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Effects of different boundary conditions and palaeotopographies on the onshore response of tsunamis in a numerical model – A case study from western Greece

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ABSTRACT

Hydrodynamic numerical models are essential in modern tsunami hazard assessment. They allow the economical simulation of possible tsunami scenarios for areas at risk and provide reliable and detailed insights into local onshore dynamics. This is especially true when simulations are calibrated with field traces of past tsunami inundation events. Following this approach, the current study focuses on palaeotsunami events indicated by sedimentary and geomorphological field traces in the northern Gulf of Kyparissia (NW Greece). Based on three different digital elevation models (DEM) – reflecting the recent and two palaeotopographies – various tsunami wave constellations according to the solitary and *N*-wave theory are numerically simulated. The main objective is to investigate the effects of both, different palaeotopographies and boundary conditions on the tsunami onshore response in the numerical model.

Tsunami landfall related to *N*-waves is found to be considerably stronger compared to solitary waves. This phenomenon, known as the *N*-wave effect, is demonstrated for the first time in a specific study area. Inundation dynamics are even stronger affected by the different palaeotopographies, which is due to substantial vertical crust movements in the northern Gulf of Kyparissia considered in the palaeo-DEMs. By applying different waveforms and palaeotopographies, the model achieves close agreement with field observations, altogether revealing a significant tsunami hazard for the Gulf of Kyparissia, which is in contrast to conventional numerical studies of the area. The marked differences between the presented scenarios emphasise the need to consider a wide variety of possible hydrodynamic boundary conditions and probable topographical conditions in order to find scenarios in plausible accordance with palaeotsunami field traces. Once a plausible scenario is found it can be applied to the recent topography in view of a reliable modern hazard assessment.

1. Introduction

Coasts have become increasingly popular, both as places of residence and centres of tourism. Accordingly, coastal hazard assessment serves a key role in today's society. Besides storm surges, tsunamis are the greatest threat to those living by the coast, having resulted in huge human and economical losses worldwide, recently in Papua New Guinea (1998), south-east Asia (2004) and Japan (2011). In terms of hazard assessment and mitigation plans, hydrodynamic numerical models play an important part. They are a powerful tool to economically simulate possible inundation scenarios for coasts known to be historically vulnerable to tsunamis. Particularly, the synthesis of numerical simulations and tsunami field traces has proven fruitful as it supports a detailed reconstruction of past tsunami events – vital for reliable future hazard assessment (Röbke et al., 2012, 2013). Field observations allow numerical models to be calibrated and verified, so that calculation results are improved. Furthermore, valuable information about the trigger mechanism of tsunamis can be derived from numerical models when calibrated with field data.

Several studies exist pursuing this promising approach in view of recent tsunami events. A common strategy is to work out the best fit between simulations and field traces by adjusting appropriate parameters in the numerical model. Frequently, different fault-plane solutions of tsunamigenic earthquakes are considered in order to determine the focal mechanism and tsunami which compare favourably with field observations. For example, Borrero et al. (2009) computed four different slip distributions and associated tsunami waves of the 12 September 2000 Bengkulu

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earthquake (Sumatra, Indonesia) to reproduce observations from DART-buoys, eyewitnesses and the field. Also Bourgeois et al. (1999) and Le Friant et al. (2008) made use of different fault-plane solutions to adjust their numerical model to field data they obtained from the 21 February 1996 Chimbote tsunami in northern Peru and the 21 November 2004 Les Saintes tsunami (Lesser Antilles) respectively. Satake et al. (2013) took this approach one step further by considering detailed tsunami tide gauge, GPS- and DART-buoy data as well as field traces in order to accurately estimate the slip distribution of the associated 25 October 2010 Mentawai earthquake (Indonesia) using a numerical model. In the case of tsunamis generated by submarine landslides, varying essential slide properties or the initial free water surface conditions characteristic of different slide scenarios allow numerical models to be adjusted with regard to survey data. This approach was taken by Lynett et al. (2003) who compared field traces of the 17 July 1998 Papua New Guinea tsunami with simulations that considered three realistic initial water surface disturbances. Finally, independent from the trigger mechanism, numerical tsunami models are calibrated with field observations by using different friction maps, as performed, e.g., by Gopinath et al. (2014) who focused on the 2004 Indian Ocean tsunami along the Tamil Nadu coastline.

The calibration of numerical models by means of field data is a particularly demanding task with regard to historical and prehistorical tsunami events. This is mainly due to (i) less accurate or even missing data of the tsunami waves and trigger mechanisms, as, for instance, seismological and gauge/buoy data or historical accounts, (ii) lower spatial resolution and accuracy of field data owing to a general low preservation level of sedimentary tsunami traces (e.g. Wheatcroft, 1990; Wheatcroft and Drake, 2003; Szczuciński, 2012; Spiske et al., 2013), (iii) the fact that tsunami deposits do not allow a precise deduction of the maximum inland penetration of tsunami waters but only of the maximum sediment transport and (iv) uncertainties about the contemporary landscape conditions concerning coastline configuration (highly variable, even in short timescales), topography or sea level. Consequently, there are only a few studies dealing with this issue, and often a simplistic approach is used.

For example, Martin et al. (2008) compared numerical simulation results of the 1969 Ozernoi and 1971 Kamchatskii tsunamis with sedimentary deposits found along the Pacific coast of Kamchatka. Despite using the recent coastline configuration and coastal topography, Martin et al. (2008) were able to untangle the identified deposits in relation to both tsunamis by investigating five different focal mechanisms and associated tsunamis for each event. Following a similar approach, MacInnes et al. (2010) simulated and compared 21 variations of the great 1952 Kamchatka earthquake and tsunami with eyewitness accounts and the alongshore distribution of tsunami deposits. Regarding the 1957 Aleutian tsunami in the Unalaska region, Witter et al. (2016) questioned the previously assumed tsunami source based on the comparison of local tsunami field traces and tsunami simulations considering different earthquake focal mechanisms.

Bondevik et al. (2005) focused on the Storegga Slide tsunami in the Norwegian Sea (almost 8,000 years ago) and associated deposits along adjacent coasts. The authors numerically simulated different slide velocities and geometries to determine a slide mechanism and tsunami which can explain the detected deposits. However, hydrodynamic calculations were based on the present sea level and coastline configuration, hindering an accurate comparison and calibration with event deposits. Furthermore, their numerical model did not include the onshore topography, which need the run-up heights to be estimated for comparison with tsunami sediments. Hill et al. (2014) expanded the simulations of the Storegga Slide tsunami by considering the regional palaeobathymetry but also refrained from calculating onshore hydrodynamics.

Synthesising field data and numerical simulations, Shishikura et al. (2011), Sawai et al. (2012), Sugawara et al. (2013) and Namegaya and Satake (2014) investigated the impact of the seismogenic 869 AD Jōgan tsunami on the Sendai Bay in north-east Japan. The authors derived the contemporary coastline from an ash layer and reconstructed the local palaeotopography by subtracting tsunami deposits and overlying sediments from the present ground surface in their DEM. Based on this and on numerous possible focal mechanisms, the authors achieved close agreement between tsunami computations and field traces, which showed that the 869 Jōgan tsunami was an unambiguous forewarning of the 2011 Tōhoku tsunami killing an estimated 17,000 people.

As demonstrated by these studies, the calibration of numerical models by means of palaeotsunami field traces requires the simulation of a variety of possible tsunami waves, based on one or even several DEMs reproducing the probable former landscape conditions. This is confirmed by the fact that each tsunami shows an individual initial waveform, amplitude, wavelength, period and spatial extent and thus can mathematically be described by several wave theories (e.g. Tadepalli and Synolakis, 1994, 1996; Carrier et al., 2003; Synolakis et al., 2008; Madsen and Schäffer, 2010; Madsen et al., 2008; Constantin, 2009; Voronina, 2011). Furthermore, coasts are one of the most dynamic landscapes on earth, frequently changing their shape over short periods of time (e.g. Bird, 2005; Scott, 2005; Thom and Cowell, 2005). This together with high tectonic activity, often observed in tsunami prone areas (cf. NOAA, 2015), emphasises the need to reconstruct and consider possible palaeolandscape conditions.

Based on sedimentary field traces and numerical simulations, this study investigates palaeotsunami events in the northern Gulf of Kyparissia (western Peloponnese, Greece; Fig. 1(a)). Due to its immediate vicinity to the seismogenic subduction zone of the Hellenic Trench (see overview map in Fig. 1(a)), the Gulf of Kyparissia is located within the most tsunamigenic region in the whole Mediterranean (Soloviev et al., 2000; Schielein et al., 2007; Röbke et al., 2013). Accordingly, sedimentary and geomorphological traces of multiple tsunami impacts were detected within fieldwork along the northern Gulf of Kyparissia during recent years. This study takes account of tsunami field findings published for three key locations in the northern gulf coast: the Katakolo Pass (Fig. 2(a) and Fig. 4; Vött et al., 2010, 2011), the Epitalio Pass (Fig. 2(b) and Fig. 4; Vött et al., 2015) and the small valley of Kato Samiko (Fig. 2(c) and Fig. 4; Willershäuser et al., 2012, 2015). All three sites repeatedly fell victim to severe tsunami inundation during the last 8,000 years, as is implied by vibracore data, geoelectrical measurements and geomorphological observations obtained in each key location (Section 3).

Taking account of the recent topography and two different palaeotopographies derived from neotectonic field data and literature and by applying the solitary and the *N*-wave theory, different tsunami scenarios are numerically simulated that reflect inundation as indicated by sedimentary and geomorphological tsunami field traces for the three key locations in the study area. In a further step, the appropriate scenarios are simulated with regard to the present topography and coastline configuration in view of a modern hazard assessment. In this process, the current study methodologically analyses the implications of (i) different hydrodynamic boundary conditions and tsunami wave theories (*N*-wave effect) and (ii) different palaeotopographies for numerical simulation results and discusses the possibility and difficulty of numerical models to be calibrated and compared with palaeotsunami field traces.