Chapter

Physical and Numerical Modeling of Landslide-Generated Tsunamis: A Review

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Abstract

Landslide-generated tsunamis represent a serious source of hazard for many coastal and lacustrine communities. The understanding of the complex physical phenomena that govern the tsunami generation, propagation and interaction with the coast is essential to reduce and mitigate the tsunamis risk. Experimental, analytical, and numerical models have been extensively used (both as separated tools and in conjunction) to shed light on these complicated natural events. In this work, a non-exhaustive update of the state of the art related to the physical and numerical modeling techniques of landslide-generated tsunamis, with a special focus on those studies published in the last ten years, is provided. As far as numerical models are concerned, a special attention is paid to the most recently developed Computational Fluid Dynamics (CFD) techniques, whose development and application have experienced a boost up the last decade.

Keywords: landslide-generated tsunamis, physical modeling, numerical modeling, computational fluid dynamics (CFD), water waves

1. Introduction

Impulsive waves (i.e. tsunamis) are likely to be generated by earthquakes, landslides, volcanic eruptions, impacts of asteroids and gradients of atmospheric pressure (Løvholt et al. [1]). There are coastal areas which are particularly prone to landslide-generated tsunami risk. The destructive effects caused by the impulsive waves, generated by landslide sources, can be strongly magnified by the characteristics of the so-called "confined geometries" (e.g. bays, reservoirs, lakes, volcanic islands, fjords, etc.). Complicated physical phenomena (e.g. trapping mechanisms, edge waves, wave runup, etc.) take place as a consequence of the interaction between the generated waves and the local bathymetry controlling the tsunami propagation and interaction with the coast. Many past events of landslide-generated tsunamis testify this reality (e.g. Lake Geneva, Switzerland, *Kremer et al.* [2]; Lituya Bay, Alaska, *Fritz et al.* [3]; Vajont Valley, Italy, *Panizzo et al.* [4]; Stromboli Island, Italy, *Tinti et al.* [5]; Papua New Guinea, *Synolakis et al.* [6]; Anak Krakatau, Indonesia, *Grilli et al.* [7]).

Figure 1 provides good examples of areas prone to landslide tsunami hazard (upper left panel: Lituya Bay, Alaska; upper right panel: Vajont Valley, Italy; lower panels: Stromboli Island, Italy). The physical process at hand is generally characterized by smaller length and time scales than those of tsunamis generated by

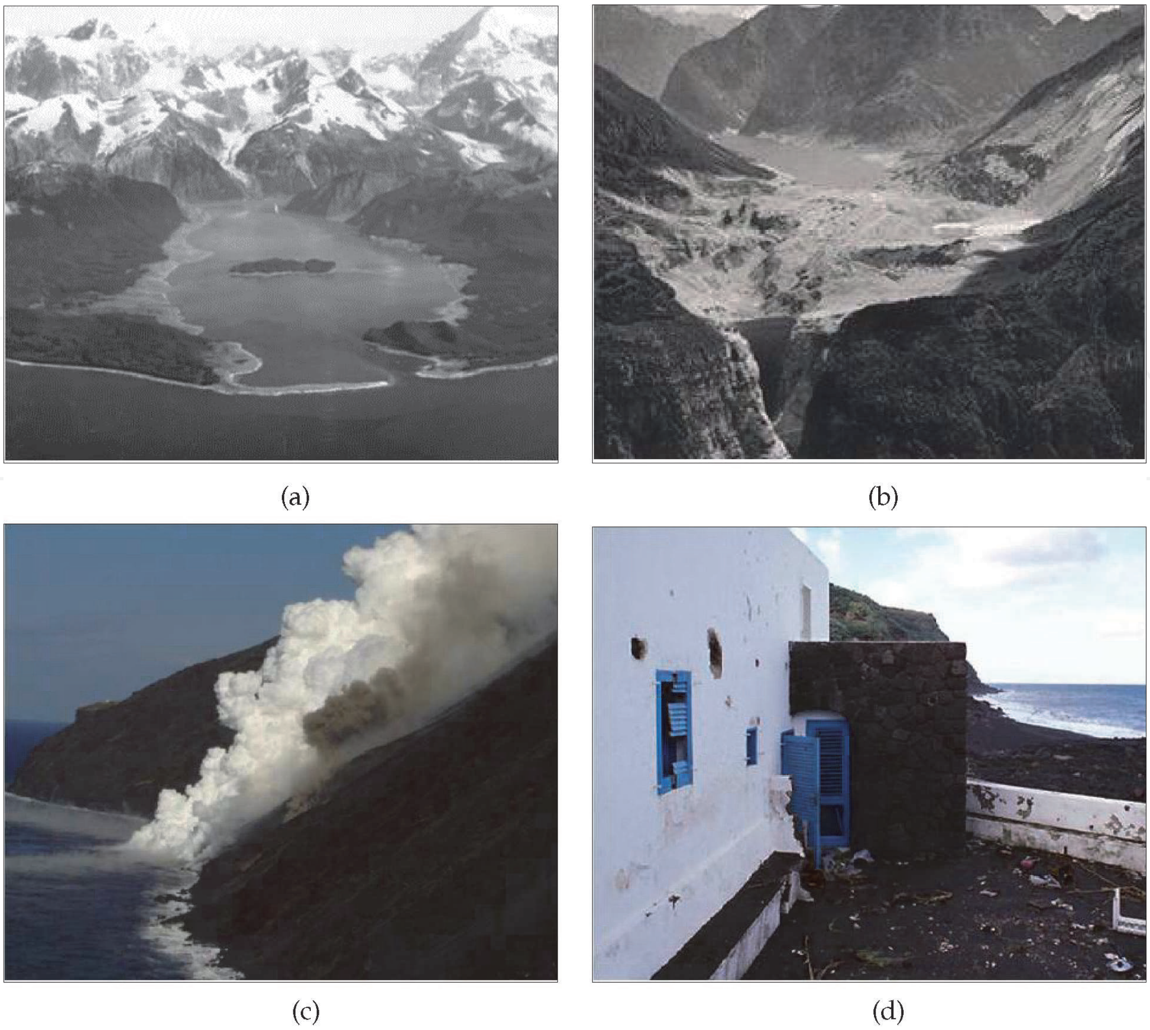

Figure 1.
Pictures of areas historically affected by landslide-generated tsunamis. (a) Lituya Bay, Alaska, 1958. (b) Vajont Valley, Italy, 1963. (c) Stromboli Island, Italy, 2002. (d) Damages at Stromboli Island, Italy, 2002.

earthquakes. The triggering mechanism (the landslide), can be classified as subaerial, partially submerged or completely submerged, depending on the initial landslide position [8, 9]. The occurrence of the landslide at the water body boundary implies that the generated impulse waves propagate both seaward and alongshore. Moreover, complicated physical phenomena due to the interaction between the waves and the sea bottom (e.g. trapping mechanisms *Bellotti and Romano* [10], *Romano et al.* [11]) are likely to plays a significant role, which comprehension is essential for designing and implementing the so-called early warning systems *Bellotti et al.* [12], Cecioni et al. [13], De *Girolamo et al.* [14].

The complex physical phenomena related, on one hand, to the landslide triggering mechanisms and, on the other hand, to the tsunami generation, propagation and interaction with the coast mechanisms are brilliantly and exhaustively described by **Figure 1** (and its description) of *Di Risio et al.* [8]. Due to its clarity and usefulness, this figure is here reported (**Figure 2** of the present manuscript). As mentioned, depending on the initial landslide position, as well as on the geometry of the near- and the far-field, the tsunami characteristics can change significantly. Therefore, to reduce and/or to mitigate the landslide-generated tsunami risk the comprehension and the right modeling of such complicated phenomena is essential. Numerous studies dealing with landslide-generated tsunamis are available in the scientific literature. Experimental, analytical, and numerical models have been extensively used (both as separated tools and in conjunction) to shed light on this complicated natural event.

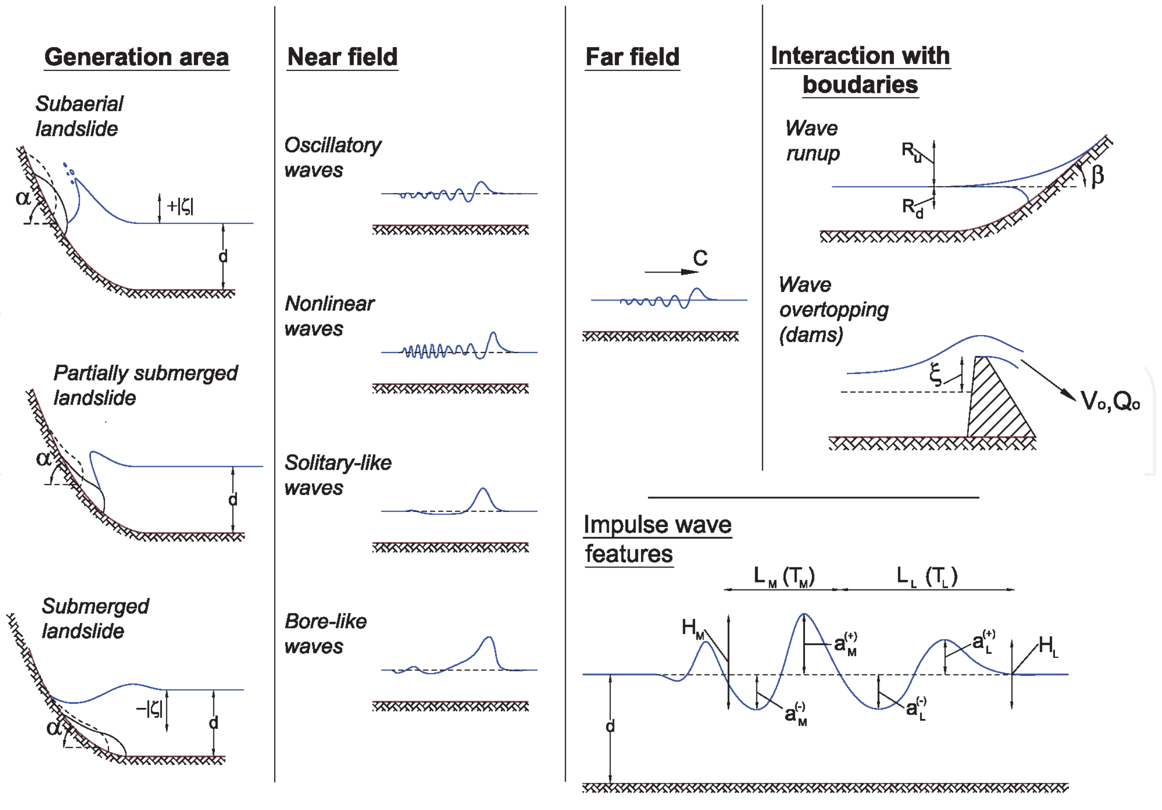

Figure 2.
Sketch of landslide-generated impulse waves [8].

In this chapter a special attention to the experimental and numerical modeling of landslide-generated tsunamis is given. It is important to highlight that this work has not the haughtiness to provide an exhaustive description, since the beginning to the present days, of the physical and numerical modeling techniques related to landslide-generated tsunamis. Indeed, brilliant and exhaustive review of the state of the art, as well as of the future challenges, related to the physical and numerical modeling of landslide-generated tsunamis are provided by authoritative Authors. It is worth to remember, among others, the excellent review of the physical model experiments, together with the main results and achievements, provided *Di Risio et al.* [8], as well as the exhaustive description of the landslide-generated tsunami numerical modeling techniques addressed by *Yavari-Ramshe and Ataie-Ashtiani* [15]. Thus, the objective of the present chapter lies in providing an update of the state of the art related to the physical and numerical modeling techniques of landslide-generated tsunamis, with a special focus on those studies published in the last ten years. Moreover, as far as numerical models are concerned a special attention is paid to the recently developed Computational Fluid Dynamics (CFD) techniques; in fact, the development and the application of these techniques has experienced a boost up the last decade. It is worth noticing that analytical modeling is not considered in the Chapter.

As stated, in this study a review of the physical and numerical modeling techniques related to landslide-generated tsunamis is provided. The main purpose of this study lies in describing, with no claim to be exhaustive and by adopting a flowing style, the main approaches exploited so far and in discussing the potentials as well as the limitation of the methods themselves. Moreover, the future challenges related to the present research field are discussed. This chapter in organized as follows. In the next section a review of the physical modeling techniques related to landslide-generated tsunamis is presented. Then, a section dealing with the numerical modeling techniques follows. Finally, concluding remarks close the chapter.

2. Landslide-generated tsunamis: physical models

In this section the most recent physical model experiments related to landslide-generated tsunamis, dealing with a large variety of geometries (plane slopes, conical islands, reservoirs, etc.) and landslide types (subaerial, partially and completely submerged), are reported. As anticipated, the studies are enumerated using a flowing style and presented in chronological order of publication. A distinction between rigid and deformable landslide models has been followed, while no distinction is made between 2D and 3D configurations.

2.1 Rigid landslide models

In 2013, *Romano et al.* [11] carried out a 3D experiment to investigate the alongshore propagation features and the trapping mechanisms of tsunamis generated by semi-elliptical subaerial landslides around the coast of a circular island. They used the same experimental setup described by *Di Risio et al.* [16] and later by *Romano et al.* [17] and, by applying the wavenumber-frequency analysis (k-f) on the records of shoreline displacement, they pointed out that the 0th-order edge wave mode is the only one relevant for shoreline runup.

Heller and Spinneken [18] performed a large number of 2D experiments in a wave flume dealing with subaerial block-shaped landslides. In their experiments they investigated, among others, the effect of three block model parameters (i.e. the landslide Froude number, the relative slide thickness, and the relative slide mass). They provided empirical equations for the maximum wave amplitude, height, and period. Moreover, by comparing the newly derived equations as obtained for block-shaped landslides with the available equations for granular landslides, they found that block-shaped landslides do not necessarily generate larger waves than granular slides.

In 2015, *Heller and Spinneken* [19] presented a new set of 3D experiments carried out in a wave tank dealing with subaerial block-shaped landslides. The authors compared the new 3D results with past 2D experimental ones, published by the same pair of Authors [18], taking advantage of the identical boundary conditions between the two sets of data. Several parameters (i.e. water depth, landslide volume and density, landslide release positions) have been changed during the new experiments. Therefore, the Authors provided some empirical equations to predict the 3D offshore and laterally onshore wave properties, identifying the waves decay law both for 2D and 3D configurations, and providing very useful discussion on the existing 2D-3D conversion formulae (e.g. *Watts et al.* [20]).

In 2016, *Romano et al.* [17] published a series of new 3D experiments dealing with tsunamis generated by semi-elliptical subaerial landslides occurring at the flank of conical islands. As pointed out by *Di Risio et al.* [16], the physical model at hand aims at reproducing, in a Froude law scale, the Sciara del Fuoco slope (see **Figure 3**), i.e. a natural sliding surface located at the Stromboli Island (Southern Thyrrenian Sea, Italy). The main objective of the experiments is to provide a benchmark dataset for the validation of numerical models of landslide-generated tsunamis. To this end, a quite unique acquisition system, consisting of both fixed and movable wave gauges, has been deployed and used. The experimental procedure is per se a novelty as each experiment consists in repeating several times the same landslide event, by changing for each repetition the position of the movable gauges, then obtaining, after checking the repeatability, a single virtual experiment with high spatial resolution measurements. Two different semi-elliptical landslide bodies have been used for the experiments (see **Figure 3**) in order to investigate the effects of the landslide volume and thickness, revealing that the mentioned parameters affects significantly only the wave amplitudes, especially in the near field,

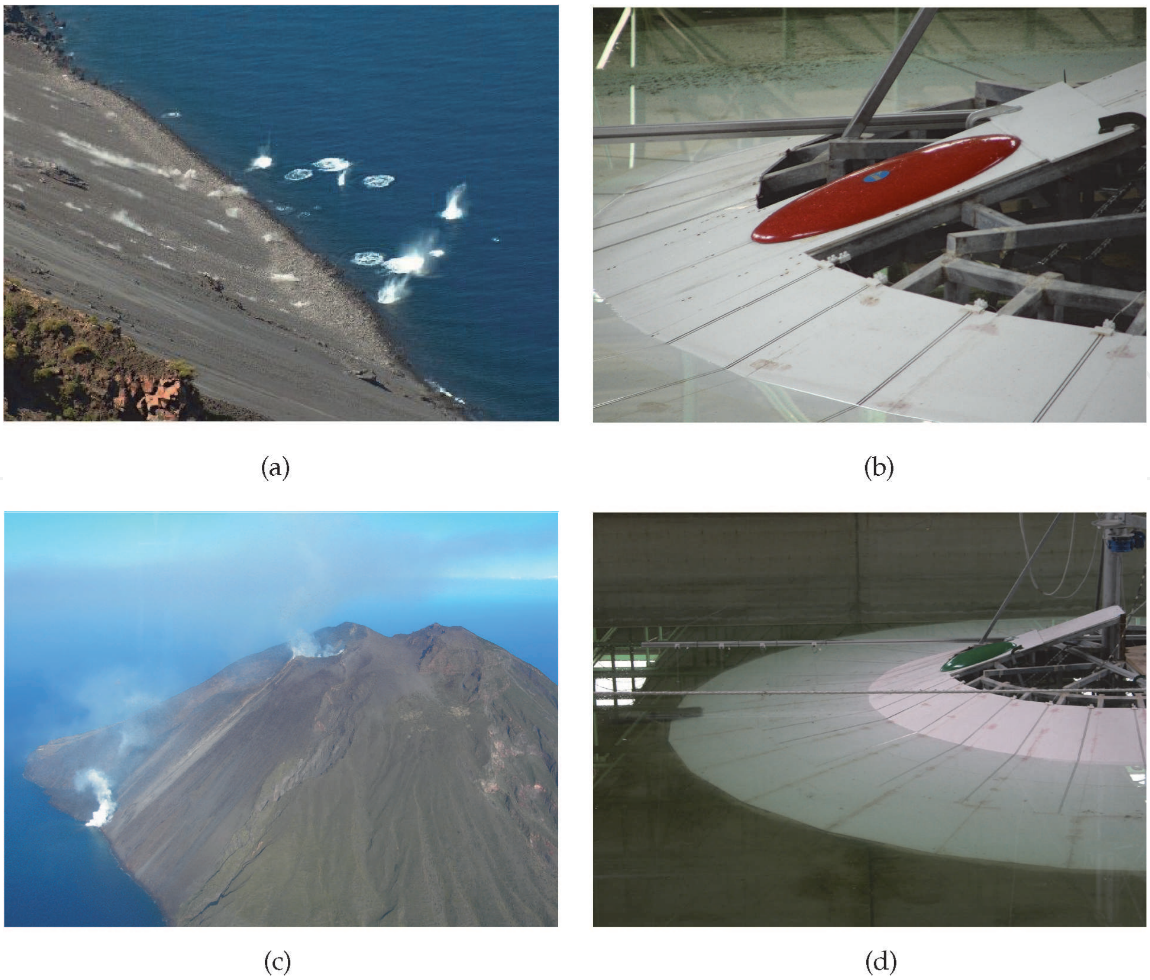

Figure 3.
Pictures of the Sciara del Fuoco (Stromboli island) and the slide placed on the conical island model. (a) Detail of Sciara del Fuoco: rock fall. (b) Detail of the slide along the conical island. (c) Aerial view of Sciara del Fuoco. (d) Lateral view of the conical island and the slide.

while for the wave periods (and celerities), a weak dependence upon these landslide parameters can be observed.

The studies cited so far are related to subaerial landslides. Few are the recent experimental works dealing with submerged landslides. Indeed, the experimental modeling of submerged landslide presents a wide range of physical restrictions. Therefore, clever technical solutions have often been employed (e.g. *Enet and Grilli* [21], *Liu et al.* [22], Watts [23]). Nevertheless, it remains the practical difficulty of exploring in detail the influence of some key governing parameters, as for instance the initial acceleration a_0. This parameter is commonly recognized to be a crucial one in the slide kinematics, in particular in the initial phase, when the energy transfer between the landslide and the water takes place [1, 20, 21, 23–26]. Several experimental studies explored the importance of a_0 by means of different techniques. *Watts* [23] changed the landslide's density to obtain different values of a_0. In 2017, *Romano et al.* [27], using the same physical model described by *Di Risio et al.* [16], *Romano et al.* [11, 17], used a mechanical system controlled by an electric motor to perform parametric 3D experiments by changing the kinematics of a semi-elliptical submerged landslide. The experimental results pointed out that as the initial acceleration increases, then the rising time of the first wave trough decreases and, in general, the wave signals exhibit a shorter wave periods. This findinds have been recently numerically confirmed by *Romano et al.* [28] (see Section 3). As far as submerged landslides are concerned, a note on the use of rigid landslide models is due. Although this represents an approximation of the real submerged landslide behavior, it is well demonstrated in the scientific literature (e.g. *Grilli et al.* [24]) that the landslide deformation does not play a significant role on submarine landslide tsunami features in the slide early time kinematics, which at short time scales is mainly governed by the initial acceleration.

Finally, innovative physical model approaches, by using rigid landslide models, have been recently used by *Perez del Postigo Prieto et al.* [29] to reproduce a coupled-source tsunami generation mechanism due to a 2D underwater fault rupture followed by a submarine landslide. Furthermore, 2D experiments have been employed to interpret the dynamics of complicated recent events, like the eruption of the Anak Krakatoa volcano (Indonesia) in December 2018. To this end, it is worth noticing the study of *Heidarzadeh et al.* [30], that applied a combination of qualitative physical modeling and wavelet analyses of the tsunami as well as numerical modeling to propose a source model of the Anak Krakatoa event.

2.2 Deformable landslide models

Quite various are the physical model tests dealing with deformable landslide models. In 2010 Heller and Hager [31] performed 2D experiments dealing with subaerial landslide by using granular slide material. The large number of tests (more than 200) aimed at exploring the influence of several governing parameters, namely: still water depth, slide impact velocity, slide thickness, bulk slide volume, bulk slide density, slide impact angle, and grain diameter. As a result, the Authors provided empirical predictive equations for all relevant wave characteristics, e.g. maximum wave height, the maximum wave amplitude (including its location and period in the slide impact zone), and both the wave height and amplitude decay and the period increase in the wave propagation zone. Furthermore, the Authors present a comparison of the presented equations with the 1958 Lituya Bay case, finding a good agreement.

In 2012, *Mohammed and Fritz* [32] carried out a massive 3D experimental campaign aimed at studying the tsunamis characteristics generated by subaerial deformable granular landslides occurring at a plane slope, using a novel approach based on a pneumatic landslide generator to control the landslide impact characteristics. In their study they found a robust correlation between the wave characteristics and the landslide Froude number, providing also some quantitative calculation of the landslide-water energy converted rate. Moreover, a deep discussion on the wave amplitudes decay, wave celerities and comparison with other 2D and 3D landslide tsunami studies is provided.

In 2014, Viroulet et al. [33] published the results of some 2D experiments dealing with subaerial landslides sliding along a rough slope. The Authors investigated mainly the influence of the slope angle and the granular material, by using three different granular materials (spherical glass beads with two different diameter, non-spherical sand), on the initial amplitude of the generated leading wave and the evolution of its amplitude during the propagation. Interestingly, the presented experiments aim at investigating the tsunami characteristics generated by landslide characterized by Froude number smaller than one. As stated by the Authors, this situation is particularly relevant to model tsunamis generated by cliff failures located just above the sea surface, which are characterized by low impact velocities.

A unique series of large-scale 3D physical model experiments is described in 2016 by *McFall and Fritz* [9]. In this study the Authors investigated the runup features, measured both on the same coast at which the landslide occurred and on an opposing hill slope, of tsunamis generated by subaerial granular landslides occurring both at planar coast and conical island. The pneumatic landslide generator described in Mohammed and Fritz [32] has been used for the experiments. Different landslides geometries and kinematics have been used and robust results and findings are provided, namely related to: maxima and minima runup and rundown location, decay along the coast and amplification; effects of the granulometry on the lateral wave runup; energy trapping properties of a circular shoreline, also confirming the findings of *Di Risio et al.* [16], *Romano et al.* [11, 17]. Finally, predictive equations for the laterally propagating wave characteristics, benchmarked against the 2007 landslide-generated tsunami in Chehalis Lake, British Columbia, Canada, are provided by the Authors.

In the same year, *Lindstrøm* [34] performed a series of 2D experiments dealing with subaerial landslides in a wave flume. The Author, keeping constant few parameters (i.e. landslide volume, initial position, slope angle and equilibrium water depth), varied only the slide material. In particular, five different slide types have been used: one block slide and four granular slides with grain diameter ranging from 3 mm to 25 mm. A very interesting aspect, pointed out by the present study, is related to the effect of the landslide porosity. Indeed, *Lindstrøm* [34] by comparing the present results with the predictive formulae of maximum wave amplitudes, available in the literature, found some differences, probably due to the effects of the landslide permeability.

Also in 2016, *Zitti et al.* [35] carried out a series of 2D experiments dealing with subaerial landslides, aiming at simulating the effects of a snow avalanche entering a body of water. To mimic a snow avalanche striking a reservoir, a lightweight granular material has been used as a substitute for snow. Morevoer, the Authors developed a theoretical model to describe the momentum transfers between the particle and water phases of such events. The presented experimental results have also been compared with those obtained by *Heller and Hager* [31], as the same relative particle density, but higher landslide Froude numbers, has been used by the two groups of Authors.

In 2017 *Miller et al.* [36] carried out 2D experiments dealing with granular subaerial landslides. The Authors presented a detailed analysis on the velocity and thickness of the granular flow, on the shape and location of the submarine landslide deposit, on the amplitude and shape of the near-field wave, on the far-field wave evolution, and on the wave runup elevation on a smooth impermeable slope. By using high-speed camera observations and standard free surface elevation measurements the Authors pointed out that only a portion of the landslide (named the "effective mass") is engaged in activating the leading wave. Furthermore, the Authors observed a good agreement between their experimental results and the values provided by existing empirical predictive formulae, available in the literature, as the so-called effective mass is used. The effective mass is defined as the percentage of the total landslide mass that enters the water body before the initial wave leaves the impact zone and it is a crucial aspect to be considered for landslides that are long and thin with very large relative mass, as in this case only a portion of the landslide mass is engaged in activating the leading wave. In the same year, *Mulligan and Take* [37], by using the experimental data discussed by *Miller et al.* [36], presented a study on the momentum flux exchange between granular landslides and water, finding that the results of their approach, based on the momentum-based equations, are in agreement with the previous laboratory data of *Heller and Hager* [31] and *Miller et al.* [36].

In the last two years, peculiar and very interesting new experimental approaches have been used. It is worth citing the study of *Tang et al.* [38] that performed 2D laboratory tests for impulse waves generated by subaerial landslides made as the combination of solid block and granular materials (glass spheres), also comparing the obtained results with those of individual models of pure solid block and granular landslides. In their experiments the Authors varied the slope angle and the mass ratio m^* (i.e. mass of the solid block divided by mass of the granular material). The experimental results suggest that the mixed landslide composition generally produces larger impulse waves in the impact zone compared with those triggered by pure solid block landslides and pure granular landslides, suggesting that the primary wave amplitudes of impulse waves might have been underestimated in previous laboratory tests with solely solid or granular assemblies when using the same slide mass and release height. Furthermore, they pointed out that, if compared with pure granular landslides, the combined landslides generally exhibit larger Froude numbers and slide thickness.

Very recently, *Bullard et al.* [39] performed 2D tests dealing with deformable subaerial landslides. The point of novelty, among others, of the present study lies in using water as sliding material. This aspect ensures a null internal shear strength, being then representative of the upper limit of high landslide mobility. Four different slide volumes have been used during the experiments and a high-speed camera has been used to measure the slide thickness and velocity. The experimental results indicate that in the near-field the maximum wave amplitude is dependent on the landslide thickness and velocity and is relatively independent of the water depth.

3. Landslide-generated tsunamis: numerical models

Although totally irreplaceable, experimental tests are often time consuming, especially if 3D models are considered. Large facilities, as well as complex experimental configurations and sophisticated measurement systems are often needed (see [9, 17]). Furthermore, it is not always possible to explore in detail the influence of all the involved parameters. In this sense, tsunamis generated by submerged landslides provide a good example. Often the waves generated by submerged landslides are too small to get reliable measurements in the experimental facilities. Moreover, as previously stated, it can be difficult to explore the influence of key governing parameters (e.g. the initial acceleration a_0, *Romano et al.* [27]).

In this sense, numerical modeling can provide a valuable complementation to the physical model experimental activities. Indeed, numerical modeling techniques have progressively supported physical ones in shedding light on the complex physical phenomena involved in the generation and propagation mechanisms of landslide-generated tsunamis. Similarly to experimental models, a multitude of approaches has been adopted during recent years for numerically modeling landslide-generated tsunamis (an extensive review has been provided by *Yavari-Ramshe and Ataie-Ashtiani* [15]). Eulerian and Lagrangian frameworks with three grid types (structured, unstructured, and meshless) have been used for tsunami simulations, employing both depth-averaged models, using Non-Linear Shallow Water or Boussinesq Equations, and Navier–Stokes models, considering both 2D and 3D configurations (e.g. [7, 13, 22, 25, 30, 40–47]).

The most recently developed tools offered by Computational Fluid Dynamics (CFD) can provide a significant support for shedding light on many of the unresolved aspects. In particular, they can be very useful to model the near-field wave characteristics. Indeed, the accurate reproduction of the momentum exchange between the landslide and the water body, achievable by the CFD methods, is crucial for a detailed modeling of tsunami generation, propagation and the interaction with the coastline.

In this last section of the chapter, a brief overview of the studies dealing with the recent CFD techniques and approaches developed and published in the last ten years is presented.

In 2010, *Abadie et al.* [48] presented the application and the experimental validation of the 3D incompressible multiple-fluid Navier–Stokes Volume Of Fluid (VOF) model THETIS to reproduce waves generated by rigid and deforming landslides valid for idealized geometries. All the domain portions (i.e. water, air, and landslide) are treated as Newtonian fluids. In this case, as far as rigid slides are concerned, a "penalty method" allows for parts of the fluid domain to behave as a solid. Thus, the coupling between a rigid slide and water is implicitly computed and it is not necessary to specify a given landslide kinematics. The comparison between numerical model simulations and experimental results, related to different landslide configuration (semi-elliptical block, vertical falling rectangular block and 2D and 3D wedges sliding down an incline), shows a good agreement.

One year later, *Montagna et al.* [49] carried out some 3D numerical computations of landslide-generated tsunamis by using the commercial code FLOW-3D, dealing with a semi-elliptical rigid subaerial landslide occurring at the coast of a conical island. A very good agreement is found by comparing the numerical runup measurements with the experimental data obtained by *Di Risio et al.* [16].

In 2015, *Ma et al.* [50] described a new two-layer model for subaerial granular landslide motion and tsunami wave generation. In this study, the modeling of the landslide motion and tsunami wave generation are simulated by separate model components. Indeed, the landslide is described as a saturated granular debris flow, accounting for intergranular stresses governed by Coulomb friction. Tsunami wave generation and propagation is simulated by the 3D Non-Hydrostatic WAVE model NHWAVE [51] that solves the incompressible Navier–Stokes equations. It is worth noticing, that the hybrid numerical approaches (i.e. coupling geotechnics and hydrodynamics models) have been successfully carried out by *Løvholt et al*. [42] and later by *Kim et al.* [25], that simulated the dynamics of the Storegga Slide and tsunami using the depth-averaged landslide model BingClaw, which implements visco-plastic rheology and remolding, and couple it to a standard tsunami propagation model, to reproduce tsunamis generated by submerged landslides.

Heller et al. [52] presented a composite (experimental-numerical) modeling approach for modeling tsunamis generated by rigid subaerial landslides. In this case, an hybrid approach based on the combined use of physical and numerical modeling has been used. Indeed, the experimental results, described in *Heller and Spinneken* [19], have been used to calibrate the 3D smoothed particle hydrodynamics (SPH) code DualSPHysics v3.1 [53], which includes a discrete element method (DEM)-based model to simulate the landslide-ramp interaction.

In 2016, *Shi et al.* [54] presented 2D simulations of the generation of impulse waves produced by subaerial granular landslides. They used a newly-developed soil-water coupling model in a smoothed particle hydrodynamics (SPH) framework. The point of novelty of the work lies in using an elasto-plastic constitutive model for soil, a Navier–Stokes equation based model for water, and a bilateral coupling model at the interface. The Authors tested their model with simulated waves induced by both slow and fast landslides, obtaining a good agreement between numerical and experimental data. The experimental benchmark data used by *Shi et al.* [54] to test their model are the ones described by *Viroulet et al.* [33], aiming at reproducing slow landslides, and by *Fritz et al.* [55], to simulate fast landslides. Another strength of their modeling approach is related to that all parameters used in the model have their physical meaning in soil mechanics and can be obtained from conventional soil mechanics experiments directly.

Whittaker et al. [47] presented the 2D physical and numerical modeling of a submerged rigid semi-elliptical block body moving along a horizontal and impermeable surface (i.e. the sea bottom). During the experiments, the body movement was controlled by mechanical system and laser-induced fluorescence measurement systems has been used for measuring both spatial and temporal variations in the free surface elevation. To numerically reproduce the experiments, the Authors used the OpenFOAM® platform [56]. In particular the Authors used IHFOAM [57, 58], a solver based on interFoam of OpenFOAM® that 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 [59, 60], coupled to the VOF, to model the rigid object as a moving bottom boundary. The Authors noticed an under-prediction between the measured and the simulated wave amplitudes, although the wave phasing is fairly reproduced.

In 2018, *Si et al.* [45] performed a series of 2D simulations dealing with subaerial landslides using an advanced two-phase model for dry granular material intruding into a water body. The water-air interface both within and outside the granular material is captured by the VOF method. The inter-granular stresses are formulated based on a general collisional-frictional law developed for underwater granular flows and a modified k-ε model is adopted to describe the turbulence effect of the ambient fluid. *Si et al.* [45] used their numerical model to reproduce past experiments related to subaerial landslides [33], finding a good agreement between experimental and numerical simulation results.

In 2019, *Kim et al.* [61] presented the validation of the 3D numerical model TSUNAMI3D based on the Navier–Stokes equations and the VOF, by comparing numerical results with a set of subaerial landslide laboratory experiments (e.g. *Mohammed and Fritz* [32]) and with the ones provided by the commercial code FLOW3D. In this model water and landslide material are considered incompressible and mainly treated as Newtonian fluids. Simplified material rheology and key parameters required for modeling subaerial landslides have been used. Furthermore, the validation results confirmed that the 3D numerical models with simplified landslide rheology can be used to understand and reproduce the complex nonlinear wave propagation and runup generated by subaerial landslides. This is an important result as very often the major source of uncertainties is related to the landslide rheology and parameters.

In the same year, *Clous and Abadie* [62] presented a detailed analysis of the energy transfer mechanisms between granular landslides and water. They used incompressible Navier-Stokes VOF model THETIS [48] to perform 2D simulations of tsunamis generated by granular landslides (both subaerial and submerged) reproducing the experiments of *Viroulet et al.* [33]. As previously stated, in the THETIS model air and water are considered Newtonian fluids. The landslide is modeled as a Newtonian fluid whose viscosity is adjusted to fit the experimental results. For the subaerial case, the Authors pointed out that the viscosity value, if properly adjusted, can be seen as a very coarse approximation of the more elaborated non-Newtonian $\mu(I)$ rheological law [63].

The last three numerical approaches described in this chapter have been published in 2020. *Mulligan et al.* [64] presented a new numerical approach to simulate impulse waves generated by highly mobile subaerial landslides by using the technique of the Particle Finite Element Method (PFEM). This approach combines a Lagrangian finite element solution with an efficient remeshing algorithm and is capable of accurately tracking the evolving fluid free-surface and velocity distribution in highly unsteady flows. To validate their numerical model the Authors reproduced the experiments carried out by *Bullard et al.* [39], in which the slide material is water, aiming at representing an avalanche or a debris flow with high mobility. The Authors found that the 2D numerical model shows a good agreement with the experimental observations in terms of landslide velocity and thickness, wave time series, maximum wave amplitude, wave speed, and wave shape.

Chen et al. [65] performed 3D simulations, by using the OpenFOAM® platform [56], to reproduce the impulse waves generated by calving iceberg. To this end, they applied the Immersed Boundary Method (IBM) which allows to handle and model large displacements of bodies. Large-scale experiments [66] have been used as a benchmark for validating the numerical simulations.

Finally, *Romano et al.* [28] presented a new 3D numerical method for modeling tsunamis generated by rigid and impermeable landslides in OpenFOAM® [56] based on the Overset mesh technique. 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(s) (i.e. moving domain) that contains a rigid body. The mutual exchange of information between the two domains is achieved by interpolation. The advantage of this approach, if compared with other methods available to simulate the interaction between a moving body and one or more fluids in OpenFOAM®, e.g. the Immersed Boundary Method [65, 67] is that the resolution around the moving body is extremely accurate (i.e. body-fitted approach) and, which is even more important, remains constant throughout the simulation. Furthermore, to fit the current requirement of the Overset implementation (i.e. required distance between the moving body and the domain boundaries) the slope, on which the landslide body moves, has been modeled as a porous media with a very low permeability by using the VARANS approach proposed by *del Jesus et al.* [68], *Lara et al.* [69] and Losada et al. [70]. The approach has been successfully validated through the experiments carried out by *Liu et al.* [22]. The new method

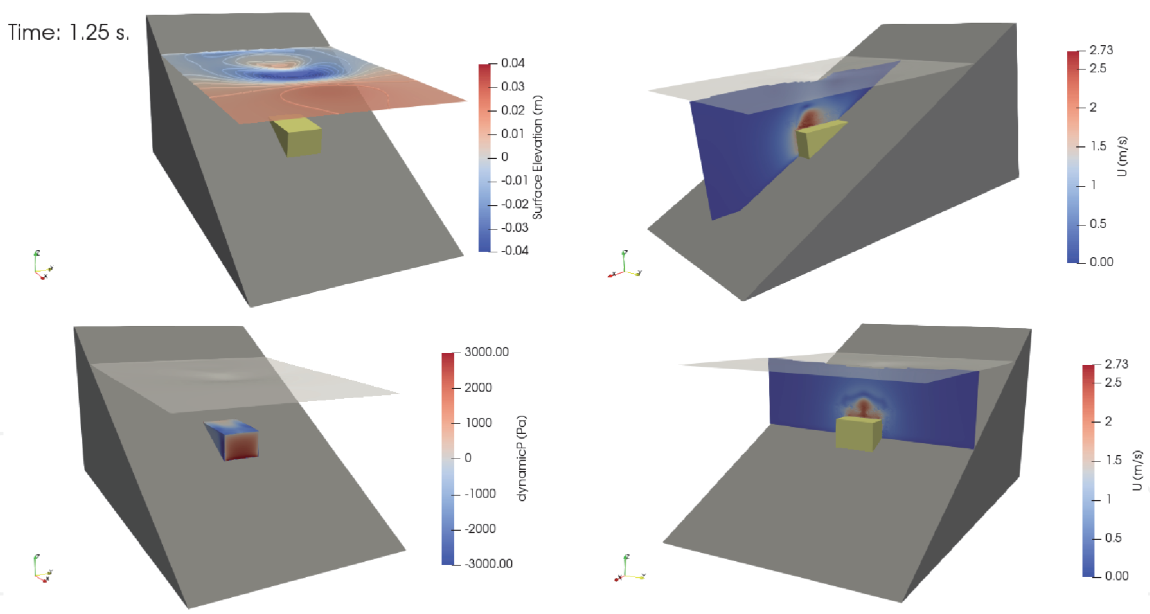

Figure 4.
Contour plot of the free surface elevation (upper left panel), dynamic pressures on the landslide (lower left panel), velocity magnitude on two cross sections (upper and lower right panels) at a given time instant of the numerical simulations described in Romano et al. [28].

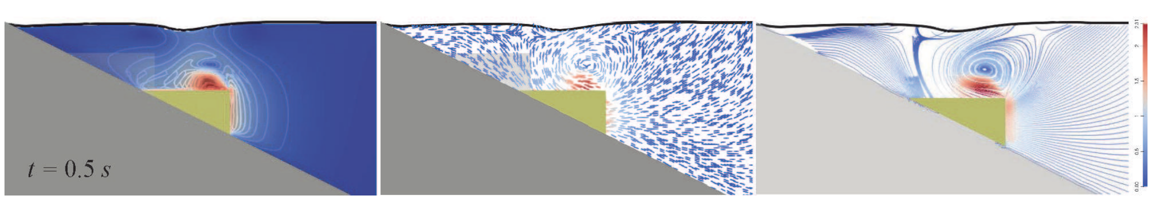

Figure 5.
Velocity magnitude, vectors and streamlines on a cross section at a given time instant of the numerical simulations described in Romano et al. [28].

has then been applied to perform a detailed numerical study of the near-field wave features induced by submerged landslides (see **Figures 4** and **5**), by varying the landslide's initial acceleration a_0. The numerical results, together with previous experimental data [21, 23, 27], have been used to obtain a relationship for predicting the wave properties in the near-field as a function of the Hammack number.

4. Concluding remarks

In this chapter a non-exhaustive update of the state of the art related to the physical and numerical modeling techniques of landslide-generated tsunamis, is presented. As stated, the objective of the present update lies in providing, with no claim to be exhaustive and by adopting a flowing style, the main experimental and numerical, with a special attention to the recently developed Computational Fluid Dynamics (CFD) techniques, approaches published in the last ten years. It is worth to remember that more detailed and complete details on the topic can be found in the detailed reviews of the physical model experiments of the numerical modeling techniques are provided by *Di Risio et al.* [8] and by *Yavari-Ramshe and Ataie-Ashtiani* [15], respectively. As far as the future research challenges are concerned, a special mention to the CFD techniques is due. Indeed, it is well recognized that the models based on the solutions of the Navier-Stokes equations are to be considered as the only alternative to accurately model the tsunami generation process [15]. This kind of modeling approach seems to be mandatory considering the nature of the complex phenomena that govern the impulse waves generation, as confirmed by the achievements obtained by the studies described in the Section 3.

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Conflict of interest

The author declares no conflict of interest.

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