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Scenario-based tsunami risk assessment using a static flooding approach and high-resolution digital elevation data: An example from Muscat in Oman

Bastian Schneider [a,*], Gösta Hoffmann [a,b], Klaus Reicherter [b]

[a] Department of Applied Geosciences, German University of Technology in Oman, P.O. Box 1816, PC 130 Muscat, Oman
[b] Institute of Neotectonics and Natural Hazards, RWTH Aachen University, Lochnerstrasse 4 20, 52056 Aachen, Germany

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ABSTRACT

Knowledge of tsunami risk and vulnerability is essential to establish a well-adapted Multi Hazard Early Warning System, land-use planning and emergency management. As the tsunami risk for the coastline of Oman is still under discussion and remains enigmatic, various scenarios based on historical tsunamis were created. The suggested inundation and run-up heights were projected onto the modern infrastructural setting of the Muscat Capital Area. Furthermore, possible impacts of the worst-case tsunami event for Muscat are discussed.

The approved Papathoma Tsunami Vulnerability Assessment Model was used to model the structural vulnerability of the infrastructure for a 2 m tsunami scenario, depicting the 1945 tsunami and a 5 m tsunami in Muscat. Considering structural vulnerability, the results suggest a minor tsunami risk for the 2 m tsunami scenario as the flooding is mainly confined to beaches and wadis. Especially traditional brick buildings, still predominant in numerous rural suburbs, and a prevalently coast-parallel road network lead to an increased tsunami risk. In contrast, the 5 m tsunami scenario reveals extensively inundated areas and with up to 48% of the buildings flooded, and therefore consequently a significantly higher tsunami risk. We expect up to 60000 damaged buildings and up to 380000 residents directly affected in the Muscat Capital Area, accompanied with a significant loss of life and damage to vital infrastructure.

The rapid urbanization processes in the Muscat Capital Area, predominantly in areas along the coast, in combination with infrastructural, demographic and economic growth will additionally increase the tsunami risk and therefore emphasizes the importance of tsunami risk assessment in Oman.

1. Introduction

The tsunami hazard was re-evaluated all around the globe in the aftermath of the 2004 Indian Ocean Tsunami (IOT). The following year bordering countries of the Indian Ocean agreed to establish an ocean-wide early warning system under the mandate of UNESCO's Intergovernmental Oceanographic Commission (IOC) (Geist et al., 2006; UNESCO/IOC, 2008). The Sultanate of Oman is among the nations currently establishing this Indian Ocean Tsunami Warning System (IOTWS). Several approaches for assessing the tsunami hazard along the coast of Oman have been carried out so far (Heidarzadeh et al., 2006, 2009a; Heidarzadeh and Kijko, 2011; Rodriguez et al., 2013; Smith et al., 2013) but the tsunami risk in the Gulf of Oman remains enigmatic (Hoffmann et al., 2014).

Various authors (Rastogi and Jaiswal, 2006; Jordan, 2008; Rajendran et al., 2008; Heidarzadeh and Kijko, 2011) established a paleo-tsunami database with events related to the Makran Subduction Zone (MSZ) (see Fig. 1). The largest recorded tsunamigenic earthquake (M_w 8.1) occurred on the night of the 27th to the 28th November 1945 (Anonymus, 1945; Beer and Stagg, 1946; Byrne et al., 1992) with a maximum wave height of 2 m along the coastline of Oman. Higher waves are reported from the coastal areas in direct vicinity to the source area (Hoffmann et al., 2013a; Kakar et al., 2014).

Heidarzadeh et al. (2009a) and Smith et al. (2013) underline the possibility of tsunamigenic earthquakes in the MSZ with a magnitude of M_w 9+ (see also Musson, 2009). Modeling approaches (Heidarzadeh et al., 2009b) suggest that the resulting tsunami waves could reach more than 15 m in the Muscat Capital Area (MCA). These modeling results are backed by geological (e.g. Shah-hosseini et al., 2011; Hoffmann et al., 2013b; Koster et al., 2014; Prizomwala et al., 2015) and archeological (e.g. Hoffmann et al., 2015) evidence along the coastlines of the Northern Indian Ocean.

Furthermore, a non-seismic tsunami trigger is of importance as recent studies (Heidarzadeh et al., 2008; Rajendran et al., 2008; Fournier

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* Corresponding author.
E-mail addresses: kartografio@gmail.com (B. Schneider), goesta.hoffmann@gutech.edu.om (G. Hoffmann), k.reicherter@nug.rwth-aachen.de (K. Reicherter).

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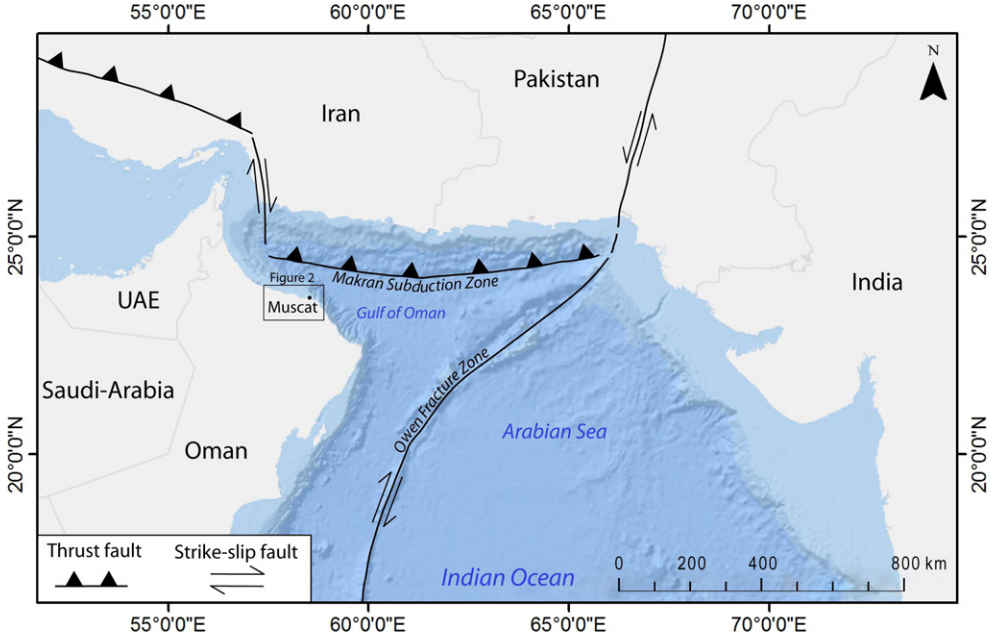

Fig. 1. General tectonic setting of the Makran region after Lin et al. (2015). Inset shows the study area in the Muscat Capital Area, Sultanate of Oman.

et al., 2011; Rodriguez et al., 2013) emphasize the risk of submarine tsunamigenic landslides in the northern Indian Ocean. Hoffmann et al. (2014) and Heidarzadeh and Satake (2015) describe a tsunami wave triggered by an onshore M_w 7.7 earthquake in Pakistan on September 24th, 2013. The resulting tsunami wave reached heights of up to 1 m and caused no known damage in Oman.

This paper aims at a first approach in tsunami vulnerability and impact modeling on a local level in the MCA. A vulnerability assessment of infrastructure and buildings for various scenarios was created in order to unveil areas of special risk. The analysis is based on a high precision digital elevation model (DEM). The results are of importance for land use, spatial planning and emergency management.

We follow the definitions of UN/ISDR (2009, p. 16) which describe geological hazards as “a geological process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”. As we focus on tsunami hazard in this study, the height of a tsunami wave is the hazard element. Due to the inundation method we used, the hazard is constant for each scenario. Vulnerability is defined as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.” (UN/ISDR, 2009, p.30, see also Hoffmann and Reicherter, 2015).This paper focuses on the physical vulnerability of infrastructure and buildings to a flooding event caused by tsunami waves.

Risk is usually defined as the product of the hazard and the vulnerability of the assets. We calculate a Relative Vulnerability Index (RVI) which considers the hazard. The RVI is finally transformed into different levels of risk as outlined by the Intergovernmental Oceanographic Commission (2009), which allow a deterministic risk assessment for the evaluated scenarios.

2. Study area

The study area is located in north-eastern Oman on the coast of the Gulf of Oman, where the MSZ is the most important tectonic feature (see Fig. 1). The MCA is located on the eastern end of the Batinah Coastal Plain (see Fig. 2), a broad alluvial plain where most of the country's farmland can be found. The MCA is Oman's administrative, economic and agricultural hub, most of its critical infrastructure is located here. Over the last decades the area experienced a rapid growth, with 50% of Oman's population being concentrated in the MCA with an average population density of 370 people per km^2 in 2015 (after National Centre for Statistics and Information, 2015).

Our study areas are two neighborhoods west of Muscat, subsequently referred to as Al Hail and Rumais (see Fig. 2), both representing a different urban setting. Whereas Rumais is a rural area, Al Hail is a highly urbanized suburb of Muscat. Both areas are located in the Batinah Coastal Plain (see Fig. 2). We regard these two areas as key-areas representative for the densely populated MCA as well as the more agriculturally dominated coastline of the Al Batinah.

2.1. Al Hail area

The area of Al Hail has an expanse of about 26 km^2 and is a densely populated residential area that stretches along the coast of the Gulf of Oman (see Fig. 2, panel b)). Several commercial buildings, mosques, schools and hotels are located in Al Hail. The area is a part of the fast-growing suburbs of Muscat. Some areas are widely used for agricultural purposes, especially date plantations. Al Hail is characterized by a dense road network, whose main roads are parallel to the shoreline.

Al Hail is generally low-lying with minor topographical features and an average altitude of about 5.6 m above local mean sea level (a.s.l.). Al Hail is built on top of the most distal part of an alluvial fan, originating in the south. Individual stream channels are oriented south–north, perpendicular to the coast. These channels flood following intense local precipitation events.

2.2. Rumais area

The area of Rumais is located in a rural area with a low population density and is characterized by agricultural areas and wastelands, *sabkha* plains and small villages. The Rumais area has an expanse of about 21 km^2 and an average altitude of about 9.4 m a.s.l.

The two villages of Abu Nukhayl and Wadi Manumah are located on sandy beach ridges. Further inland halophilic shrubbery gradually becomes agricultural land. The villages of Manumah and Al Duwika are situated in between the highway and the *sabkha* plains at 4–10 m altitude (see Fig. 2, panel a)). These villages are almost exclusively residential with associated farmlands, but show no industrial or large-scale commercial land use. The road network in the area is sparse and few