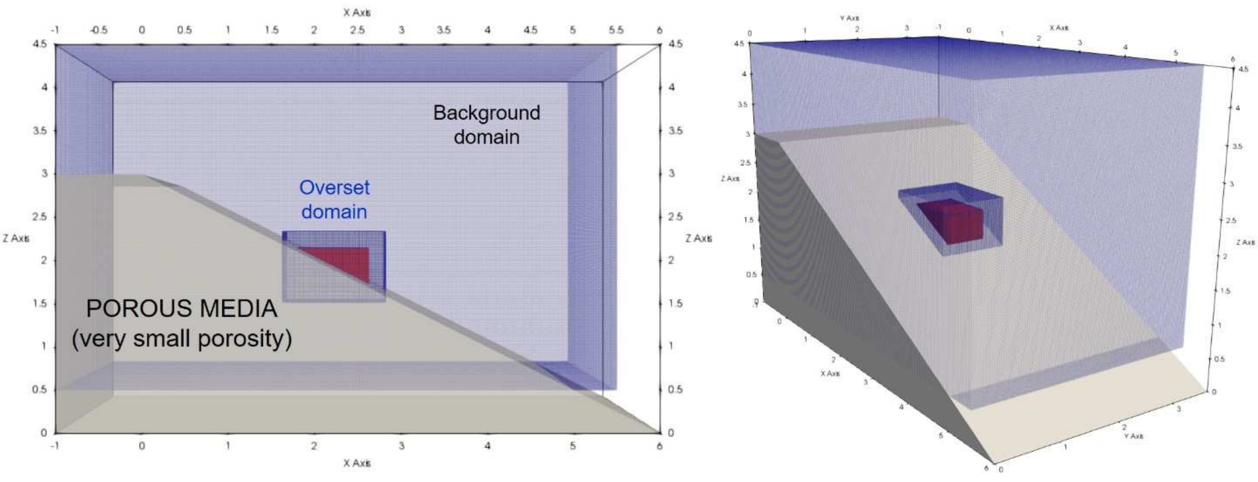

Fig. 6. Left panel: side view of the numerical domain. Right panel: perspective view of the numerical domain.

An active absorption boundary condition has been applied at the right side on the numerical wave tank, while along the solid impermeable boundaries (lateral walls, left side, roof and bottom) a no-slip velocity condition has been imposed. Furthermore, as described in the previous section, the plane slope (i.e. the sloping coast) along which the body slides has been modeled as a porous media characterized by a very low hydraulic permeability (a = 10, b = 0, c = 0.34, ϕ = 0.05, D_{50} =0.003m). As previously mentioned, the floating domain (and obviously the body contained in it) moves through the background domain accordingly to the law of motion as obtained by the analytical solution proposed by Watts (1998) and shown in the left panel of Figure 5.

3.4 Comparison with experimental data

It is worth to highlight that the main objective of this paper is to present a new numerical approach for numerically modelling landslide-generated tsunamis in the so-called near-field. Thus, aiming at validating the approach by comparing the numerical results with the experimental ones obtained by Liu et al. (2005), the landslide's law of motion, and consequently the numerical simulation, has been stopped after 1.6 s from the beginning of the landslide's motion. Indeed, in this time window the near-field wave features (i.e. first wave trough and first wave crest), evaluated by means of three free surface elevation time series, are completely developed (see the right panel of Figure 4). Therefore, the comparison between numerical and experimental results, described in the current subsection, has been carried out in the mentioned time window. Furthermore, other features of this numerical tool are shown within this subsection.

The numerical results have been analyzed in post-processing in order to extract the free surface elevation time series measured at the positions of the three wave gauges deployed by Liu et al. (2005). In Figure 7 the comparison between numerical (red lines) and experimental (black dots) results is presented. Figure 7 shows the excellent agreement between the two sets of data. Starting from the upper panel of the figure, which refers to the free surface elevation time series measured by the first wave gauge (the closest to the shoreline), it is evident that the numerical model is able to carefully catch and reproduce the physics of the phenomenon. As the submerged landslide starts to move, a small wave trough develops. A similar behavior is shown in the middle panel of Figure 7 (second wave gauge).

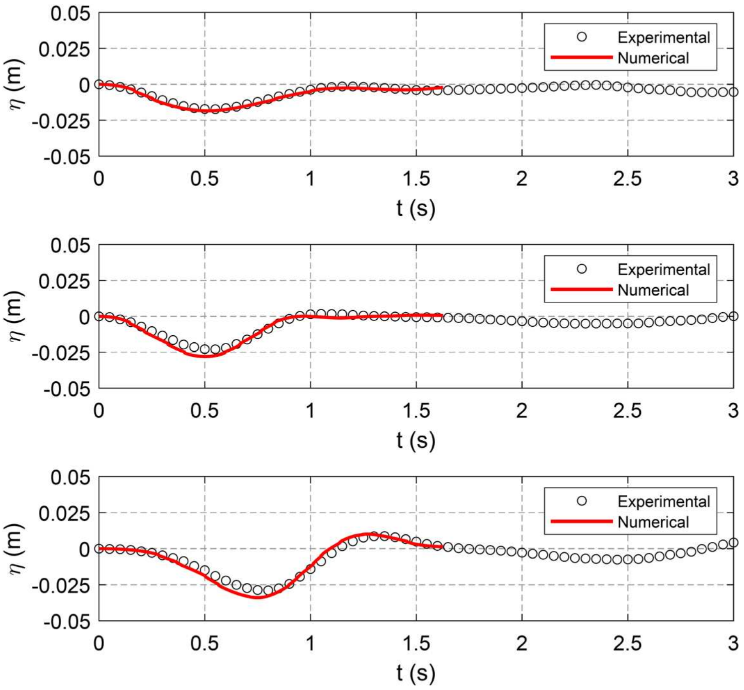

Fig. 7. Comparison between experimental (black dots) and numerical (red lines) results, in terms of free surface elevation time series, evaluated at the positions of the three wave gauges deployed by Liu et al. (2005).

Looking at the lower panel of Figure 7 (third wave gauge, the farther from the shoreline), the free surface elevation time series firstly exhibits a wave trough which is followed by a wave crest, jointly induced by the rebound of the first wave trough and by the piston-like mechanism, which is a peculiar feature of the waves generated by submerged landslide. Figure 7 clearly highlights the capability of the numerical model to reproduce such a complicated physical phenomena. Moreover, in order to appreciate the complicated near-field waves pattern, in Figure 8 a contour plot the free surface elevation evaluated at four different time instants is presented.

Furthermore, the CFD tool allows to fully describe, in the whole numerical domain, the 3D velocity field induced by the landslide's motion. Figure 9 shows the velocity field, induced by the movement of the landslide at a given time instant (t = 1.4s), evaluated on a cross section placed in the middle of the numerical domain and perpendicular to the shoreline. The two panels of the figure, representing the velocity field in the whole domain (left panel) and in the floating domain (right panel) respectively, highlight the capability of the model in reproducing the complicated hydrodynamics induced by the landslide. In Figure 9 the free surface elevation is identified by a thick black line.

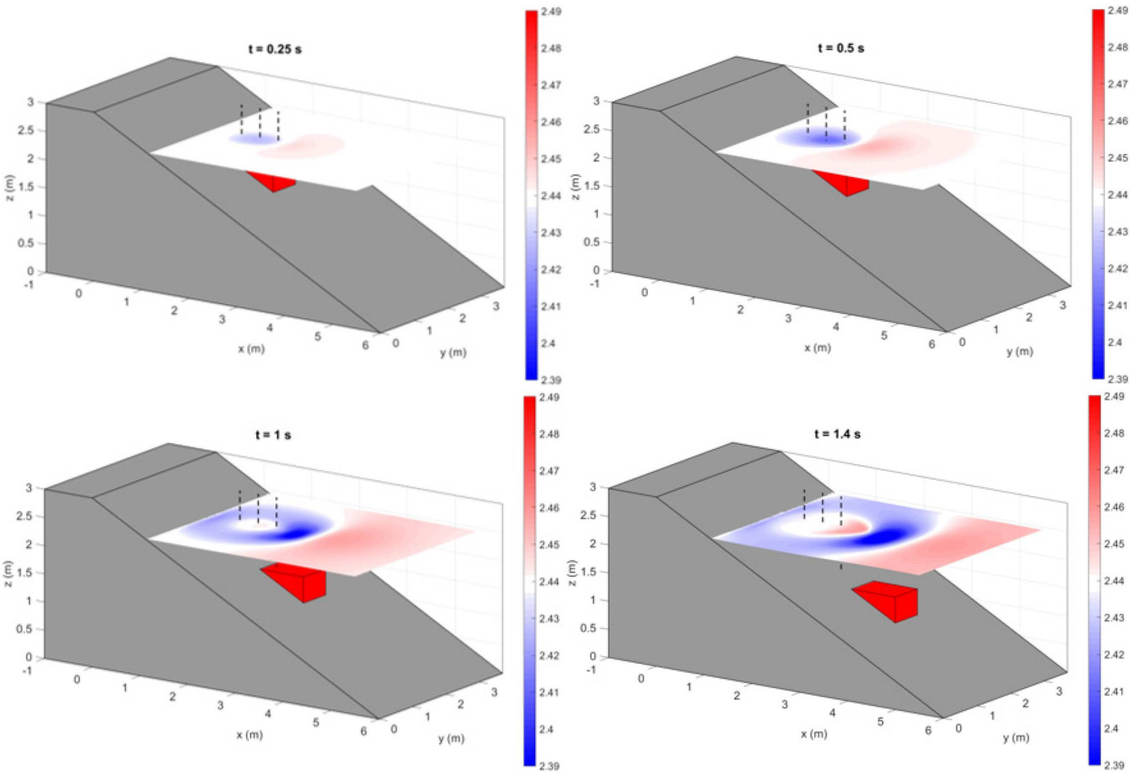

Fig. 8. Contour plot the free surface elevation evaluated at four different time instants.

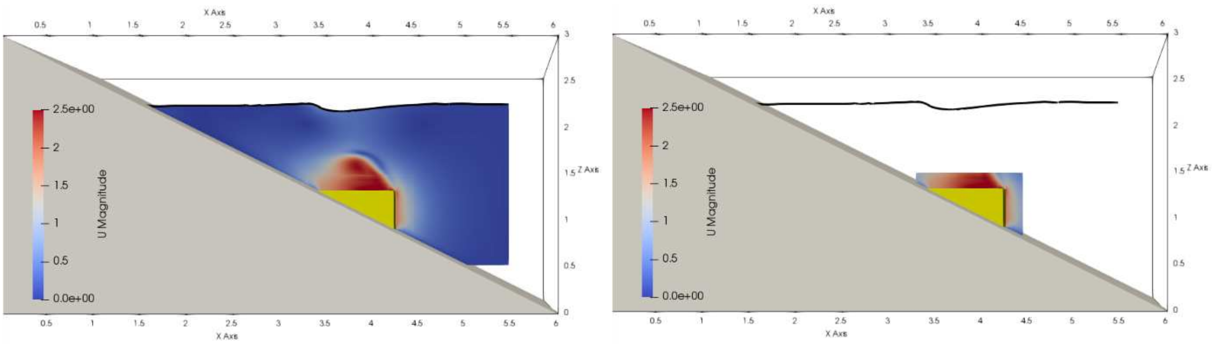

Fig. 9. Velocity field at a given time instant (t = 1.4s) evaluated on a cross section placed in the middle of the numerical domain and perpendicular to the shoreline. Left panel: velocity field in the whole domain. Right panel: velocity field in the in the floating domain. Note: the thick black line represents the free surface elevation (VOF = 0.5).

4 Concluding remarks and ongoing research

In this paper a new method for numerically modelling tsunamis generated by solid and impermeable landslides with OpenFOAM® has been presented and preliminarily validated. The proposed method consists in coupling the Overset mesh technique, which is a new and a promising one in the coastal engineering field, with the well-known porous media approach currently implemented in IHFOAM (Higuera et al., 2014a; Losada et al., 2016). This coupling allowed to overcome a drawback of the Overset mesh method as far as the modelling of a solid body moving in touch with an impermeable surface is considered. The excellent agreement between the numerical results and the experimental data obtained by Liu et al. (2005), referring to landslide-generated tsunamis triggered by a solid and impermeable wedge at a sloping coast, highlights the ability of the new approach in reproducing such a complicated phenomenon and promote the new tools offered by the CFD methods for shedding light on the unresolved aspects related to the landslide-generated tsunamis. Further research dealing with more complicated geometries, different landslide triggering mechanisms and landslide rheology is currently ongoing.

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