1. Risk Assessment and Reduction

1.1. Advance Risk Knowledge

1.1.1. Tsunami causative mechanisms

Tsunamis are gravity sea waves with typical periods ranging from a few minutes up to ~1 hour or more and wavelengths from tenths to hundreds of kilometers depending on the dimensions of the causative source. The majority of tsunamis (~80%) is produced by submarine, shallow (focal depth ≤100 km) and sizable (magnitude exceeding ~6.5) earthquakes with faulting mechanism that usually involves a significant component of vertical motion. However, the tsunamigenic potential of the nearly horizontal component of fault motion should not be neglected.

The largest seismic tsunamis are produced along active zones of lithospheric subduction such as the ones in the circum-Pacific belt, in the Indonesian arc, in the eastern Mediterranean Sea and in the Atlantic Ocean offshore SW Iberia. However, tsunamis are also generated from other sources with a variety of mechanisms, including aerial and submarine landslides, volcanic eruptions and large-scale meteorological changes (meteotsunamis).

Sources of tsunamigenic landslides may include either aseismic landslides, which are due to only the gravity action, or co-seismic landslides that are caused by the strong earth shaking. Tsunamis are also produced by landslides associated with volcanic processes, like pyroclastic and/or debris flows that move downstream the volcanic cone. However, other volcanic mechanisms could also produce tsunamis, including caldera collapse, submarine explosions and air waves of explosions. The combined action of several mechanisms may conclude in the generation of multiple tsunami waves. An example is the tsunami generation after a single strong submarine earthquake but from two different mechanisms, i.e. the co-seismic fault displacement at the sea bottom and the landslide due to the earth shaking.

Sea waves having physical features similar to those of the tsunamis can be produced by air-pressure disturbances, which are frequently associated with fast-moving weather events. These waves, commonly known as meteotsunamis, can propagate at long distances and cause destruction in coastal zones although they do not take sizes as large as the tsunamis.

1.1.2. Understanding and improving our knowledge of global tsunami hazard and risk

Tsunami waves may cause significant impact in the human communities, in their properties and in the natural environment. The tsunami risk reduction is based on the synergy of various actions which, among others, may include preparedness, operation of early warning systems, public education and awareness, and emergency plans. However, understanding the physical processes that govern the generation, propagation and inundation of tsunamis as well as the assessment of the tsunami hazard and risk are of crucial importance for an effective development of the various tsunami risk reduction actions.

The concept of risk as related to earthquakes was given in the frame of UNESCO in the 1970's and was considered as the convolution of three main attributes: hazard, vulnerability, and value exposed to hazard. This definition was later generalized and applied to other types of risks including tsunamis. The above definition of risk is consistent with recent terminologies and glossaries adopted in the frame of international organization such as UNISDR, EU and IOC/UNESCO. In this context, according to the IOC Tsunami Glossary (2019) tsunami hazard is meant as the possibility that a tsunami of a particular size may strike a particular section of coast, while the tsunami risk is the probability, of a particular coastline being struck by a tsunami, multiplied by the likely destructive effects of the tsunami and by the number of potential victims.

However, the mode of convolution, of which the risk is composed by definition, is not standardized. The reason is that it depends on the type of risk under consideration, on the availability of relevant data sets and on the types of assets which are exposed to the hazard. Consequently, the initial concept of risk is transformed to a more generalized convolution scheme:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability} * \text{Exposure} * \text{Value} \quad (1)$$

Tsunami risk could be approached qualitatively or quantitatively and this again depends on the data availability and on the kind of risk needed to assess. Formula (1) implies that the risk assessment is a quite complicated issue that requires the assessment of each one of the various components involved.

The methods developed for the tsunami hazard assessment are classified in two main classes, the deterministic and probabilistic ones. Consequently, the methods proposed for the tsunami risk assessment follow also this general categorization. The deterministic hazard approach is usually based on the extreme tsunami scenario or the so-called worst-case credible tsunami scenario. This approach takes into account the largest tsunami causative source for the study area. A characteristic historical event, e.g. a large earthquake, is usually taken as the largest causative tsunami source, although a hypothetical event could also be considered. Starting from the seismic faulting process according to the worst-case scenario, the tsunami wave is numerically simulated in three stages: generation at the seismic source, propagation in the open sea, inundation at the coastal land and run-up calculation in the coastal segment of interest. The last stage practically concludes with the determination and mapping of the so-called tsunami hazard zone.

On the other hand, the Probabilistic Tsunami Hazard Assessment (PTHA), which in the last years has gained ground, follows in many ways the experience obtained from the Probabilistic Seismic Hazard Assessment (PSHA) since the 1960's. At the beginning, the research focuses on the investigation of the seismic (or other) sources that are potentially capable to produce tsunamis threatening a particular coastal segment. Taking into account the probabilities of activation of each seismic source, with certain earthquake magnitudes in certain time frames, and after numerical simulations of the waves produced by each source, the probabilities of exceedance of certain run-up values in the coast of interest are calculated.

At the present stage of research both the probabilistic and deterministic methods suffer from a variety of uncertainties. The effort for the tsunami hazard determination is characterized also by significant gaps in the availability of the data sets needed. Such gaps include the incomplete knowledge of the seismic sources, such as their dimensions, the faulting styles and the rates of activation with large magnitude earthquakes. Other data gaps concern the limited accuracy of the bathymetry in many parts of the sea bottom, particularly in the near-shore domain, as well as the frequent lack of appropriate digital elevation models needed to map tsunami hazard zones.

The relative sparsity of instrumental tsunami records by tide-gauges along the coasts or by tsunameters at the sea bottom, creates an important research gap in PTHA and, therefore, hazard estimates are directly derived from historical tsunami records. Nevertheless, even such data sets are not equally available in all the parts of the global ocean. Catalogues that list paleoearthquake and paleotsunami events, which are identified by geological methods, e.g. by the recognition of tsunami sediment deposits, may provide further enrichment of the tsunami catalogues and useful input for the calculation of repeat times of large events. However, possible overweighting of large past tsunamis should be treated with caution. Such issues were examined in details by a worldwide network of specialists working together in the frame of the European COST tsunami project AGITHAR. Of special interest are approaches developed initially for the PSHA with the utilization of incomplete and uncertain earthquake catalogues containing instrumental, historical and paleoearthquake data. Such approaches are suitable for hazard assessment associated with rare events and, therefore, recently were tested for the PTHA too with promising results.

The estimation of tsunami losses is closely connected to damages in buildings and infrastructures. Therefore, physical vulnerability and exposure constitute important components in the convolution scheme for the tsunami risk assessment as generalized by formula (1). In this sense, vulnerability is closely associated to damage or fragility functions This issue has been examined mainly on the basis of data collected either after the Indian Ocean 2004 and Japan 2011 mega tsunamis or from local building statistics and field inspections without a reference to the impact of particular tsunami events. However, a lack of consensus has been noted as regards the various aspects related to the fragility vulnerability modeling. Important research gaps include the data limitation about asset types. On the other hand, the effect of multiple hazards on the empirical tsunami fragility mode is also important. For example, the building damage caused by the earthquake occurrence before the tsunami attack may increase building vulnerability. An important gap is referring to the difficulty of "quantifying" social vulnerability, which is referring either to populations or to individuals. Recently some researchers underlined that despite the rhetoric of vulnerability, the measurement of progress towards disaster risk reduction in the Sendai Framework for Disaster Risk Reduction (2015−2030) remains event/hazard-centric.

The exposure data provide information about the characteristics and the location of people and of various assets at risk. Several techniques for the acquisition of exposure data exist, although with different degrees of resolution and precision. The exposure modeling, however, is also characterized by several gaps, including lack of data or lack of data detail and lack of tsunami exposure model and taxonomy. As regards populations residing in, or visiting, coastal zones, particular attention should be given to the time-dependency of exposure. Seasonal and 24-hour patterns of people gathering at the seashore is of crucial importance for the assessment of population exposure.

Traditionally the tsunami risk assessment includes qualitative or quantitative scenario-based methods. However, PTHA methods are becoming progressively a standard basis for the Probabilistic Tsunami Risk Assessment (PTRA) as well. PTRA methods have been developed more recently with a variety of approaches. However, less progress has been noted in PTRA with respect to PTHA. This is due to that for the hazard assessment only data on the physical parameters of the events are needed, while for the risk assessment vulnerability, exposure and value data are also required. Data sets of these types are limited or even lacking in many coastal areas of the world. For these reasons the several components involved in the tsunami risk assessment are susceptible to a variety of epistemic and aleatory uncertainties making the risk assessment a highly complex procedure. As a consequence, the several methods tested so far are quite variable and closely dependent not only on the kind of the data sets available but also on the data quality and reliability. Therefore, no standard methods for the tsunami risk assessment have been concluded so far.

Financial values exposed to tsunami hazard have been considered in a few studies. Relevant losses have been expressed using as metrics either the probable maximum loss for a given return period of the extreme tsunami event or the probabilistic average annual loss and the loss exceedance curve. An interesting approach is the one developed for the scenario-based method. In this approach, absolute monetary cost is calculated for building reconstruction and replacement after an extreme tsunami inundation.

1.2 Cascading Risk

1.2.1. Understanding the impact and the socio-economic cost of tsunamis on livelihood, critical infrastructure and marine assets

In human communities the tsunami impact may include fatalities and injuries as well as damage or even destruction in a variety of assets, such as buildings, infrastructures, life lines, vessels, material of several kinds, and coastal cultivated areas. The tsunami impact may also include social disruption and direct or indirect losses in financial terms. In the natural environment there are several effects caused by the tsunamis, like destruction of flora and fauna, ground erosion, transport of sediments and deposition of medium-fine grained material, boulders and megaclasts.

The catastrophic potential of tsunamis is exemplified by some devastating waves that occurred in the historical past but also in about the last 20 years. Extreme cases are the Boxing Day 2004 tsunami in the Indian Ocean and the 11 March 2011 tsunami in NE Japan, both generated by big earthquakes of moment magnitudes Mw9.2 and Mw9.0, respectively.

The great Sumatra earthquake of 26 December 2004 caused one of the largest and more disastrous tsunamis experienced ever. An estimated 230,000 people lost their lives. The tsunami affected directly 16 nations all around the Indian Ocean and indirectly many other nations around the globe given that thousands of Europeans, Americans, Asians and other tourists/visitors lost their lives in coastal zones hit by the tsunami. The highest death toll, of about 130,000, was reported from Banda Aceh and Meulaboh along the northwestern coast of Sumatra where the tsunami run-up heights exceeded 30 m. Within hours the tsunami propagated to all directions of Indian Ocean affecting Thailand, Sri Lanka, India, Maldives and as far as east Africa. Extensive damage was caused to buildings of several types, such as houses, schools, hospitals and governmental buildings, as well as to infrastructure including harbors, bridges and railways.

About three months later, a second very large earthquake of Mw8.6 ruptured to the south extension of the rupture zone of the 26 December 2004 earthquake. The tsunami caused was smaller as compared to the one of 26 December 2004 but powerful enough to kill approximately 900 people and to renter 22,000 people homeless.

A few years later, on 11 March 2011, a very large earthquake ruptured offshore NE Japan in the Pacific Ocean. The earthquake generated an equally large tsunami, which devastated the NE coastal zone of Japan, particularly the Tohoku region where the wave height reached up to about 40 m, while the tsunami penetrated inland up to about 5 km. An estimated 19,508 people lost their lives including missing persons, nearly 90% of them due to the tsunami. Within hours the tsunami propagated to all directions of Pacific Ocean affecting as far as California, where damage was noted in Crescent City.

Destruction in infrastructures and economic impact such as that caused in NE Japan by the 2011 tsunami was never reported in the past. For example, in Fukushima, nuclear power plants were drastically affected by the tsunami with the result that three reactors meltdown. In the aftermath of the accident, voices of criticism were heard for the reason that the tsunami risk plan in Fukushima ignored published research results showing clearly that an equally large seismic tsunami hit exactly the same coastal area during the 9th century AD. This historical event could be used as the worst-case scenario for the area. However, the Onagawa nuclear power plant, located 15 m above sea level, underwent a small amount of tsunami inundation, but there was no damage to the reactor buildings and equipment, which shut down safely following the earthquake. In Sendai, massive tsunami inundation occurred in the coastal airport, which remained closed for about one month.

The economic impact of the Tohoku tsunami and earthquake has been global. In the aftermath of the catastrophic 2011 event all nuclear power plants were shut down within Japan. This resulted to power shortages by about 30% of the total national need, which turned to the need of importing fossil fuels with negative consequences for the Japanese economy. Outside Japan the Fukushima disaster marked the beginning of huge reduction in nuclear power generation around the world, e.g. in Germany, Switzerland and Italy. The impact of this global transition from nuclear to fossil fuel power generation marked a serious setback in the struggle to control global warming.

1.2.2 Cascading tsunami risk including the impact from climate change

Tsunami waves often are produced as the result of cascading effects, which may involve several combinations of physical processes, like earthquake-landslide-tsunami, volcanic eruption-earthquake-tsunami and others. For example, a strong coastal or submarine earthquake may cause a landslide that turns to a tsunami generation agent although the fault displacement, which is associated to the earthquake, does not produce tsunami. This possibility is of importance for the assessment of the tsunami hazard and risk. Therefore, relevant studies should not neglect the possible cascading effects in areas which are susceptible to processes of this type.

In the last years, particular attention has been attracted by the possible effects that the climate change may have on the long-term assessment of the tsunami hazard and, consequently, of the tsunami risk. For example, increase of raining rates in certain areas is expected to accelerate landslide processes that are potentially capable to produce tsunamis. This may happen not only along coastal zones but also in the submarine environment where increase of the sedimentation rate is expected.

The long-term but gradual Sea Level Rise (SLR) is a crucial parameter that should be taken into account when considering the possible effect of the climate change on the tsunami hazard assessment. In very recent studies new PTHA approaches have been tested to meet such challenges in time frames of a century or so. However, the SLR very likely is a non-stationary procedure and, therefore, probabilistic models incorporating Poissonian but non-stationary rates of SLR variations have been tried. Such models have been applied successfully to the PSHA in the past and, therefore, are promising for the PTHA as well.

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