Ocean Engineering 134 (2017) 1–12

Contents lists available at ScienceDirect

Ocean Engineering

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

A modelling study on tsunami propagation in the Red Sea: Historical events, potential hazards and spectral analysis

J.M. Abril, R. Periáñez*

Dpto. Física Aplicada I, ETSIA, Universidad de Sevilla, Ctra. Utrera km 1, 41013-Sevilla, Spain

ARTICLE INFO

Keywords:
Red Sea
Tsunami
Numerical simulation
Fluid dynamics
Spectral analysis

ABSTRACT

This work reports results from numerical simulations of the tsunami triggered by 1995 Nuweiba earthquake, in the Gulf of Aqaba, which are consistent with the available observations. A series of 12 potential tsunamigenic sources are then considered in the Red Sea: related to major submarine earthquakes; volcanism (entry of pyroclastic flows and caldera collapse) and submarine landslides. Numerical simulations have been carried out to solve the spatial distribution of maximum amplitudes of water elevations and currents, and the flooded coastal areas. The peak energy in the simulated events range from 1 kt (1 kt=4.18×10^{12} J) up to 1.5 Mt, and global flood volumes range from 0.005 km3 up to 4.4 km3. A linear correlation can be established between both magnitudes for the set of tsunamis triggered by earthquakes up to 300 kt. Tsunamis triggered by submarine landslides show high directionality, but they occur in deep waters and showed lower impacts on the shoreline, as those triggered by volcanism. A FFT analysis shows that in this basin, tsunamis excite low frequency constituents which can be interpreted as eigenmodes. High frequencies are excited only in the proximity of the source, and the Gulf of Suez excites only those eigenmodes close to the ones of the main basin.

1. Introduction

The geodynamics of the Red Sea area is governed by the interactions between the African, Arabian and Levantine-Sinai plates, being the most relevant geophysical features the Rift of Suez, the Dead Sea shear zone, the Red Sea Rift and the Afar triple junction (Mascle et al., 2000; Bosworth et al., 2005; d'Almeida, 2010). This complex tectonic is responsible for intense earthquake and volcanism activity. Seismicity in the area has been studied, among others, by Foster and Jackson (1998), Bosworth et al. (2005) and Mohamed et al. (2012). Large earthquakes are possible particularly along the Gulf of Aqaba-Dead Sea transform and the Northern Red Sea triple junction point (Mohamed et al., 2012). The major recent events were the 1995 Nuweiba earthquake in the Gulf of Aqaba, with magnitude M_w=7.3 (on June 2015 another event in the same area reached magnitude 5.5); and the 1977 Massawa earthquake in southern Red Sea, with M_w=6.6. The Abu Dabbab seismogenic zone extends offshore in the Red Sea and it is characterized by "cannon" earthquakes, long continued seismic activity, and frequent earthquake swarms. An unique property is that earthquake signals can be heard by humans due to the location of an active fault below a large, rigid, non-deformed block of Precambrian igneous rock, which reaches a depth of ~10 km (El Khrepy et al., 2015).

The Zubair archipelago, along with the Jebel at Tair and the Hanish-Zukur islands are the main exponents of volcanism in the southern Red Sea. From September 2007 to January 2008 the Jebel at Tair eruption event took place, which expelled a bulk volume of 2.2×10^7 m^3 of lava (Xu and Jónsson, 2014). In 2011–2013 submarine eruptions lead to the formation of two new volcanic islands in the Zubair archipelago (Xu et al., 2014).

At the central Red Sea, Miocene evaporites, kilometers in thickness, were deposited during its continental rifting phase, later being covered with hemipelagic sediments of up to some hundred meters thick. Mitchell et al. (2010) identified a remarkable series of structures resembling viscous gravity flows around Thetis Deep, and interpreted as flowage of the evaporites. They found flow-parallel lineaments and extensional faults lying, respectively, parallel and orthogonal to the direction of maximum seabed gradient. Feldens and Mitchell (2015) have identified six salt flows with heights of several hundred meters and widths between 3 and 10 km around Thetis Deep and Atlantis II Deep, and between Atlantis II Deep and Port Sudan Deep. They found flow speeds of several mm/year for the offshore salt flows in certain locations. Mass wasting events have not been identified, although in other scenarios salt tectonics have triggered some giant gravity-driven landslides (Loncke et al., 2009).

The intense earthquake and volcanism activity may have triggered large tsunamis in the past. Thus, Shaked et al. (2004) provided

---

* Corresponding author.
E-mail address: rperianez@us.es (R. Periáñez).

http://dx.doi.org/10.1016/j.oceaneng.2017.02.008
Received 19 July 2016; Received in revised form 16 November 2016; Accepted 12 February 2017

evidence of a catastrophic sedimentary event at the north-west margins of the Gulf of Aqaba, dated at 2.3 ka BP, that killed the Elat fringing coral reef. The event would have been likely triggered by a tsunami. Salem (2009) reported evidences of paleo-tsunami deposits on a coastal area of the Red Sea north of Marsa Alam city, Egypt.

The Red Sea coastline is mostly a desert and, historically, only very few permanent human settlements have been located there. For such desert regions it is difficult to establish an accurate catalogue of historical tsunamis. The NGDC/WDS Global Historical Tsunami Database (NGD, 2016) records 5 tsunamis in the last millennium. In 1068 a tsunami originated in the Gulf of Aqaba at 34.950°E, 29.500°N, with intensity 4.0 in the NEAMTIC scale. In 1879 a tsunami was triggered by a earthquake with epicenter in the Gulf of Suez (33.000°E, 29.000°N). At Tor, in Sinai, a sea-wave flooded the village. A landslide is a possible source for this tsunami, but there is not any documentation in the historical records (Jordan, 2008). A damaging earthquake occurred in Eritrea in July 1884, with epicenter offshore Massawa (39.600°E, 15.700°N). High sea waves built up in the harbor of this city and the sea flooded the land several times. On March 1969 an earthquake with epicenter in the Gulf of Suez (34.000°E, 27.700°N) affected the islands of Shadwan, Tawila and Gubal. Dead fish and some agitation of the sea were noticed after the main shock.

A strong earthquake, M_w=7.3, occurred in the Gulf of Aqaba on 22 November 1995, with epicenter at 34.75°E, 28.97°N (Baer et al., 2008). In the cities of Aqaba (Jordan) and Eilat (Israel), at the northern reaches of the gulf, a small wave swept the beach according to witnesses (Klinger et al., 1999). Major damage occurred at the city of Nuweiba, where five people died and 11 were injured. Many buildings and the harbor area suffered structural damage, and liquefaction phenomena were also reported (Al-Tarazi, 2000; Klinger et al., 1999). Basta et al. (1996) mentioned that a tsunami 3–4 m high hit Nuweiba harbor. The source parameters of the Nuweiba earthquake have been determined by several independent studies (Klinger et al., 1999; Baer et al., 2008 and references within), which allows numerical simulations of the tsunami propagation.

The numerical modelling of tsunami propagation is a relatively well established methodology which has been validated against recorded data from historical events over the world (Choi et al., 2008; Alasset et al., 2006; Ioualalen et al., 2010; Periáñez and Abril, 2013, 2014a). The main agents triggering tsunamis are earthquakes by geological faults, submarine and sub-aerial landslides, entry of pyroclastic flows and caldera collapse in volcanoes. Reliable modelling strategies have been developed for all of them (Iglesias et al., 2011; Novikova et al., 2011; Okal et al., 2011; Periáñez and Abril, 2014a).

As far as we know, tsunami modelling works have not been previously conducted in the Red Sea area. This paper is aimed at studying the tsunami propagation in these waters by adapting previously tested numerical tools. The characterization of the source parameters for the 1995 Nuweiba earthquake, along with the scarce description of the tsunami effects (as above commented) provide a minimum basis for supporting a modelling exercise. From the available studies on the seismicity in this area, it is possible to construct hypothetical tsunamigenic sources by handling the known focal parameters, namely the epicenter and fault angles. Similarly, from the known main features of the volcanism and salt flows, it is possible to built hypothetical scenarios for the entry of pyroclastic flows, for caldera collapse and submarine landslides. These numerical exercises are expected to provide some insight on the main features of the tsunami propagation in this marine system, which exhibits a quite singular geometry. Results can allow the assessment of regional exposure. Thus, the Red Sea and the gulfs of Aqada and Suez conform long and narrow open basins for which fundamental periods of several hours (within the range of those of the main tidal constituents) are expected (Rabinovich, 2009). Studying eventual wave amplification and resonance effects may be of particular interest for the main cities in the coastal area, and for assessing the potential risks for the Suez Canal, of great commercial and strategic value (Finkl et al., 2012).

The model is briefly described in Section 2.1 and the different tsunami sources are presented in Section 2.2. Results are described in Section 3. Initially, the simulation carried out for the 1995 Nuweiba Earthquake, for which some observational data exist, is presented (Section 3.1). Then, results on the potential tsunamis triggered by other earthquakes, landslides and volcanic activity are described (Section 3.2). The spectral analysis which has been carried out is described in Section 3.3. Some general discussion on tsunami hazard in the Red Sea closes the paper (Section 3.4).

2. Methods

2.1. Model description

The tsunami propagation model is based on the 2D depth-averaged barotropic shallow water equations, which describe the propagation of surface shallow water gravity waves. The numerical tool has been adapted from previous works, and it has proved to be a very robust computational tool (Periáñez and Abril, 2013, 2014a, 2014b).

The two components of the depth-averaged water current(u, v, in the east-west and south-north directions, respectively), along with the water surface elevation above the reference level, ζ, are given by the equations for conservation of mass and momentum:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Du) + \frac{\partial}{\partial y}(Dv) = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} - \Omega v + \frac{\tau_u}{\rho D} = A\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + \Omega u + \frac{\tau_v}{\rho D} = A\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \tag{3}$$

where h is the undisturbed water depth, ζ is the displacement of the water surface above the undisturbed sea level measured upwards, $D = h + \zeta$ is the total water depth, Ω is the Coriolis parameter ($\Omega = 2w\sin\lambda$, where w is the Earth rotational angular velocity and λ is latitude) and A is the horizontal eddy viscosity. τ_u and τ_v are friction stresses which have been written in terms of a quadratic law:

$$\tau_u = k_f \rho u \sqrt{u^2 + v^2}\,\tau_v = k_f \rho v \sqrt{u^2 + v^2} \tag{4}$$

where k_f is the bed friction coefficient. All the equations are numerically solved using explicit finite difference schemes (Kowalik and Murty, 1993) with second order accuracy. In particular, the MSOU (Monotonic Second Order Upstream) is used for the advective non-linear terms in the momentum equations.

Values of k_f=0.0025 and A=10 m^2/s have widely proved their use in models for tide and tsunami propagation (e.g., Periáñez and Abril, 2013, 2014a, 2014b).

The model domain (Fig. 1) extends from 32.0°E to 45.0°E, and from 10.0°N to 30.5°N, with a spatial resolution of 60 s of arc. A higher resolution sub-domain has been used for the northern Red Sea, which is 30 s of arc resolution, and extends from 32.0°E to 39.0°E and from 24.0°N to 30.0°N. The bathymetries have been obtained from the GEODAS and GEBCO08 (60 and 30 s of arc respectively) databases, available on-line. Due to the wide range in latitude, the Coriolis parameter and the spatial resolution in longitude are allowed to vary with λ. The continuity equation was appropriately written to account for such variation in Δx. Time steps of 1 s and 2 s were fixed for the 30″ and 60″ mesh resolutions, respectively.

A gravity wave radiation condition is used for sea surface elevation (Periáñez and Abril, 2014a) along the open boundary in the south-eastern side of the domain. A wetting/drying algorithm is implemented following the numerical scheme described in Kampf (2009). It allows the calculation of runup over land. Still waters (zero water elevations and velocities over all the domain) are used as initial conditions in all