Coastal Engineering 127 (2017) 145–169

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Tsunami taxonomy and detection from recent Mediterranean tide gauge data

M. Masina [a], R. Archetti [a], G. Besio [b], A. Lamberti [a,*]

[a] Department of Civil, Chemical, Environmental and Materials Engineering – DICAM, University of Bologna, Bologna, Italy
[b] Department of Civil, Chemical and Environmental Engineering – DICCA, University of Genoa, Genoa, Italy

ARTICLE INFO

Keywords:
Sea level oscillations
Tide gauge
Tsunami
Meteotsunami
Wavelet
Hilbert transform
Mediterranean

ABSTRACT

Sea level records, collected in digital form with high sampling rate by recently upgraded tide gauges located along the Mediterranean coasts, are subjected to a posteriori investigation to examine and characterize occurrence of sea level oscillations in the tsunami period range, induced by both underwater or coastal earthquakes and by meteorological events. After performing a rigorous quality control procedure on the raw sea level time series, a wavelet based analysis is applied to 2 h high-pass filtered data to identify oscillations generated by earthquakes, and a few events are modeled aiming to verify travel time and expected spectral shape. Seismic tsunami oscillations that are not reported in published catalogues are identified in the sea level records of the period 2010–2014 just after three different earthquake events. A method is proposed to detect occurrence of tsunami-like oscillations of meteorological origin from the available tidal records based on the distribution of the detided level process over spectral bandwidth parameter and mean period. The developed methodology is also the first presented which allows to distinguish sea wave induced harbor seiches from fluctuations of meteorological origin associated with passage of atmospheric disturbances (meteotsunamis) in sea level time series. The results of the analyses show that, during the considered period, in the Mediterranean Sea tsunamis of seismic origin are rare and weak; meteotsunamis on the contrary are relatively frequent and in critical areas may reach intensities exceeding astronomical tide. The availability of the recently acquired high frequency records and the presented approach allow to extend the list of recorded tsunami events of both seismic and meteorological origin. The identified event sets may be used for improved hazard analyses and risk assessments along the Mediterranean coasts.

1. Introduction

Following the devastating Sumatra tsunami of 26 December 2004, an upgrade of the sea level monitoring networks was required in every area at risk. Due to the recommendations of the NEAMTWS Working Group 3 on the upgrade of the tide gauges in the Mediterranean region to high frequency data sampling and real-time transmission for operational tsunami monitoring and early warning (IOC UNESCO, 2007), the monitoring system in the Mediterranean Sea was updated mostly to 1 min acquisition rate, and the ability to describe short period sea level oscillations was dramatically improved in recent years. By the invitation sent from the NEAMTWS WG3 to all the member states to share their data through the Intergovernmental Oceanographic Commission (IOC) Sea Level Station Monitoring Facility for best monitoring the operational status of the network, these high frequency tidal records are currently publicly accessible through the IOC portal http://www.ioc-sealevelmonitoring.org/ and available for a wide range of scientific investigations.

The newly upgraded tide gauge networks with improved sampling resolution are accurate enough to record also tsunami-like sea level oscillation events of non-seismic origin, generated from propagating atmospheric perturbations related to dynamic instability, trains of internal gravity waves, pressure jumps, active frontal passages, convective systems and associated squall lines.

Sea level oscillations caused by high frequency atmospheric pressure disturbances can result in significant coastal flooding and damaging events due to the combination of different resonance mechanisms: an external resonance between the moving atmospheric perturbation and the open sea waves (Proudman, Greenspan and shelf resonances) and an internal resonance between the arriving waves and the fundamental Helmholtz mode of a harbor or an embayment (Rabinovich, 2009).

Occurrence of tsunamis of meteorological origin (also referred to as

* Corresponding author.
E-mail address: alberto.lamberti@unibo.it (A. Lamberti).

http://dx.doi.org/10.1016/j.coastaleng.2017.06.007
Received 13 October 2016; Received in revised form 16 April 2017; Accepted 6 June 2017

meteotsunamis) is quite frequent in the Mediterranean region, as a number of studies have pointed out (e.g. Monserrat et al., 2006; Vilibić and Šepić, 2009; Šepić et al., 2015b; Orlić, 2015). The Balearic Islands, the Eastern Adriatic Sea, the Sicily Channel and the Malta region are hotspot areas within the Mediterranean basin for large amplitude meteotsunami events, due to the presence of an extensive shallow shelf and elongated bays, predisposing conditions for resonant excitation. Exceptionally large wave heights reaching 4–5 m were observed at Ciutadella inlet on the Menorca island (Spain) during the meteotsunami event of 15 June 2006, and 6 m were recorded in Vela Luka bay on the island of Korčula (Croatia) during the most severe documented episode occurred on 21 June 1978 (Monserrat et al., 2006). Less pronounced high frequency sea level oscillation events causing little or no damage but instrumentally recorded do occur, however, several times a year throughout the Mediterranean (see e.g. Šepić et al., 2015a).

On the other hand, the Mediterranean region is characterized by a complex geodynamic regime mainly related to the tectonically active convergence between the Eurasian and Nubian plates at a present-day rate of ~4–6 mm/yr in NW-SE direction (Serpelloni et al., 2007; DeMets et al., 2010) and to the differential subduction rates of ~5–10 mm/yr across the Northern Hellenic subduction boundary and ~35 mm/yr along the southern one (Royden and Papanikolaou, 2011).

This region results consequently affected by a significant seismic activity, both in frequency and intensity, which exhibits a moderate continuity in time (e.g. Ambraseys, 2009; Papazachos and Papazachou, 1997; Grünthal and Wahlström, 2012; the SHARE European Earthquake Catalogue, http://www.emidius.eu/SHEEC/) and exposes the densely populated Mediterranean coasts to a relevant hazard from tsunamis of seismic origin, as it is extensively documented by various original historical earthquake descriptions, chronicles, memories, reports and modern event catalogues (e.g. Soloviev et al., 2000; Tinti et al., 2007; Papadopoulos et al., 2010; Salamon et al., 2011; Altinok et al., 2011; Pasarić et al., 2012; Maramai et al., 2014).

According to the Euro-Mediterranean Tsunami Catalogue recently published by Maramai et al. (2014), a total number of 221 tsunami events occurred between 6150 BCE and 2004 CE and originated in the Mediterranean and Marmara Seas, most of which (180) directly generated by undersea or coastal earthquakes, 16 attributed to landslides or submarine slides triggered by earthquakes, 13 directly or indirectly related to volcanic activity, 7 due to gravitational instability not ascribable to the causes indicated above and 5 classified as tsunamis of unknown origin.

An improved map of 22 main tsunamigenic zones and their relative potential for tsunami generation has been inferred by Papadopoulos et al. (2014) through a careful analysis of the tsunami intensity and occurrence frequency characteristics derived from the examination of geological, geomorphological, archeological, historical and instrumental tsunami records in the Mediterranean region and its connected seas, including the Marmara Sea, the Black Sea and the southwestern Iberian margin in the northeastern Atlantic Ocean. Papadopoulos and Papageorgiou (2014) indicate that the estimated magnitudes of the tsunamigenic earthquakes documented historically and/or geologically in the Mediterranean region and its adjacent seas in the last 2.5 millennia range from M_w 6.5 to about 8.5 and that no tsunami event generated by earthquakes with a focal depth greater than ~70 km was reported.

Most of the research works on seismic tsunamis in the Mediterranean region focuses on numerical modeling of hypothetical events caused by extreme earthquakes associated with known seismotectonic structures, within hazard assessment procedures or even for creation of a database of precomputed tsunami scenarios in support to operational applications (e.g. Pelinovsky et al., 2002; Tinti et al., 2005; Paulatto et al., 2007; Lorito et al., 2008; Tiberti et al., 2008; Basili et al., 2013; Necmioglu and Özel, 2015). Less numerous are the studies which simulate real seismic tsunami events and confront computed values of run-up elevation and arrival time with field surveyed data (e.g. Piatanesi et al., 1999; Piatanesi and Tinti, 2002; Favalli et al., 2009; Okal et al., 2009) or compare predicted water levels, travel times and spectral characteristics of the oscillations against information contained in actual tide gauge measurements (e.g. Eva and Rabinovich, 1997; Alasset et al., 2006; Larroque et al., 2012; Vela et al., 2014).

A reliable numerical simulation of real seismic tsunamis requires:

- modeling of earthquake induced seafloor displacement,
- hydrodynamic modeling of wave propagation and interaction with the littoral,
- validation and calibration of previous models based on an adequate database of identified events being certainly of seismic origin.

In the authors opinion only hydrodynamic modeling is presently reliable, requiring however a detailed bathymetric description in particular of the area where tsunami effects evaluation is requested.

For determining the seafloor displacement pattern induced by an earthquake, the closed analytical expressions proposed by Okada (1985) for surface displacement due to an inclined rectangular fault in a homogeneous elastic half-space have been widely used also for their relatively simple formulation. Recently, to take into consideration a more realistic non-uniform distribution of slip along the fault surface, the fault plane is subdivided in a finite number of elementary rectangular subdomains and the bottom deformation is evaluated by superposition of each patch contribution using Okada formulas. Available co-seismic geodetic observations, such as GPS and InSAR data, are employed together with seismological information to provide a further constraint to the fault geometry and slip distribution (e.g. Briole et al., 2015; Saltogianni et al., 2015).

A horizontally layered model like that suggested by Wang et al. (2003) may be adopted to compute the displacement components when the earthquake source is located in a stratified elastic medium. Seismic studies have highlighted how three-dimensional variations in elastic properties of the medium and in surface topography have significant effects on surface displacements when the fault slip occurs close to gradients in rigidity or topography (Hsu et al., 2011; Pulvirenti et al., 2014). Models that incorporate realistic rheology, geological structure and three-dimensional topographic relief of the seismic source zone still remain poorly applied in estimating the co-seismic displacement distribution and therefore also their effects on tsunami wave generation process are scarcely investigated.

Mareographic records of tsunami waves are very useful to validate and calibrate the co-seismic displacement estimates and tsunami propagation models. Availability of sea level disturbances instrumentally recorded by tide gauges following seismic events is generally documented in tsunami catalogues. From the Euro-Mediterranean Tsunami Catalogue (2014) it emerges that tsunami waveforms induced by earthquake were recorded by tide gauges within the Mediterranean Sea only for 12 events, the first of which occurred on 23 February 1887 and the last on 21 May 2003. The list of seismic tsunami events recorded at tide gauges extends to a total of 22 considering also the Atlantic northeastern coast, ranging from Canary to Azores islands included, and the Black Sea. Recorded tsunami oscillations exist, therefore, only in a limited number and cover a backward confined time horizon, the beginning of which roughly corresponds to starting of the systematic recording of tidal data in the Mediterranean region. According with the six-degree Sieberg-Ambraseys scale (Ambraseys, 1962) adopted by Maramai et al. (2014) for the catalogue compilation, a very light tsunami intensity, namely tsunami wave so weak as to be perceptible only on tide gauge records, is attributed to 9 events out of the 22 identified. Among the tsunamis recorded at tide gauges, the maximum intensity degree, “disastrous”, was reached by the Messina 1908 and Amorgos 1956 events.

Detection and extraction of long waves from coastal tide gauge records for accurate a posteriori assessments of their principal features involve several steps. Sea level data processing and analysis techniques have been described and successfully applied by Rabinovich and Thomson (2007), Goring (2008), Thomson et al. (2009), Rabinovich et al. (2011), Mungov et al. (2013) and Rabinovich and Eblé (2015).