

# Hazard Specific Risk Assessment: Geophysical

## 2 - Tsunami Hazard and Risk Assessment

*Key words: tsunami hazard, physical vulnerability, probabilistic tsunami hazard analysis (PTHA), tsunami early warning systems*

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.

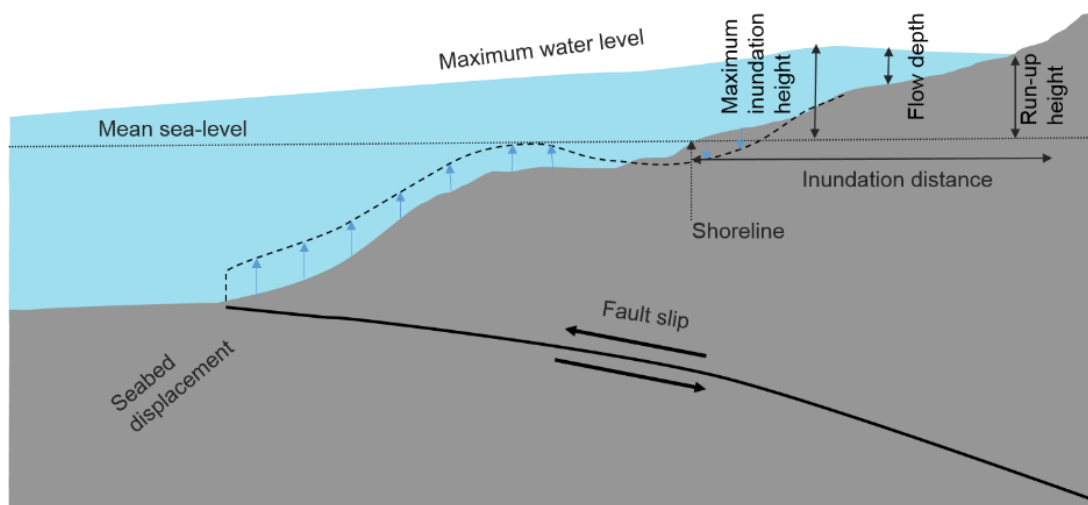
The 'low frequency/high consequences' character of tsunamis induces considerable uncertainty into tsunami hazard and risk assessments. Recent history highlights that these uncertainties are commonly underestimated. The 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami caused more than 225,000 and 19,800 fatalities, and 9.9 BN USD and 210 BN USD 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% 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 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: (i) the possibility that M9 earthquakes might occur on virtually every major subduction zone<sup>4</sup>, and; (ii) the complexity of recent earthquakes and tsunamis, in terms of tsunami generation and resulting impacts.

The second most important tsunami sources are volcanoes and landslides. Tsunamigenic landslides are often triggered earthquakes, but other mechanisms can also triggered 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 17th century BC Santorini (Greece) and the 1883 Krakatau (Indonesia) volcanic tsunamis, or the 1958 Lituya Bay earthquake-triggered landslide in Alaska. 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 effectively. Thus, they should be considered, at least for local tsunami hazard assessments.



**FIGURE 3** – 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.

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

Description of Input Data	The national entities that most commonly have this data	Examples of Existing open databases available from international sources
Bathymetry and Topography	National Mapping Agencies; Geological Survey; Marine Science Institutions; Meteorological, Marine, Environmental Protection Agencies	GEBCO <sup>5</sup> , ETOPO <sup>6</sup> , SRTM <sup>7</sup> (not suitable for high-resolution inundation modelling).
Tsunamigenic Sources	Geological Survey; Earth Science, Geophysical Institutions	ISC-GEM Catalogue <sup>8</sup> ; global CMT Catalog <sup>9</sup> ; GEM faulted earth <sup>10</sup> ; Literature
Past Tsunami Observations	Meteorological, Marine, Environmental Protection Agencies; Geophysical Institutions	NOAA NGDC <sup>11</sup> ; Euro-Mediterranean Tsunami Catalogue <sup>12</sup> ; HTDB/WLD Database <sup>13</sup> ; Literature
Exposure	Local government; National Agency responsible for census; Various Ministries, Private Sector, United Nations	WorldPop <sup>14</sup> , Landsat <sup>15</sup> , or GPW Global Population Data Global Exposure Database <sup>16</sup>
Vulnerability Models	Engineering Community; Academia	Literature (e.g. reporting post-tsunami surveys or laboratory testing); Geoscience Australia; CAPRA <sup>17</sup>

## Exposure and vulnerability assessment

Tsunami inundation will vary depending on the topography and surface roughness, but is limited to within a few kilometers 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. The latter is influenced by socio-economic 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>18</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 IOC Member State. 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. These elements are not in place in many countries with tsunami risk. Engineered mitigation measures such as breakwaters and seawalls are even less common globally, due to their cost to construct and maintain, but have been built along the coastlines of Japan. The construction of tsunami evacuation buildings has 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 likely reduced the overall death tolls. Tsunami educational programs have therefore been implemented across the world to expand this awareness.

#### **BOX 1** - Master Plan for reducing tsunami risk

**Indonesia** - Following the 2004 Indian Ocean Tsunami, Indonesia invested heavily in disaster management. In 2007 a Disaster Management Law was passed, establishing the National Disaster Management Agency (BNPB), followed in 2008 by 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 timeframes for evacuation in many parts of the country.<sup>19</sup>

A first national scale PTHA was undertaken in 2012<sup>20</sup> and incorporated into the national Master Plan for Reducing Tsunami Risk 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 to implement 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, 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

Freely available software exists for simulating tsunami propagation and inundation. Some widely used open source or community models include ComMIT (NOAA, USA), GeoClaw (Univ. Washington, USA), ANUGA (Australian National University and Geoscience Australia) and TUNAMI (Tohoku Univ., Japan), among many others. However, these models require appropriate skills and training to be used effectively. It is furthermore crucial that such codes are validated and verified. Relevant information about models, past events, and much more, can be found through national stakeholders, such as the US Pacific Marine Environmental Laboratory, PMEL<sup>21</sup>. We also refer to the International Tsunami Information Center, ITIC<sup>22</sup>, the North-East Atlantic and Mediterranean Tsunami Information Center, NEAMTIC and the Indian Ocean Tsunami Information Center, IOTIC<sup>23</sup>.

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 ASCE guidelines for assessing forces due to tsunami loads have recently become available. General open risk assessment modules and initiatives, such as CAPRA<sup>24</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 the UNISDR's GAR15<sup>25</sup>. We also refer to the tsunami risk guidelines of UNESCO-IOC<sup>26</sup>.

At present, 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. 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 GTM is not yet fully operational, many publications illustrate methods that can be adapted for future hazard and risk analysis in the GTM framework.<sup>27 28 29</sup>

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