Marine Geology 350 (2014) 39–51

Contents lists available at ScienceDirect

Marine Geology

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

Effects of coastal submarine canyons on tsunami propagation and impact

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ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form 22 January 2014
Accepted 29 January 2014
Available online 14 February 2014

Communicated by D.J.W. Piper

Keywords:
tsunami
multi-scenario
numerical simulation
submarine canyon

ABSTRACT

We analyse the variations produced on tsunami propagation and impact over a straight coastline because of the presence of a submarine canyon incised in the continental margin. For ease of calculation we assume that the shoreline and the shelf edge are parallel and that the incident wave approaches them normally. A total of 512 synthetic scenarios have been computed by combining the bathymetry of a continental margin incised by a parameterised single canyon and the incident tsunami waves. The margin bathymetry, the canyon and the tsunami waves have been generated using mathematical functions (e.g. Gaussian). Canyon parameters analysed are: (i) incision length into the continental shelf, which for a constant shelf width relates directly to the distance from the canyon head to the coast, (ii) canyon width, and (iii) canyon orientation with respect to the shoreline. Tsunami wave parameters considered are period and sign. The COMCOT tsunami model from Cornell University was applied to propagate the waves across the synthetic bathymetric surfaces. Five simulations of tsunami propagation over a non-canyoned margin were also performed for reference.

The analysis of the results reveals a strong variation of tsunami arrival times and amplitudes reaching the coastline when a tsunami wave travels over a submarine canyon, with changing maximum height location and alongshore extension. In general, the presence of a submarine canyon lowers the arrival time to the shoreline but prevents wave build-up just over the canyon axis. This leads to a decrease in tsunami amplitude at the coastal stretch located just shoreward of the canyon head, which results in a lower run-up in comparison with a non-canyoned margin. Contrarily, an increased wave build-up occurs on both sides of the canyon head, generating two coastal stretches with an enhanced run-up. These aggravated or reduced tsunami effects are modified with (i) proximity of the canyon tip to the coast, amplifying the wave height, (ii) canyon width, enlarging the areas with lower and higher maximum height wave along the coastline, and (iii) canyon obliquity with respect to the shoreline and shelf edge, increasing wave height shoreward of the leeward flank of the canyon. Moreover, the presence of a submarine canyon near the coast produces a variation of wave energy along the shore, eventually resulting in edge waves shoreward of the canyon head. Edge waves subsequently spread out alongshore reaching significant amplitudes especially when coupling with tsunami secondary waves occurs. Model results have been groundtruthed using the actual bathymetry of Blanes Canyon area in the North Catalan margin. This paper underlines the effects of the presence, morphology and orientation of submarine canyons as a determining factor on tsunami propagation and impact, which could prevail over other effects deriving from coastal configuration.

1. Introduction

Tsunamis are ocean waves produced by vertical seafloor shifts generated as a result of earthquakes, underwater mass failures or volcanic activity, or by the displacement of the water surface due to a significant impact such as a subaerial landslide or a meteorite entering the water body. Their large wavelength in the open ocean and the height they can attain at the coast confer to tsunami waves a known destructive effect. Several strategies have been developed to understand tsunami generation, propagation and impact, so that at the end casualties and infrastructural damage could be minimised. The use of numerical models has emerged as one of the most useful tools for tsunami risk assessment. This approach is particularly valuable given the inability of directly observing the triggering of tsunamis in most cases and their relatively long recurrence periods involving significant gaps in datasets on past tsunamis. Mitigation efforts recently focus on improving forecasting systems for distant tsunamis, based on their detection by specially designed buoys and sets of pre-computed numerical models (Tang et al., 2009), such as the *Short-term Inundation Forecasting for Tsunamis* (SIFT) tool developed by NOAA (Gica et al., 2008).

The gradual shoreward shallowing of a typical continental margin from the base of slope up to the continental shelf and coastline produces the decrease of the tsunami wavelength and velocity, and the increase

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http://dx.doi.org/10.1016/j.margeo.2014.01.013
0025-3227/

of height wave, which is known as shoaling effect (Ward, 2011). The significance of this effect changes according to the particular shape and depth of every slope and shelf. In terms of tsunami hazard, a wide continental shelf induces a strong shoaling effect that can translate into a late arrival time to the coastline but also into a larger run-up, that is, the onshore maximum height above sea level reached by a tsunami.

Continental slopes and shelves around the world are often incised by submarine canyons i.e. deep and relatively steep seafloor valleys (see definitions in Daly, 1936; Shepard and Dill, 1966; Normark and Piper, 1969; Bates and Jackson, 1980). Submarine canyons are a very common feature in continental margins of the world ocean, with a global average spacing of an isolated canyon every 21.5 km (Harris and Whiteway, 2011). Recent multibeam bathymetry data have shown the noticeable morphological variability of submarine canyons (Jobe et al., 2011). The ability of submarine canyons to modify, enhance and funnel oceanographic processes and flows such as geostrophic currents, upwelling and downwelling currents, and density flows has been described in numerous locations and settings (Klinck, 1989; Allen, 2000; Wåhlin, 2002; Canals et al., 2006; Allen and Hickey, 2010).

In this paper, we address the role of submarine canyons and their diverse morphology on tsunami propagation and subsequent coastal impact, a topic that has been addressed a few times with contradictory results. For instance, Matsuyama et al. (1999) and Tappin et al. (2001) have considered that the canyon located on the Sissano Shelf was mostly responsible of high tsunami run-outs on Sissano Lagoon on 1998. Likewise, Ioualalen et al. (2007) suggested that the submarine canyon off the Bangladesh shelf produced wave amplification on the Barisal coast of the 2004 Indian Ocean tsunami. Contrarily, Divyalakshmi et al. (2011) suggested that the presence of Palar canyon produced a local wave height reduction in the southeast India coast during the same event. Therefore, in order to shed light on this issue, we evaluate how submarine canyons modify wave arrival times and maximum tsunami wave heights over the adjacent coastline considering a synthetic multi-scenario approach to overcome the difficulty of distinguishing the influence of a submarine canyon from other effects also deriving from shoreline, shelf and slope configuration and related resonance phenomena. This approach also allows isolating and evaluating the effects of each of the parameters under study for each tsunami simulation. As a groundtruthing exercise, we also present the analysis of a hypothetical tsunami impact in an actual bathymetric configuration, the Blanes Canyon area in the North Catalan margin. This allows us assessing the effects due to the canyon against other local effects as mentioned above. The aim of this work is to provide general clues for tsunami hazard and associated risk analysis in canyoned margins.

2. Methodology

2.1. Synthetic bathymetries

To understand the effect of single canyon geometries on tsunami propagation, synthetic bathymetries of canyons with different shapes and orientations were generated jointly with a non-canyoned continental margin segment. An inclined arctangent was used to simulate the non-canyoned margin including continental rise, slope and shelf, defined by the characteristic slope height (i.e. the vertical distance between the shelf edge and the base of slope, *Sh*), slope width (i.e. the horizontal distance from the shelf edge to the base of the slope, *Sw*), and shelf gradient after a reference modern continental margin (*Ss*). The spatial domain (i.e. regional scale) of this study allows discarding the Coriolis effect and using a right handed Cartesian coordinate system with the *y*-axis parallel to the coast assumed to be running south to north (Fig. 1). To avoid grid boundary effects, we have extended the *y* axis range by running the simulations over additional areas northward and southward of the primary target region, which is the only region we will consider from here onwards (Fig. 1).

A balance was pursued between complexity, so that morphology is as realistic as possible, and simplicity, so that isolating the consequences of parameter variation is straightforward, when defining the canyon geometry. The typical concave-shaped longitudinal profile of most canyons (Covault et al., 2011; Amblas et al., 2012) was obtained with the negative part of an arctangent placed in the centre of the grid. A Gaussian function was used to generate the profile across the canyon, with variable width along the canyon following a cosine function. The orientation of the canyon axis was defined by multiplying the Gaussian function by a rotation matrix.

The resulting equation allows parameterising a number of variables and subsequently generating a huge amount of bathymetric surfaces according to the number of discrete values chosen for each parameter. An example of synthetic surface is shown in Fig. 1. In this study we analyse the effect of three essential canyon parameters: (i) canyon incision into the continental shelf (*Ci*), measured from the nearest shelf edge to the canyon tip; (ii) canyon width (*Cw*), measured over the continental slope; and (iii) orientation of the canyon axis (α), measured with respect to the shelf edge strike (i.e. the canyon azimuth) (Fig. 2). Canyon incision is measured perpendicularly to the shelf edge and not necessarily along the canyon axis, so that for a constant incision, canyon length increases with decreasing intersection angles. Other geomorphic characteristics typical of submarine canyons, such as sinuosity and dendricity (Clark and Pickering, 1966; Pirmez et al., 2000; Harris and Whiteway, 2011; Lastras et al., 2011a), have been discarded according to the above-mentioned constraints.

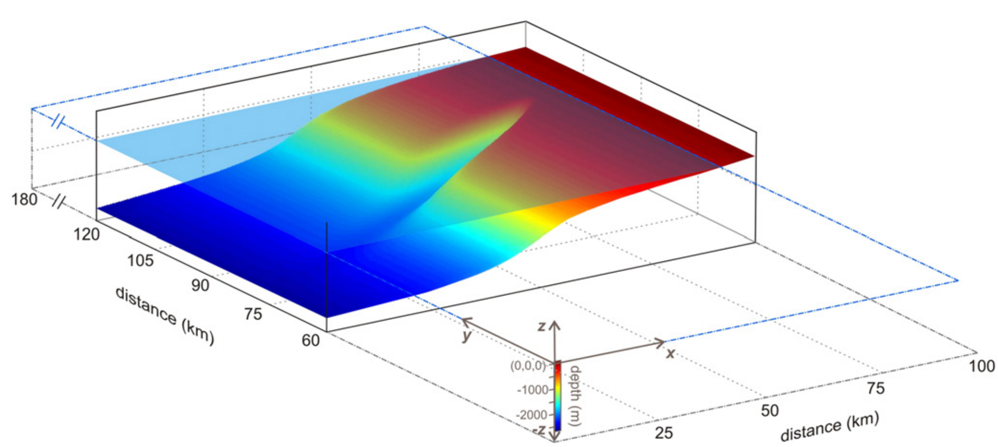

Fig. 1. Example of one of the synthetic surfaces used in this study, corresponding to a submarine canyon with an incision length of 14 km, a width of 20 km and orientation of 70° with respect to the surrounding depth contours and margin orientation. The location of the origin of coordinates and the extension of the study area are depicted. Additional areal extension sideward of the central study area in the *y* direction has been used in the simulations to prevent edge effects but is not displayed in the following figures.