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Tsunami early warning system based on real-time measurements of hydro-acoustic waves

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Abstract

The paper presents a numerical model to reproduce the tsunami generation and propagation, which can be applied in real-time to be used as a forecasting tool. Free surface elevation measurements in a point close to the tsunami generation area, allows the real-time prediction of tsunami in the far field. This is possible due to an inversion technique. The measurements and modeling of hydro-acoustic waves could shorten the time for spreading the alarm and reduce the number of false alerts. In the paper new investigation about hydro-acoustic waves are also presented in order to outline their possible use to support Tsunami Early Warning System.

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1. Introduction

Tsunamis are impulsive waves mostly generated by underwater earthquakes or landslides. Their propagation occurs at high celerity and, approaching to shallow water, their wave height can potentially become very large. The inundation effects are therefore tragically known. Although a tsunami cannot be prevented, the coastal impact of such wave can be mitigated through community preparedness, timely warnings, and effective response. The Tsunami Early Warning Systems (TEWS) are therefore the most effective tool in order to reduce or avoid human victims. TEWS must show some mandatory features in order to be effective, as: fast prediction, reliable response and efficient alarm. Tsunamis have the energy to propagate across the ocean, therefore the longer are the distances covered, the longer is the time to spread the alarm and more effective actions can be taken by local emergency authorities in order to save lives and properties. Indeed in smaller seas, as the Mediterranean sea, tsunami detection, sea-level assessment and warning must be completed within few minutes to provide reliable warnings to the population. The initial warning is based on seismic wave as indirect measurement of tsunami generation, which provides the epicenter location and therefore allows to roughly obtain the tsunami arrival time prediction. Then tsunamis are detected by bottom pressure records

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or wind-waves gauges. There exist several algorithms in order to automatically perform the real-time detection of a possible tsunami within recorded signals (Beltrami et al., 2011). Once the tsunami occurrence is confirmed by the measurements, it is unfeasible to wait that the whole tsunami has been recorded for timely evacuation measures. It is therefore preferable that tsunami recording occurs close to the generation area, in order to gain time in the tsunami forecasting faraway from it.

Several researches have been carried out in order to improve the reliability of TEWS, testing different models of wave propagation, and various tsunami inversion techniques. Among many previous studies, it is worth to cite Satake (1987), Johnson et al. (1996) and Tinti et al. (1996). Recently Wei et al. (2003) and Titov et al. (2005) proposed a method which combines real-time seismic and water level data with a database of precomputed tsunami scenarios. Both works make use of a forecasting inversion technique based on Green's function approach.

The present paper describes a numerical model, which reproduces tsunami generation and propagation and it allows real-time tsunami prediction when just a truncated signal of the tsunami is known at specific points. Furthermore a new approach for improving the reliability of TEWS is presented, based on the measurements of hydro-acoustic waves, which could, together with the seismic information, improve the knowledge of the tsunami source.

It has been proved that sudden displacements of the sea bottom, as those associated with submerged earthquakes, generate hydro-acoustic (pressure) waves, propagating at the celerity of the sound in water (1500 m/s). These waves are precursors of tsunamis, since their propagation speed is much faster than that of the free surface waves. The idea of using measurements of hydro-acoustic waves in order to anticipate the warning of tsunami arrival, dates back to the work of Ewing et al. (1950). The modeling of tsunami in a weakly compressible fluid, has been investigated in the past by several researchers, as Miyoshi (1954), Kajiura (1970), Yamamoto (1982). More recent studies (Nosov and Kolesov, 2007; Chierici et al., 2010 and Bolshakova et al., 2011) have been carried out, especially after the experimental evidence of the existence of hydro-acoustic waves measured during the Tokachi-Oki 2003 tsunami event.

The paper is structured as follows: the next section describes the numerical model which reproduces the generation and propagation of tsunami; the model is that proposed by Bellotti et al. (2008) and hereinafter is only given a brief outline of it, especially referring to the inverse technique which allows its real-time application for tsunami forecasting. Section 3 presents an example of large scale application of the forecasting proposed method, based on a probable hypothesis of tsunami recording in front of Stromboli island (South Tyrrhenian sea, Italy). Section 4 refers in details the mathematical problem of wave generation and propagation in a weakly compressible fluid. The analysis of different tsunami scenarios is reported, showing the correlation between the generation features (i.e. earthquake parameters) and the produced hydro-acoustic waves. Moreover the application of a depth-integrated equation which considers the weakly compressibility of the water is presented. In section 5 conclusions of the present work and future research development are reported.

2. Description of the numerical model

The numerical model (Bellotti et al., 2008) solves the linearized depth-integrated mild-slope equation, MSE (Berkhoff, 1972); it describes the small amplitude transient wave propagation in mildly sloped sea bed. In the frequency domain the MSE has the following elliptic form:

$$\nabla \cdot \left(cc_g \nabla N \right) + \omega^2 \frac{c_g}{c} N = -\frac{1}{cosh\,(kh_b)} \tilde{h_{tt}}, \tag{1}$$

where ∇ is the gradient in the horizontal plane (x, y), $N(x, y, \omega)$ is the Fourier transform of the free surface elevation, c and c_g are respectively the phase and group celerity, k is the wave number and ω is the angular frequency. The right hand side of equation (1) represents the source term, which allows the incorporation of wave generation due to the sea floor movements. Named $h\,(x, y, t)$ the water depth, which varies in time reproducing the occurrence of underwater landslide or seismic sea floor movement, the term $\tilde{h_{tt}}$ in the equation is the Fourier transform of its second time derivative. The term $1/cosh(kh_b)$ represents a filter function, which takes into account the bottom movement effects on the free surface, and $h_b(x, y)$ is the undisturbed water depth. In order to reproduce the frequency dispersion of broad banded spectra, as those of tsunamis, the model solves a set of equations as (1), one for each frequency ω, with the appropriate boundary conditions. The free surface elevation in the time domain, $\eta\,(x, y, t)$, can be then

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