

## **3. Tsunami Hazard and Risk Assessment**

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**Key words:**

tsunami hazard, physical vulnerability, probabilistic tsunami hazard analysis (PTHA), tsunami early warning systems

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Globally, tsunami risks are dominated by rare but often very destructive events. Assessment of tsunami hazard and risk is required to support preparedness measures and effective disaster reduction. In most coastal locations, highly destructive tsunami events are not well represented in historical records, which tend to be short compared to the return period of large tsunamis (hundreds to thousands of years). In this way, tsunamis are different from more frequent hazards (such as floods or cyclones) for which historical records often provide a more useful reference for understanding the hazard and its impacts.

The “low frequency/high consequences” character of tsunamis induces considerable uncertainty into tsunami hazard and risk assessments. Recent history highlights that these uncertainties are commonly underestimated. The 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami caused more than 225,000 and 19,800 fatalities, and US\$ 9.9 billion and US\$ 210 billion in direct monetary losses, respectively.<sup>1</sup> But the impact of those events was not widely anticipated or planned for,<sup>2</sup> in spite of the fact that these two events constituted a major proportion of the global fatalities and economic losses due to natural hazards in the last 100 years.

## Sources and setting

Submarine earthquakes have generated about 80 per cent of all tsunami events recorded globally. The majority of tsunamigenic earthquakes occur at subduction zones along the Ring of Fire in the Pacific Ocean, while other important source regions include the Sunda Arc and the Makran subduction zone in the Indian Ocean, the northeastern Atlantic, Mediterranean and connected seas,<sup>3</sup> eastern Indonesia and the Philippines, and the Caribbean Sea.

Subduction zone earthquakes with magnitudes above M9 cause the largest tsunamis and these can propagate across oceans. Smaller earthquakes can also generate locally damaging tsunamis. Finally, a class of earthquakes termed “tsunami earthquakes” generate more intense tsunamis than expected from their seismic moment magnitude. Considering that recent events in all of these categories were not fully anticipated and integrated in pre-existing tsunami hazard assessments, we must be cautious in future hazard assessments, accounting for: (a) the possibility that M9 earthquakes might occur on virtually every major subduction zone<sup>4</sup> and (b) the complexity of

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1 Centre for Research on the Epidemiology of Disasters (CRED). 2009. Emergency Events Database (EM-DAT). Available from [www.emdat.be](http://www.emdat.be)

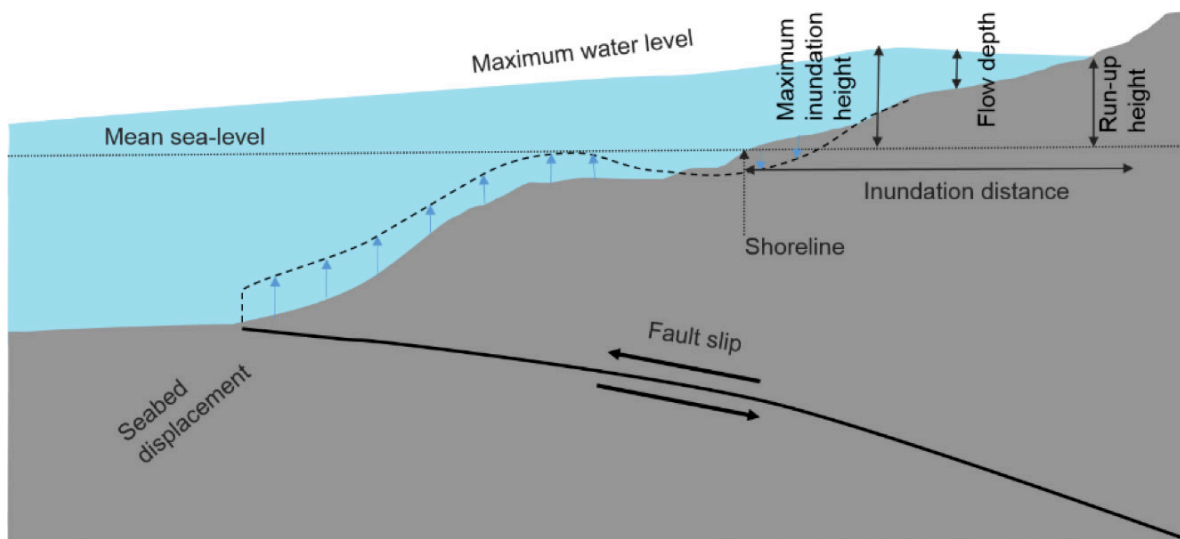
2 Synolakis, C. and U. Kanoglu (2015). The Fukushima accident was preventable. *Philosophical Transactions of the Royal Society*.

3 Papadopoulos G. A. and others (2014). Historical and pre-historical tsunamis in the Mediterranean and its connected seas: geological signatures, generation mechanisms and coastal impacts. *Marine Geology*, vol. 354, pp. 81-109.

4 Kagan, Y.Y and D.D. Jackson (2013). Tohoku Earthquake: A Surprise? *Bulletin of the Seismological Society of America*, vol. 103, pp.1181-1194.

recent earthquakes and tsunamis in terms of tsunami generation and resulting impacts.

The second most important sources of tsunamis are volcanoes and landslides. Tsunamigenic landslides often trigger earthquakes but other mechanisms can also trigger them. Tsunami hazard and risk assessment methods for these sources are less well established than those for earthquakes because they are less frequent and because their tsunami generation mechanisms are complex and diverse. Some of the most powerful tsunamis in history, however, have been caused by these sources, such as the seventeenth century B.C. Santorini (Greece) and the 1883 Krakatau (Indonesia) volcanic tsunamis, or the 1958 Lituya Bay (Alaska) earthquake-triggered landslide. Compared with earthquakes, landslides and volcanoes tend to produce tsunamis that are more spatially localized, although they can result in much higher run-up. Tsunamis from these tsunami sources are also more difficult to warn against effectively. Thus they should be considered at least for local tsunami hazard assessments.



**Figure 1** - Sketch showing main features of tsunamis induced by earthquake slip. The fault slip causes a seabed displacement that generates the tsunami. Shoaling gives rise to increased maximum water levels towards the coast.

## Tsunami hazard assessment

While tsunami hazard assessments were previously routinely developed using worst-case scenarios, probabilistic approaches for estimating tsunami hazard and risk are progressively becoming the new standard.

In a probabilistic tsunami hazard analysis (PTHA), parameters that describe all possible tsunami sources and their occurrence rates are established first.

Subsequently, tsunami propagation and inundation metrics are modelled, most often by means of numerical models combined with high-resolution bathymetry and topography. The results are then aggregated according to the source probability and modeled tsunami impact, providing hazard curves describing the exceedance probability for different tsunami intensity thresholds.

PTHA explicitly addresses different types and sources of uncertainty, caused by lack of knowledge of the source mechanism and the frequency of the largest events, limitations of input data, and modelling approximations. As a consequence, different alternative models are usually developed to quantify the uncertainty.

Another source of uncertainty derives from the lack of sufficiently accurate high-resolution digital elevation models and the computationally intensive nature of tsunami propagation modelling, which together limit the model resolution and the number of scenarios that can be simulated. When available, empirical tsunami data can be integrated into the analysis or be used for checking PTHA results.

Description of input data	National entities that most commonly have these data	Examples of open databases available from international sources
Bathymetry and topography	national mapping agencies; geological survey; marine science institutions; meteorological, marine, environmental protection agencies	GEBCO, ETOPO, SRTM (not suitable for high-resolution inundation modelling).
Tsunamigenic sources	geological survey; earth science, geophysical institutions	ISC-GEM Catalogue; global CMT Catalog; GEM faulted earth; literature
Past tsunami observations	meteorological, marine, environmental protection agencies; geophysical institutions	NOAA NGDC; Euro-Mediterranean Tsunami Catalogue, HTDB/WLD Database; literature
Exposure	local government; national agency responsible for census; various ministries, private sector, United Nations	WorldPop, Landscan, or GPW Global Population Data Global Exposure Database
Vulnerability models	engineering community; academia	Literature (e.g. reporting post-tsunami surveys or laboratory testing); Geoscience Australia; Comprehensive Approach for Probabilistic Risk Assessment (CAPRA)

**Table 1** - Sources of data at each stage of the probabilistic tsunami hazard analysis

## Exposure and vulnerability assessment

Tsunami inundation will vary according to the topography and surface roughness, but is limited to within a few kilometres of the coastline. In the inundation zone, the exposure encompasses both the population and the built-up environment (buildings, infrastructure and critical facilities).

The possible effect of a tsunami is quantified by measures of vulnerability – the relationship between tsunami flow depth or velocity, and the resulting damage or loss. Vulnerability is often divided into the study of (a) the probability of human casualties, influenced by a population’s risk awareness and behaviour during a tsunami, (b) structural damage and the resulting economic loss, influenced by building type and construction material and (c) social vulnerability, which deals with damage to livelihoods and communities and their post-event recovery.

Socioeconomic vulnerability is influenced by socioeconomic factors, gender, availability of infrastructure, and coping capacity. Assessing impacts entails very large uncertainty; even the most common damage metric, probability of structural damage is not yet very well understood. The landmark 2004 and 2011 tsunamis are relatively recent events, and the tsunami community is still in the early stages of understanding how to quantify both the physical and the societal vulnerability.

## Tsunami risk assessment use in national DRR measures

Local- and regional-scale risk assessments should combine the modelled hazard (e.g. overland flow depths, velocities) with exposure databases and vulnerability models, ideally using a probabilistic approach to risk quantification. Regional and global assessments are generally broad-scale and hence are not suitable to directly perform local-scale decision making; but rather they can serve as a guide to understanding national level tsunami risks to prioritize regions requiring more detailed site-specific studies.<sup>5</sup>

Long-term tsunami risk reduction measures can be devised based on local or regional scale risk assessments through approaches such as land-use planning, tsunami building codes, early warning systems and evacuation planning, installation of engineered defenses, and specific measures for nuclear and non-nuclear critical infrastructure.

Several tsunami DRR measures are now implemented worldwide. Regional Tsunami Early Warning Systems (TEWS) are today operational almost everywhere and provide regional scale warnings for any Member State of the

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<sup>5</sup> Løvholt, F., J. Griffin and M.A. Salgado-Gálvez (2015). Tsunami hazard and risk assessment on the global scale. *Encyclopedia of Complexity and Systems Science*. Meyers R.A., ed. Berlin and Heidelberg: Springer.

Indian Ocean Commission. However, they might be ineffective without one of the most important DRR measures at the national level: the local scale assessment of the regional warning and the implementation of “last mile” actions in response – rapid alert dissemination and evacuation on pre-established evacuation routes.

However, in many countries with tsunami risk, these elements are not in place. Engineered mitigation measures such as breakwaters and seawalls are even less common globally because of the cost of constructing and maintaining them, but they have been built along the coastlines of Japan. Tsunami evacuation buildings have also been implemented, although in limited areas. These enable vertical evacuation of people in flat or isolated locations with few options to evacuate inland during near-field tsunamis. Although the physical measures may be effective in places, in general they cannot eliminate the risk. Even with warning systems and engineered solutions, risk awareness among the population is necessary for reducing casualties.

In countries such as Chile and Japan, the relatively high rate of self-evacuation in recent events is likely to have reduced the overall death tolls. Tsunami educational programmes have been implemented across the world to expand this awareness.

## CASE STUDY

### Box 1 - Master Plan for Reducing Tsunami Risk

#### Indonesia

Following the 2004 Indian Ocean Tsunami, Indonesia invested heavily in disaster management. In 2007 it passed a Disaster Management Law, establishing the National Disaster Management Agency (BNPB).

This was followed in 2008 by the establishment of the multi-agency Indonesian Tsunami Early Warning System (InaTEWS), with the support of international partners. Investment in the full warning chain, from monitoring, decision support and warning systems through to “last mile” dissemination and evacuation planning has been critical, especially due to the short time frames for evacuation in many parts of the country.

A first national scale PTHA was undertaken in 2012 and incorporated into the national Master Plan to spatially prioritize where to invest in tsunami mitigation. Technical guidelines defining minimum standards for hazard and risk assessment have been written to support implementation of the Master Plan, assisting local governments in implementing informed tsunami risk reduction activities such as evacuation planning and tsunami shelter construction.

In line with a strong political agenda to develop Indonesia’s maritime-based economy, tsunami risk assessment is identified as an important tool for safeguarding development investments and coastal industries, including fishing and tourism, and for building resilient coastal villages. Although challenges remain, Indonesia demonstrates how a robust understanding of tsunami risk can underpin tsunami risk reduction measures at national and local level.

## Resources for further information

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Freely available software exists for simulating tsunami propagation and inundation. Some widely used open source or community models include ComMIT (National Oceanic and Atmospheric Administration, United States), GeoClaw (University of Washington, United States), ANUGA (Australian National University and Geoscience Australia) and TUNAMI (Tohoku University, Japan). However, these models require appropriate skills and training to be used effectively.

It is also crucial that such codes be validated and verified. Relevant information about models, past events, etc. can be found through national stakeholders, such as the Pacific Marine Environmental Laboratory (PMEL) (United States).<sup>6</sup> Others include the International Tsunami Information Center (ITIC),<sup>7</sup> the North-Eastern Atlantic and Mediterranean Tsunami Information Center (NEAMTIC)<sup>8</sup> and the Indian Ocean Tsunami Information Center (IOTIC).

In contrast, there are no comparable widely used models for quantifying tsunami frequencies or vulnerability because of the diversity of approaches used to model these factors. Notwithstanding, new guidelines from the American Society of Civil Engineers (ASCE) for assessing forces due to tsunami loads have recently become available.

General open risk assessment modules and initiatives, such as CAPRA,<sup>9</sup> can combine the hazard, exposure and vulnerability, to quantify commonly known risk metrics such as average annual losses, probable maximum losses and loss exceedance curves, as done at the global level for UNISDR's GAR15.<sup>10</sup> We also refer to the tsunami risk guidelines of UNESCO-IOC.<sup>11</sup>

At present, the approaches for tsunami risk analysis are not well standardized. Therefore, current methods, some of which are described in the online references, need guidelines accepted by the tsunami community.

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6 NOAA Center for Tsunami Research (2017). Pacific Marine Environmental Laboratory. United States Department of Commerce. Available from <http://nctr.pmel.noaa.gov>

7 International Tsunami Information Center. 2017. Intergovernmental Oceanographic Commission of UNESCO. Available from <http://itic.ioc-unesco.org/index.php>

8 North-Eastern Atlantic, Mediterranean and connected seas Tsunami Information Centre. 2017. Intergovernmental Oceanographic Commission of UNESCO. Available from <http://neamtic.ioc-unesco.org>

9 Indian Ocean Tsunami Information Center (2017). *Intergovernmental Oceanographic Commission of UNESCO*. Available from <http://iotic.ioc-unesco.org>

10 United Nations Office for Disaster Risk Reduction (2015). *Global Assessment Report on Disaster Risk Reduction 2015*.

11 Chock, G. and others (2016). Target structural reliability analysis for tsunami hydrodynamic loads of the ASCE 7 standard. *Journal of Structural Engineering*, vol. 10, 1061/(ASCE) ST. 1943-541.

To organize and focus efforts on such issues, a Global Tsunami Model has been proposed to provide coordinated action for tsunami hazard and risk assessment. While the Model is not yet fully operational, many publications illustrate methods that can be adapted for future hazard and risk analysis in the Model.<sup>12,13 14</sup>

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12 United Nations Educational, Scientific and Cultural Organization and Intergovernmental Oceanographic Commission (2009). *Tsunami Risk Assessment and Mitigation for the Indian Ocean: Knowing Your Tsunami Risk and What to Do About It*. Paris: UNESCO.

13 Geist, E. and T. Parsons (2006). Probabilistic analysis of tsunami hazards. *Natural Hazards*, vol. 37, pp. 227-314.

14 Davies G. and others (2017). *A Global Probabilistic Tsunami Hazard Assessment from Earthquake Sources*. Geological Society of London Special Publications, 456.



**Figure 4** – Exposure model (left), average annual economic losses (centre) and socioeconomic vulnerability index (right) for the residential building stock in Colombia<sup>28, 29</sup>