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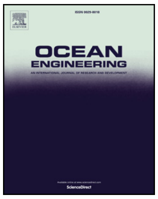

Evaluation of tsunami wave energy generated by earthquakes in the Makran subduction zone

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ABSTRACT

The Makran subduction zone, an approximate 1000 km section of the Eurasian–Arabian plate, is located offshore of southern Iran and Pakistan. In 1945, the Makran subduction zone (MSZ) generated a tsunamigenic earthquake with a magnitude of M_w 8.1. The region has also experienced large historical earthquakes but the data regarding these events are poorly documented. Therefore, the need to investigate tsunamis in Makran must be taken into serious consideration. Using hydrodynamic numerical simulation, we evaluate the tsunami wave energy generated by bottom motion for a tsunamigenic source model distributed along the full length of the Makran subduction zone. The whole rupture of the plate boundary is divided into 20 segments with width of the order of 200 km and a co-seismic slip of 10 m but with various lengths. Exchanges between kinetic and potential components of tsunami wave energy are shown. The total tsunami wave energy displays only 0.33 % of the seismic energy released from the earthquake source. As a result, for every increase in magnitude by one unit, the associated tsunami wave energy becomes about 10^3 times greater.

1. Introduction

The catastrophic effects of the 2004 Indonesia (moment magnitude of $M_w \sim 9.1$) and 2011 Japan ($M_w \sim 9.0$) tsunamis motivated researchers to study different characteristics of tsunami waves. One of those characteristics is the tsunami wave energy. Tsunami wave energy includes the transformed part of seismic energy into the water. Computation of tsunami wave energy is a way to measure the power of tsunamis and reflects the potency of their generators. Tsunami wave energy has not been investigated as widely as other characteristics of tsunami *e.g.* travel time, amplitude, velocity, *etc.* Nevertheless, it has been discussed in some studies (Kajiura, 1970; Ward, 1980; Dotsenko and Korobkova, 1997; Velichko et al., 2002; Okal and Synolakis, 2003; Kowalik et al., 2007; López-Venegas et al., 2015; Omira et al., 2016). The far-field impacts of tsunamis caused by earthquakes are well understood (Ruiz et al., 2015). Estimating the seismic moment M_0 of a submarine earthquake is sufficient to compute the impact of tsunamis at far field, whereas evaluating the severity of near-field tsunamis is relatively controversial. Tsunami run-up distributions are used usually to measure the near-field effects of tsunamis which can be highly uncertain depending on several factors (Geist, 2002; Dutykh et al., 2011; Ruiz et al., 2015). The run-up heights and local tsunami amplitudes widely vary respecting the moment magnitude (M_w) of the associated earthquake (Dutykh et al., 2012). While run-up distributions along coastlines rely on site-specific conditions and local bathymetric variations, tsunami wave energy can be a better representative to understand the overall severity of local tsunamis.

The shallow great earthquakes at subduction zones generate the most destructive tsunamis (Satake and Tanioka, 1999). The subduction of Arabian plate beneath the Eurasian plate in the northwestern Indian Ocean has generated the Makran subduction zone (MSZ) with a length of 900–1000 km. The rate of convergence increases from 2.3 cm/y in the western edge to 2.9 cm/y at the eastern boundary of Makran (Regard et al., 2005), but with no obvious deep-sea trench (Schlüter et al., 2002). The Makran subduction zone is seismically split into an active eastern and an apparently inactive western segment. The present-day offshore seismicity in the Makran is generally low (Smith et al., 2012). Nevertheless, it generated a tsunamigenic earthquake on 1945 November 27, which triggered a significant regional tsunami with 11–13 m maximum run-up (Ambraseys and Melville, 1982; Okal and Synolakis,

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2008; Shah-hosseini et al., 2011). According to Heidarzadeh and Satake (2017), the 1945 M_w 8.1 Makran earthquake can not be solely responsible for such large height of run-up and a delayed submarine landslide triggered by the main shock probably amplified the tsunami run-up. Future earthquakes along the Makran subduction zone can potentially trigger submarine landslides due to very thick sediments on the continental shelf which is of the order of 7 km. Such submarine landslides will amplify the wave heights of local tsunamis as was observed. The data regarding the exact impacts of the 1945 tsunami on the coastlines are really limited; however, the reports suggest that the event caused remarkable destruction and about 4000 deaths (Heck, 1947; Ambraseys and Melville, 1982; Heidarzadeh et al., 2008). Similar events can reoccur by the Makran subduction zone between about 125 and 250 years based on Page et al. (1979) computations. Byrne et al. (1992) mentioned that similar events can be repeated every 175 years in the eastern Makran. Despite the very limited historical data, Quittmeyer and Jacob (1979) mentioned four possible large historical events in 1483, 1851, 1864 and 1765. There is no strong evidence to suggest that those events caused tsunamis. However, Ambraseys and Melville (1982) indicated that the 1765 event caused a tsunami (Zarifi, 2006). Byrne et al. (1992) approximated the rupture area of 1765, 1851 and 1945 large earthquakes (Fig. 1). They considered the 1864 event to have occurred inside the 1851 rupture area since they impacted the same region. The 1483 event is considered as the only major event that may have occurred in the western Makran. However, there are some studies on the coastal terraces suggesting that a probable earthquake on the western segment in 1008 AD caused about 2 m of uplift and a tsunami with about 4 m of wave heights (Ambraseys and Melville, 1982; Shah-hosseini et al., 2011; Frohling and Szeliga, 2016). There is no proof to accurately estimate the location of these events.

Despite the fact that understanding of the present tsunamigenic behavior of the Makran subduction zone is complex, it is worth studying the tsunami properties in the Makran region. Frohling and Szeliga (2016) using the GPS measurements concluded that the Makran subduction zone is partly locked and accumulating strain. They inferred that sectional locking of the MSZ makes it capable of generating earthquakes up to M_w 8.8. The length of MSZ (900-1000 km) is about the same as Sumatra 2004 mega-thrust earthquake rupture length (~ 1000 km) (Ammon et al., 2005). Assuming the locking of the MSZ, especially the western segment (Musson, 2009; Rajendran et al., 2013), it has potential to generate plate boundary earthquakes, hence tsunamis. Tsunami in the Makran subduction zone will be a real threat to northern Indian Ocean countries, especially Iran, Oman, Pakistan and India. As the number of facilities and residences are increasing along shores of those countries, the exposure and vulnerability to tsunami hazard are also increasing.

In this study, we compute the energy of waves generated by sea floor motion for a tsunamigenic source model involving the full length of the Makran subduction zone. The distribution of maximum tsunami amplitudes is also presented to evaluate the near-field tsunami hazard from the source model. Tsunami numerical modeling assists us in our computations.

2. Methodology

2.1. Tsunami wave energy

Very long tsunami waves lose little energy as they propagate from the generation area to coastlines and cause greater run-up than storm waves (Bryant, 2008). The strength of a tsunami depends on type and characteristics of the source. Tsunami energy is distributed all through the water column immediately after its generation. Stronger sources displace more volume of water, therefore cause more energetic tsunamis. Tsunamis generated by shallow undersea earthquakes are usually stronger than submarine landslide-generated tsunamis and lose less energy. The uplift motion of sea floor due to a subsurface rupturing immediately pushes up the sea water from the bottom and displaces the sea surface. The life-cycle of tsunami energy can be described in three general sequential phases (Dutykh and Dias, 2009); i) a portion of seismic energy is pumped into the ocean by bottom motion; ii) during the propagation stage kinetic and potential energies are constantly exchanged; iii) tsunami energy is used to inundate the coasts during wave run-up.

In this context, we compute tsunami energy based on Dutykh and Dias (2009) as they conducted a comprehensive theoretical investigation on the energy of tsunami waves generated by sea floor motion. Using the incompressible fluid dynamics equations, they drove the equation of energy E as the sum of kinetic K and potential Π energies. In the case of the free surface incompressible flows, the kinetic energy is based on the horizontal velocity field and the potential energy on the

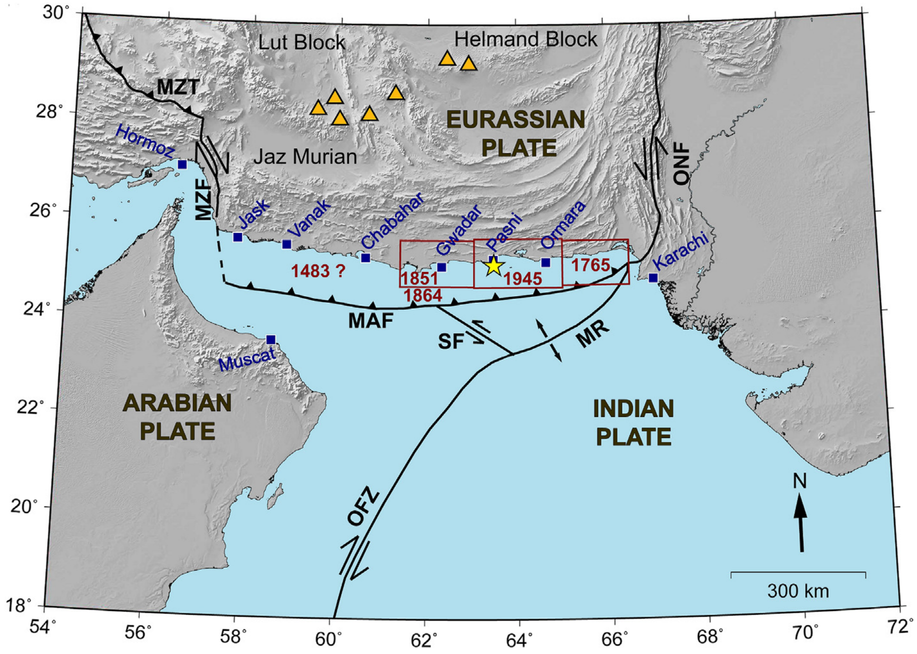

Fig. 1. Tectonic features of the Makran region. MAF Makran accretionary front, SF Sonne fault, MZF Minab-Zendan fault, MZT main Zagros fault, OFZ Owen fault zone. The triangles denote the volcanoes. The yellow star shows the epicenter of 1945 earthquake. The three blocks stand for the possible rupture areas of 1851 (1864), 1945 and 1765 earthquakes based on Byrne et al. (1992). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)