Nat Hazards (2012) 63:1273–1278
DOI 10.1007/s11069-012-0162-0

SHORT COMMUNICATION

Civil nuclear power at risk of tsunamis

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Received: 8 June 2011 / Accepted: 23 March 2012 / Published online: 8 April 2012

Abstract Tsunamis have caused severe destruction to vulnerable populations through the ages. Commonly generated from oceanic subduction zones, they still remain difficult to predict. Recent instrumental record on risk of occurrence can be enhanced when complemented by historical, archeological, and geological studies. We assessed the coast at risk and overlaid civilian nuclear sites active, in expansion and under construction. The worldwide distribution of threatened nuclear sites revealed a clustering in South and South-East Asia. We identified four areas for urgent policy attention, including the need for funding to translate scientific risks assessment into effective policy.

Keywords Nuclear power · Risk assessment · Development · Tsunami · Earthquake

1 Tsunamis and human civilizations

A marine tsunami is a high-energy wave caused by the displacement of a large body of water, often leading to inundation of coastal areas by sea water with consequent disruption to vulnerable human populations (Noji 1997; Ziegler et al. 2009). The genesis of marine tsunamis can be terrestrial or extraterrestrial (i.e., bolides), and the former can be caused by marine earthquakes, volcanic explosions, and coastal or submarine landslides (Dawson and Stewart 2007). Seismic areas with the greatest potential to produce large tsunamis (i.e., Mw >8.0) are located in oceanic subduction zones with the capacity to activate reverse faults in the seabed (Moore et al. 2007). However, the various sources of tsunamis and the relatively recent instrumental record of earthquakes complicate the predictability of these phenomena, despite progress in predicting future ruptures in well-studied faults (Hergert and Heidbach 2010; Nalbant et al. 2005; Parsons et al. 2000). Historic, archeological, and geological records

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are not only useful to confirm what is known but also to identify undetected regions affected by large tsunamis in the past (Scheffers and Kelletat 2003) for which the tsunamigenic mechanisms are not well understood (Dominey-Howes 2007; Rodríguez-Vidal et al. 2011).

The magnitude-9.0 (Mw) shock of the 11th March 2011, the largest on record in Japan, in an area considered by some experts only able to produce up to magnitude-8.0, emphasizes our limited understanding of these processes and often results in the underestimation of the real risk. In addition to the disproportionate human and economic toll of the disaster, the nuclear crisis that was triggered reveals the serious dangers brought about by the interaction of extreme events with state-of-the-art technologies, even in highly developed and wealthy countries such as Japan.

Destructive tsunamis have not only struck with significant human impact during the last century (Noji 1997; Ziegler et al. 2009), but detailed paleo-tsunami studies have indicated that such events have occurred repeatedly through history, frequently affecting human civilizations (Baptista and Miranda 2009; Cummins 2007; Minoura et al. 2001; Shaw et al. 2008). In recent times, the intensive environmental transformation of coastal areas (Danielsen et al. 2005; Das and Vincent 2009, Syvitski et al. 2009), along with the socio-economic impacts of climate change in vulnerable populations (Patt et al. 2010), is likely to be increasing human susceptibility to tsunamis and other coastal hazards. All these risks are further aggravated by increasing population size in hazardous areas (Adger et al. 2005).

2 Nuclear power at risk of large tsunamis

Considering the enormous health, and socio-economic impacts of large tsunamis and their low predictability, assessing the coastline at risk is necessary to identify current and future threats to human settlements and infrastructure. We focus our assessment on tsunamis that are exclusively generated by marine earthquakes. Assuming known tsunamigenic subduction zones as possible source areas of large tsunamis (US Geological Survey 2011), we selected low-lying coasts that were parallel and near these faults. We validated these against published historical, archeological, and geological records (Cummins 2007; Heidarzadeh et al. 2008; Jankaew et al. 2008; Kelsey et al. 2005; Nanayama et al. 2003, 2007; National Geophysical Data Center 2011; Scheffers and Kelletat 2003; Shaw et al. 2008). In this process, we also noted the occurrence of tsunamis in areas where the tsunamigenic mechanism remained unidentified (Dominey-Howes 2007; Rodríguez-Vidal et al. 2011; Scheffers and Kelletat 2003) (Fig. 1). These areas were also included in our analysis. These were then overlaid with the civilian nuclear sites that are active, in expansion and under construction on the shoreline (International Atomic Energy Agency 2011), thereby revealing the worldwide distribution of nuclear plants at risk today and those that will be at risk in the future (Fig. 2).

In total, we identified 23 sites (22 excluding Fukushima I) with 74 (68) reactors at risk. Of these sites, 13 with 29 reactors are active, 4 sites (20 reactors) are being expanded with 9 new reactors, and 7 new sites with 16 reactors are under construction. Although the coastline at risk is vast (Fig. 1), the nuclear sites threatened by large tsunamis are clustered in South and South-East Asia (Fig. 2). Of the 7 at-risk sites (19 reactors) in Japan, one reactor is currently under construction in a new site. South Korea is further expanding 2 currently active sites with 5 additional reactors that have been identified at risk by this study. One site at risk was identified in both India (2 reactors) and Pakistan (1 reactor). China shows the greatest civilian nuclear power expansion in at-risk areas, with overall 6 new sites, including 1 in Taiwan, and 2 active sites being expanded with overall 19 new reactors (see Fig. 2).

Fig. 1 Worldwide coastline at risk of large tsunamis produced by marine earthquakes in active subduction zones. Shoreline at risk (*red line*), including at-risk coastline for which the tsunamigenic mechanisms remain unidentified (*red dashed line*)

Fig. 2 Active, in expansion, and under construction civilian nuclear sites located in tsunami risk areas. Names and geographical location and of the nuclear sites identified at risk, including under construction sites (*brown dashed line*). The number of nuclear reactors active or under construction in each site is indicated in brackets. Daya Bay and Ling Ao are adjacent nuclear plants and considered as a single site. Ling Ao's fourth reactor is currently under construction. Fangjiashan nuclear power plant is currently under construction. It is adjacent to Qinshan's, and both considered as a single site. One reactor is presently under construction at the Qinshan site. Two additional reactors, Shin-Wolseong 1 and 2, are in trials at this time at the Wolseong site. Three reactors, Shin Kori 2-4, are presently under construction at the Kori site. Nuclear research, military, and any planned nuclear facilities are not included in this figure

Considerable uncertainty remains, related to the local characteristics of each site, which could minimize or amplify the run up of the tsunami, including the focusing configuration of the source region, waveguide structure of mid-ocean ridges, the shape of the continental shelves (Titov et al. 2005), the physiography and geology of the impacted site, wave arrival direction, tides, and geotechnical design of the settlement. Also, identical tsunamis could produce different infrastructure damage, depending on specific characteristics and security systems of the involved plants. More detailed work should identify site-specific vulnerabilities. Although military and research facilities were not considered in this work, they will, as well as planned civilian nuclear construction, require further assessment.

3 Policy

Twenty-seven of the 64 nuclear reactors currently under construction in the world are located in China (International Atomic Energy Agency 2011), giving an indication of the ongoing massive investment in nuclear power in this country. More importantly, 19 (including 2 in Taiwan) of these 27 reactors are being built in the at-risk areas identified in our study. Rapid expansion of this sensitive technology in at risk shorelines underlines the potential threats posed by a large tsunami hitting any of these locations. In addition, the propensity to build new reactors in existing nuclear sites increases geographical aggregation, potentially increasing the risks of chain reactions if something goes wrong (Macilwain 2011).

Vulnerable shorelines are not only important in the planning of nuclear facilities but also for future construction of sensitive build, including human settlements. These should be safer if constructed further away from the coast using the maximum inland travel distances of the waves as the minimum benchmark of safety (Borrero et al. 2006). In view of our recent experience of damages due to tsunamis, appropriate laws and regulations for land zoning and urbanization that take into consideration such risks should be put in place.

Given the uncertain interactions of potential tsunamis with nuclear power plants, we suggest that a more conservative approach may be appropriate to achieve sustainable human development. Similarly, the potential damage due to other natural hazards should be also considered. For this, multi-hazard maps should be developed (Dilley et al. 2005) but with higher resolution than those currently available (Guha-Sapir et al. 2011). We further suggest that not only recent instrumental records, which do not approximate the cycles of these natural phenomena (Scheffers and Kelletat 2003), are included but also relevant historical, archeological, and geological evidence.

Funding of scientific research to better delineate disaster risks is extremely important and should be expanded given increasing global vulnerability. But equally, effective mechanisms to translate existing disaster risk research, such as the one on the tsunami risks on the Sendai plain (Minoura et al. 2001), into policy are urgently needed.

Despite the long-lasting disruptive effects of past nuclear catastrophes such as Chernobyl's (Smith et al. 2000), and the anxiety due to the unknown health impacts of radioactivity (Editorial 2011), the risks of living in hazardous areas are too easily overlooked. The Fukushima disaster should not be justified by the rareness of the earthquake and tsunami event, as enough evidence exists that contradicts this argument (Minoura et al. 2001; Nanayama et al. 2003, 2007). Recent examples from the large 2004 Indian tsunami reveal that lessons from the past have not been transformed into effective policy. Despite identified risk along these coastlines (Nalbant et al. 2005), human habitations continue to be built at rates greater than the pre-tsunami levels, thereby exposing larger populations to future likely events (Ziegler et al. 2009).

The Fukushima crisis has occurred in a wealthy country with the highest standards of scientific knowledge and technological infrastructure. Should a similar event occur in a country that is less well-equipped to manage the catastrophic consequences of such a coincidence of events, the impact will be far more serious for the world.

Acknowledgments The FEDER–Spanish MICINN project (CGL2010-15810) and the agreement number AID-OFDA-A-10-00009 funded this work. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We thank A. Diaz for assistance with map edition, C. Finlayson for comments. The authors declare no conflict of interest.

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