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Lattice Boltzmann approach for hydro-acoustic waves generated by tsunamigenic sea bottom displacement

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ABSTRACT

Tsunami waves are generated by sea bottom failures, landslides and faults. The concurrent generation of hydro-acoustic waves (HAW), which travel much faster than the tsunami, has received much attention, motivated by their possible exploitation as precursors of tsunamis. This feature makes the detection of HAW particularly well-suited for building an early-warning system. Accuracy and efficiency of the modeling approaches for HAW thus play a pivotal role in the design of such systems. Here, we present a Lattice Boltzmann Method (LBM) for the generation and propagation of HAW resulting from tsunamigenic ground motions and verify it against commonly employed modeling solutions. LBM is well known for providing fast and accurate solutions to both hydrodynamics and acoustics problems, thus it naturally becomes a candidate as a comprehensive computational tool for modeling generation and propagation of HAW.

1. Introduction

Submarine earthquakes and submarine mass failures (SMFs), such as landslides and slumps, can generate long gravitational free surface waves (or tsunamis), and pressure waves or hydro-acoustic waves, HAW. The latter are emitted by the column of water above the generation zone, which, due to its compressibility, acts as an oscillatory generator for quasi-horizontally traveling HAW (Fig. 1). Tsunami waves can travel for long distances and are known for their dramatic effects on coastal areas. HAW travel roughly 10 times faster than the tsunami, effectively at the speed of sound in water. The presence of HAW in a pressure record therefore can anticipate the arrival of the tsunami, thus serving as a potential means for tsunami warning.

Researchers have studied two frequency ranges for acoustic waves associated with tsunamigenesis: (1) low frequency HAW with characteristic frequencies ~0.1Hz, and (2) T-waves, in frequencies in the range between 2 and 100Hz. Low frequency HAW generated by seabed motion were measured during the Tokachi-Oki 2003 and Tohoku-Oki 2011 tsunami events by the Japan Agency for Marine-earth Sciences and TEChnology observatory and later have been used to estimate amplitude, duration, and velocity of bottom displacements, and as benchmarks for 3D and 2D numerical models (Nosov and Kolesov, 2007; Bolshakova et al., 2011; Abdolali et al., 2015d). During the 2012 Haida Gwaii event in Canada, bottom pressure signals were used to reveal the frequency ranges associated with gravity waves and HAW (Abdolali et al., 2015a). Higher frequency HAW records, or T waves, have also been applied to a number of tsunami characterization problems ,including determination of the timing of the 1998 Papua New Guinea SMF event (Okal, 2003), estimation of the rupture length and velocity of bottom deformation of the 2004 Great Sumatra earthquake (de Groot-Hedlin, 2005), and estimation of the submarine landslide speed during the West Mata eruption in 2010 (Caplan-Auerbach et al., 2014). The variation of sound speed within the water column, multipathing of sound waves, and summation of direct and surface-reflected arrivals causes interference patterns in the hydro-acoustic spectrum, giving useful insights into the recognition of the type of bottom motion (i.e. earthquake, landslide or eruption), depth of occurrence and duration (Chierici et al., 2010).

To date, HAW as precursors of tsunamis have been numerically modeled by means of linear models (Nosov and Kolesov, 2007; Bolshakova et al., 2011) derived from the Compressible Euler (or inviscid Navier–Stokes) equations (hereinafter CEE). As these approaches are computationally demanding, resort has been made to vertically integrated formulations of the same set of equations, as in Sammarco et al. (2013) and Abdolali et al. (2015c). These mod-

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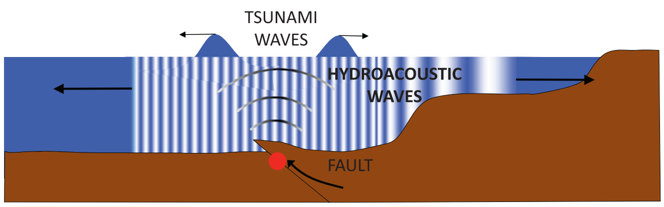

Fig. 1. Sketch of the mechanism of generation and propagation of tsunami and HAW: the tsunami waves travel at a lower speed than the HAW.

els proved to be not only accurate enough to capture the main far-field features of HAW for idealized cases, but also efficient enough to be employed to reproduce real tsunamis (Abdolali et al., 2014; 2015a; Cecioni et al., 2015; Abdolali et al., 2015d). The main drawback of these depth-integrated models lies in leaving out both the horizontal component of bed deformation and vertical variations of the propagation medium. These omissions may be the limiting factor to accuracy in all cases when the multiple reflection between uneven seafloor and surface causes non-trivial propagations patterns. The interplay between the abovementioned aspects occurs when wave reflection, induced by uneven seafloor, gives rise to modification of the grazing angle of wave fronts, which in turn allows for high frequency bands to be trapped into the SOFAR channel (Johnson et al., 1963; Talandier and Okal, 1998; de Groot-Hedlin and Orcutt, 1999; Williams et al., 2006). In order to simulate these phenomena, resort has to be made to fully 3D (or 2D in the vertical x-z plane) models whose computational demand makes their employment over large areas, even for the reproduction of mid-frequencies bands, often prohibitive. The approach that we propose in this work is to solve the non-linear compressible Navier–Stokes equations by means of the Lattice Boltzmann Model (LBM), which guarantees enough computational efficiency to make the non-depth-integrated solution feasible also for real cases (Prestininzi et al., 2014). Moreover, as further explained later, LBM, being a fully non linear fluid dynamics solver, does not rely on any assumption either on the magnitude or the type of bottom displacement, thus effectively opening the possibility to directly simulate HAW deriving by complex SMFs (De Girolamo et al., 2014). Regarding computational efficiency, in the specific field of acoustics, LBM has been proven to require a lower number of operations to advance the solution for a fixed time interval, given a fixed absolute dispersion error, than is commonly required in conventional finite difference methods (Marié et al., 2009). Moreover, the ease of parallel implementation and the extreme scalability of the LBM lie at the heart of its huge worldwide spread as a computational fluid dynamics solver. Several works (Bernaschi et al. (2009) and Obrecht et al. (2013), for example) have reported quasi-ideal speed-up of LBM on thousands (16384) of cores or GPU. These impressive performances naturally suggest the LBM as an efficient computational framework very attractive for performing coupled hydro-acoustic/hydrodynamic simulations for real and deferred time tsunami simulation.

The LBM approach not only allows us to overcome the aforementioned limitations of the depth integrated models, but provides further intrinsic advantages also over the 3D CEE models: it opens the possibility to integrate an hydro-acoustic solver with an efficient and extremely flexible hydrodynamic solver, leading to what is known as the "direct approach" that is, modeling the hydrodynamic processes leading to the formation of HAW, just like their counterpart in aeroacoustics (de Jong et al., 2013). In perspective such LBM direct approach could be easily coupled with LBM wave models in order to perform efficient planetary-scale hydro-acoustic simulations (Metz et al., 2016).

The aim of this work is to present and validate a LBM model for the generation and short range propagation (∼10 times the fault length) of pressure waves in an idealized 2D $(x-z)$ compressible ocean. Generation consists in a fast vertical displacement of a portion of the seafloor. No free surface is modeled at this stage, and thus the gravity mode representing the main tsunami gravity wave does not appear as part of the solution. Validation is carried out employing results from a previously validated model. Section 2 provides an overview of formation of HAW. Section 3 describes the Lattice Boltzmann Method for compressible fluids, scaling and forcing boundary condition. Verification of the LBM model is carried out for constant and varying geometries against both numerical and analytical solutions of CEE in Section 4. Conclusions and perspectives are given in Section 5.

2. Hydro-acoustic waves generated by seabed movement

HAW recorded during tsunami events are often characterized by highly energetic power spectra, which segregate into discrete peaks centered around cutoff mode frequencies. Their energy content is comparable to that of the tsunami gravity wave. The dominant frequency range in the wave spectrum can be expressed by a discrete set of normal frequencies $f^{(n)}$ given by

$$f^{(n)} = (2n-1)\frac{c}{4h}, \qquad n = 1, 2, 3, \dots \tag{1}$$

where h and c are respectively the depth and the speed of sound of water. It has previously been highlighted (Nosov and Kolesov, 2007) that the assumption of perfectly reflecting seabed could introduce inaccuracies in the modeling of the propagation of HAW. Indeed, introducing a single underlying sediment layer, acting together with the water column, lowers the spectral peak frequencies, $\gamma^{(n)}$, which are then determined from the following transcendental equation (Abdolali et al., 2015b):

$$\tan\left[\frac{2\pi\gamma^{(n)}h}{c}\right]\tan\left[\frac{2\pi\gamma^{(n)}a}{c_s}\right] = \frac{\rho_s c_s}{\rho c} \tag{2}$$

where a, c_s and ρ_s are respectively thickness, sound speed and density of the sediment layer; ρ is water density. Equation (2) relies on the treatment of the sediment layer as a "fluid like" layer (Chierici et al., 2010). More complex and physically grounded approaches have also been proposed (Balanche et al., 2009; Maeda and Furumura, 2013), but require the coupling between different models.

Another important aspect related to the propagation of HAW into complex geometries is the filtering effect induced by shallow regions. Indeed HAW generated at large depths, dominated by the first normal mode, undergo a cut off condition when propagating into shallower regions. This shift in the power spectrum should be taken into account when planning the arrangement of new measurement probes, or accounted for when analyzing arriving signals at shallow depths. A test case investigating the filtering effect of the shallow areas is included in the following.

Stiassnie (2010) provided an analytic and detailed calculation for wave radiation by a piston bottom displacement, in a compressible ocean of constant depth to calculate the nondimensional free surface and dynamic bottom pressure acoustic-gravity wave modes at a large distance from the source within the framework of a two-dimensional linear theory. This analytical solution has been employed as a reference solution in the following. In order to better explain the generation and propagation dynamics, the reader is referred to the provided supplemental video, showing the pressure field in the whole domain for a test case introduced later on.)