International Journal of Disaster Risk Reduction 10 (2014) 406–418

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

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

Global tsunami hazard and exposure due to large co-seismic slip

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ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form
14 March 2014
Accepted 2 April 2014
Available online 13 April 2014

Keywords:
Tsunamis
Hazard analysis
Global study
Population exposure
Economic loss
Cascading effects
Critical facilities

ABSTRACT

Tsunamis are infrequent events with the power to cause massive loss of life, large economic losses, and cascading effects such as destruction of critical facilities. Historical tsunamis and paleotsunami evidence indicates indirectly that massive megathrust earthquakes leads to the majority of the losses due to tsunamis. There is a need to quantify the tsunami hazard from megathrust events in order to compare tsunamis with other natural hazards on a global level, as previous attempts have been lacking. Here, we determine the earthquake induced tsunami hazard for a return period of 500 years using both a deterministic scenario based approach as well as a probabilistic tsunami hazard assessment method (PTHA). The resulting hazard level for a set of selected areas in South and South East Asia are compared quantitatively for both methods. The comparison demonstrate that the accuracy of the analysis is rather rough, which is expected given the global character of the analysis. Globally, the exposed elements at risk such as population, produced capital, and nuclear power plants are determined for each nation affected. It is shown that populous Asian countries account for the largest absolute number of people living in tsunami prone areas, more than 50% of the total exposed people live in Japan. Smaller nations like Macao and the Maldives are among the most exposed by population count. Exposed nuclear power plants are limited to Japan, China, India, Taiwan, and USA.

1. Introduction

Recent megatsunamis have changed our understanding of how to deal with these rare and high consequence events [1,2]. The spotlight was put on the risk to human lives, but also on critical facilities that should withstand destructive tsunamis having a low probability. The 2011 Tohoku tsunami caused remote and indirect economic consequences such as reduced industrial production in countries not hit by the tsunami, as well as resulting in the phasing out of nuclear power plants in Germany [3]. These events have highlighted the global repercussions. Such events are reinforcing the need for a comparable basis for assessing the risk posed by tsunamis worldwide. Previously, most hazard assessments have been spatially constrained to local sites or regions [4–8]. Following Løvholt et al. [9], this study is the first to

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http://dx.doi.org/10.1016/j.ijdrr.2014.04.003
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cover the major earthquake sources worldwide, and to quantify both exposed critical facilities and population living in inundated areas.

The Hyogo Framework for Action (HFA) was adopted by the United Nations International Strategy for Disaster Risk Reduction (UN-ISDR) in January 2005 in order to reduce disaster risk. As an instrument to compare the risk due to different natural hazards worldwide, an integrated worldwide study was implemented and published in several bi-annual Global Assessment Reports (GAR) by UN-ISDR [3]. This paper concerns the global tsunami hazard and exposure for a return period of 500 years. Contrary to a local assessment, the present study therefore aims to capture average trends on a country level across the globe.

Using the NGDC tsunami database [10] it is found that 54 of the reported historical tsunamis have caused a thousand or more fatalities, with these 3% generating 97% of the total fatalities. A majority of these were reported to occur in the last 400 years, as older records are more sparse. Hence, it is clear that the next large tsunami disaster is linked to a low probability. Furthermore, the sources of these tsunamis are dominated by earthquakes (the NGDC tsunami database [10] reports that more than 80% are due to earthquakes). Gonzalez et al. [7] conducted a probabilistic tsunami hazard assessment (PTHA) for the city of Seaside (USA), and found virtually no inundation for the 100-year return period. Using a characteristic magnitude-frequency distribution, they found that the predicted tsunami run-up increased abruptly when the return period was increased. As a consequence, an almost complete inundation of Seaside was found for the 500-year return period, and that this was predominantly due to local megathrust sources. Paleotsunami information from Chile indicates a relatively regular recurrence of major tsunamis in the order of 500 years [11]. Based on the damage of the 2004 Indian Ocean tsunami, Nadim and Glade [12] postulated that the damage characteristics of the tsunami is highly non-linear, with a rapid transition from low to high fatality for an increasing return period. Recent damage characteristics on buildings derived from the 2004 Indian Ocean and 2011 Tohoku tsunamis [13] also indicate a rapid transition from small damage to total destruction as a function of the tsunami flow depth.

The findings from the brief discussion above [7,10–13] suggest that the tsunamis driving the risk are associated with low probability of occurrence, and that the risk may change rapidly from one return period to another. The findings from Seaside and Chile are partly based on paleotsunami data, indicating that a return period of 500 years may constitute the main risk driver. Clearly however, this is site dependent, and in other areas such as Portugal (see e.g. the study of Matias et al. [8]) earthquakes having longer return periods are likely to contribute more to the risk. In Japan, the last event of size similar to the 2011 Tohoku tsunami is believed to be the 869 Jogan tsunami [14], indicating a somewhat longer inter event time. Meanwhile, Japan has been hit by at least three other earthquake induced events each with reported fatalities exceeding 10000 [10] which are each comparable to the losses caused by the 2011 Tohoku tsunami. To this end, Kagan and Jackson [2], based on McCaffrey [15], indicate a return period close to 500 years for a Mw 9.0 earthquake for Japan. Clearly, it is difficult to define a characteristic return period representative for major events globally. Yet, the indicated 500-year return period represent the order of magnitude for the lower bound return period of major subduction zone events. Hence, we choose to quantify the global tsunami hazard at the 500-year return period.

Previous models for linking earthquake potential to parameters such as lithospheric plate age, thickness, and convergence rate to the earthquake potential has recently been refuted [1,2]. Hence, it is presently difficult to rule out the occurrence of large earthquakes for any major subduction zone or fault worldwide.

2. Methods

The hazard results reported here comprises both those originating from a scenario based method, supplemented with tsunami hazard maps using a probabilistic tsunami hazard assessment (PTHA) method [6] for the Indian Ocean and the South West Pacific. However, the quantification of the run-up and exposure are comprised by a joint method. The different methods are briefly outlined below.

2.1. Description of the scenario based hazard assessment method

The earthquake scenarios are confined to those with the potential for tsunami generation due to co-seismic dip-slip motion. For the scenario earthquakes, earthquake faults of uniform width, length and slip are established, and in turn converted to seabed displacement using the standard analytical formula of [16]. The hydrodynamic response from the seabed dislocation is smoothed using the model of Kajiura [17,18]. For most of the subduction zones, new scenarios were constructed assuming fault locking over a period of 500 years (the exception is South America, where scenarios taken from Løvholt et al. 2012 [9] were used). Convergence rates obtained from Bird [19] are used. Related magnitudes were deduced from the scaling relations of Blaser et al. [20]. By making assumptions on the fault shear strengths, related fault lengths and widths were in turn derived from the scaling. Typically the shear strengths were in the range of 20–40 GPa. In the more tectonically complex regions, including the Adriatic Sea, Cascadia subduction zone, Sicily, eastern Indonesia, and Portugal, worst case scenarios from the literature are used directly or adapted [7–9,21–23]. Altogether this gives relatively conservative estimates for the scenario earthquakes. However, as discussed below, there are several other assumptions in the overall methodology that are non-conservative.

Near source and regional tsunami propagation are modelled using a linear dispersive wave model GloBouss [24–26], on publicly available ETOPO1 grids. For convergence, the grids are refined to the desired resolution by bi-linear interpolation. The maximum water level obtained from the time series at the control points is used to compute the further amplification to the shoreline. The near shore control points have an approximate spacing ranging from 20 to 50 km. The control points are extracted automatically by a contouring algorithm (GMT [27]) at a small reference depth of 50 m.