Una aproximación multidisciplinar al estudio de las fallas activas, los terremotos y el riesgo sísmico

Editores:
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Fidel Martín González

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THE COASTAL RECORD OF TSUNAMIS IN THE INQUA ESI-2007 SCALE

El registro litoral de tsunamis en la Escala ESI-2007 de INQUA

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Abstract: *Seismic Intensity scales are based on the effects of earthquakes on man, man-made structures and on natural environment. However, the effects on the environment have been usually minimized because they were considered as inaccurate features. The growth of Palaeoseismology as an independent discipline led to the development of the ESI-2007 Intensity Scale, based on the effects of earthquakes on the environment and ratified by INQUA during its XVII Congress (Cairns, Australia-2007). This scale can be used alone or jointly with other intensity scales, but it becomes especially useful for seismic intensity higher than X, when damage-based scales get saturated and environmental effects are still diagnostic. Tsunamis are only considered in the ESI-scale by the height of the waves, and no by their geological or sedimentary record. Data from present day tsunamis (authors' own work and other's published data) are used as a first approach to the implementation of this record in the ESI-scale. However, the joint effort of an international working group is desirable in order to properly match effects and intensity degrees.*

Key words: *Environmental Effects of Earthquakes, tsunami intensity, tsunami environmental effects, environmental seismic intensity.*
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The importance of Earthquake Environmental Effects EEE´s as a tool to measure earthquake intensity is based on (Guerrieri et al., 2007): (a) The EEE size is the most reliable tool for the intensity assessment of strong earthquakes. For major earthquakes (intensity ≥X) the effects on human environment suffer from saturation (man- made structures are nearly completely destroyed), therefore any assessment based on the level of damage to buildings cannot work properly; (b) The use of EEEs offers the possibility of comparing earthquake intensity assessments worldwide; (c) Intensity based on EEEs is the best tool to compare recent, historical and pre-historical earthquakes.

The ESI-scale comprises twelve intensity degrees and it considers primary and secondary effects, depending on whether they are caused directly by earthquake energy reaching the surface, or they are induced by ground-shacking. However the effects on coastal settings are not properly and specifically considered. This work aims to take a first step in including the coastal record in this scale by gathering all the available information on the effects of earthquakes in this environment.

Related with the measuring of the size and effects of tsunamis we refer to the classical bibliography about magnitude and intensity of tsunamis (Sieberg, 1927; Ambraseys, 1962; Ilda, 1970; Soloviev, 1970; Shuto, 1993). Papadopoulos and Imamura (2001) proposed a new tsunami intensity scale based on the following basic principles: (a) independence from any physical parameter such as wave height; (b) sensitivity, that is, incorporation of an adequate number of grades in order to describe even small differences in tsunami impacts; and (c) a detailed description of each intensity grade by taking into account all possible tsunami impacts. They proposed a 12-point scale of tsunami intensity analogous to earthquake intensity scales like the EMS98. Even they tried to don´t use physical parameters; they correlate his intensity domains with the scale and H proposed by Shuto (1993). Lavigne et al. (2009) tried to propose a new scale with 6-point intensity scale and based on the effects in buildings. They called it ''Macrotsunamic Intensity Scale'' as they tried to correlate with the Macroseismic Intensity Scale. Because they back to 6-point intensity scale, is out of any further discussion.

The last proposal came from Lekkas et al. (2013) that proposed an Integrated Tsunami Intensity Scale (ITIS 2012), a 12-grade scale based that takes into account: (1) the quantities of the phenomena, (2) the direct impact on humans, (3) the impact on mobile objects, (4) the impact on coastal infrastructure, (5) the impact on the environment, and (6) the impact on structures. The scale tries to be compatible with the widely used EMS1998 and ESI2007 scales and proposed a reliable horizontal correspondence throughout the groups of criteria.

In summary, most of the aforementioned Intensity and magnitude scales for tsunamis only regard with the energy or size of the tsunami wave itself, but not properly with the intensity zones (degrees) considered in the Macroseismic Scales. Only the tsunami Intensity scales based on the original proposal of Papadopoulos and Imamura (2001), such as the ESI-07 Scale (Guerrieri and Vittori, 2007) and the ITIS-12 Scale (Lekkas et al., 2013), relate the tsunami features, impact and type of record with the classical 12 intensity zones of macroseismic scales.

In this paper we improve and update the environmental record of the tsunamis (Tsunami Environmental Effects-TEE) considered in the ESI-07 Scale by means of: (a) inclusion of the same physical parameters (wave height and run-up; extension of the inundated area inland) for all the intensity levels with potential environmental record (VI – XII); (b) The tsunami wave height reefers to the Shuto (1993) intensity/magnitude scale, the only one that includes maximum tsunami height (H) at shoreline; (c) use of the terminology defined by the Tsunami Glossary (2013) and Tsunami Survey Field Guide (Dominey-Howes et al., 2012) recently published by the Intergovernmental Oceanographic Commission.

These three aspects give internal coherence to the structure of the proposed TEE Scale, to be used as an update of the ESI-07 for tsunami and paleotsunami research. In this sense, the proposed scale incorporates quantitative data on the potential sedimentary (i.e. sand layers) and erosional record (i.e. beach scours, boulders) of tsunamis, which is an advantage on paleoseismological research.

ESI-2007 Intensity	***Tsunami Environmental Effects Scale (TEE-2014)***
I. Not felt *II. Scarcely felt* *III. Weak* *IV. Largely observed* *V. Strong*	Tsunami height ≤1m. No permanent effect in environment.
VI. Slightly damaging	Tsunami height between 1-2m. The maximum run-up can reach 2-4m. Limited flooded areas. Absent or scarce erosion. No sedimentation. Some debris near shore.
VII. Damaging	Tsunami height between 2-4m. The maximum run-up reached 4-6m. Flooded areas can extend tens of meters inland. Presence of sand layers in near-shore areas, commonly discontinuous.
VIII. Heavily damaging	Tsunami height between 4-6m. The maximum run-up can reach 8-12 m. Flooded areas can extend few hundreds of meters inland. Presence of largely distributed cm-thick sand layers, commonly discontinuous. Occurrence of pebbles and cobbles in near-shore areas. Observable features of beach erosion. Bushes uprooted in near-shore areas.
IX. Destructive	Tsunami height between 6-8m. The maximum run-up reached 12-16 m. Flooded areas extended to several hundred meters inland. Presence of largely distributed cm-thick sand layers, commonly continuous over large areas. Occurrence of pebbles and cobbles in near-shore areas. Noticeable features of beach erosion with the development of several cm depth scours. Bushes and some trees uprooted in near-shore areas.
X. Very destructive	Tsunami height between 8-12 m. The maximum run-up reached 16-25 m. Flooded areas may extend even 1 km inland. Presence of largely distributed cm-thick sand layers, normally continuous over large areas. Pebbles and cobbles largely extended in near-shore areas. Metric boulders transported near shore. Significant features of beach erosion with the development of cm to dm depth scours. Bushes and trees wash away in near-shore areas. Noticeable forest erosion in the littoral.
XI. Devastating	Tsunami height 12-24 m. The maximum run-up reached 25-40 m. Flooded areas extended more than 1 km inland. Widespread deposit of Sand layers <30cm thick even several hundred meters inland. Pebbles and cobbles largely extended in near-shore areas. Tn boulders transported near-shore and inland over distances less than one hundred metres. Important features of beach erosion with the development of dm depth scours. Large erosion and significant morphological changes on beaches, dunes and river-mouths. Significant forest erosion in the littoral. Coast- line can retreat several m.
XII. Completely devastating	Tsunami height >24m. The maximum run-up reached >40 m. Flooded areas extended to several kilometres inland. Sand layers <30cm thick extended inland over distances of more than one kilometre. Pebbles and cobbles largely extended in near-shore areas. Tn boulders dragged near-shore and inland over distances of even hundred meters. Outstanding features of beach erosion with the development of dm to m depth scours. Strong erosion and outstanding morphological changes on beaches, dunes and river-mouths. Erosional features can extent hundred meters inland. Strong forest erosion in the littoral. Coast-line can retreat several tens of m.

Table 1: Proposed Intensity scale of tsunami environmental effects (TEE-14) to be applied to the different intensity levels of ESI-07 Scale.

To define the new scale related with the environmental effects of earthquake-tsunami events at different intensity levels we propose use a range of maximum tsunami height and tsunami run-up for each level of intensity. Even the size of the tsunami wave depend on the bathymetry, coastal morphology and other local characteristics once the wave reaches the coast, but these parameters are directly related with the tsunami environmental effects onshore. To define the tsunami height for each intensity level we propose the use of the correlation suggested by Papadopoulus and Imamura (2001) between their defined intensity domains and the H (maximum tsunami height in m) and intensity values of Shuto (1993). Also, others parameters as maximum inundation distance, occurrence of sediment layers, type and thickness of sediments, dimension of some erosional features and transport of debris, pebbles and boulders of different size, are used to characterize each intensity level as described in Table 1.

The proposed scale follows the guide-lines of the ESI-07 scale, but has the advantage of (a) an internal coherence using always the same terminology and parameters refereed to the Shuto Scale (1993); (b) to use environmental effects checked in post-tsunami surveys of recent tsunami events published in the international literature; (c) to cross-check USGS instrumental intensity records with the ESI-07 Scale at known distances from the affected coasts; (d) to include specific erosive features; and (e) to include the occurrence of discontinuous-continuous sediment layers and their thickness. These two last points (d and e) has the advantage to be applied to the geological record of past tsunami events, and consequently of use for paleoseismological research.

Tsunami Event, year	**Mw**	**Δ (km)**	**MM Intensity**	**ESI-07 Intensity**	***TEE* Intensity**
Indian Ocean, 2004	9.1	155	VIII -IX*	XII	XII
Java, 2006	7.7	200	VI	X	VIII-IX*
Bengkulu, 2007	8.5	130	VII	VIII	VII
Peru, 2007	8.0	50	VIII	IX	VIII-IX*
Samoa, 2009	8.1	300	V	XI	X
Mentawai, 2010	7.7	70	VII	XI	X
Chile, 2010	8.8	100	VIII	XI	X-XI*
Tohoku, 2011	9.0	70	VIII-IX*	XII	XI

Table 2: Summary data on maximum intensities based on tsunami environmental effects, Modified Mercalli Intensity (MM) extracted from the USGS ShakeMaps-Archive, Moment-Magnitude (Mw) and epicentral distance (Δ) of the affected areas. * Intensities locally recorded in the affected littoral zones.

The proposed scale is based on the ESI-07, but also on data collected for recent tsunami events occurred during the present 21st Century (≥ 7.7 Mw). These have been reviewed and classified, developing a cross-checking among ESI-07 intensities, proposed TEE-14 intensities and MM Intensities extracted from the Instrumental Intensity ShakeMaps of the USGS. The performed evaluation clearly indicate no relationships between the MM intensity and ESI-07 or TEE ones, but a better approach to the new proposed scale, since the ESI-07 intensities are in most of the cases over- magnified.

Even taking into account that the tsunami size is not only related with the earthquake size (i.e. Mw), but also with the epicentral distance, and local bathymetry and/or morphology of the affected coastal areas, in the studied cases we found direct relation between Mw of the earthquakes and proposed TEE-14 intensity. In this sense, it is clear that the recorded
TEE intensity is not related with the local MM instrumental intensity recorded in the affected zones, but with the size of the causing earthquake event. Therefore tsunamis seems to be efficient processes in transfer the “energy” released offshore to coastal areas even over distances of hundreds of kilometers. In other words, tsunamis transfer the theoretical damage (intensity) experienced in the epicentral offshore area to the closer coastal areas constituting a valuable tool to estimate the maximum size of past events and consequently paleoseismological interest.

We apply the TEE-14 scale to the events cited in Table 2. Two examples are present here:

2007 Bengkulu tsunami, Sumatra (Borrero et al, 2009): Tsunami triggered by an earthquake Mw 8.5. The maximum wave height was 1.65 m. The run-up height average was established in 2 m. with a maximum of 5 m. The average extension of the inundation was <100 m, with a maximum extent of 500 m inland determined by occurrence of debris lines. There was no signal of erosion on the beaches berm ridges, and littoral dune belts. There are no descriptions on the occurrence of sediment layers, either sand, pebbles or boulders. Maximum intensity in the southwest coastal zone of Sumatra (Bengkulu) about 130 km southwest of the epicentre was of VII MM. The application of the ESI-07 Scale indicates that environmental damage reached intensity VIII. The maximum environmental effect of this tsunami is proposed to be classified between Intensity VI (Slightly damaging) and Intensity VII (Damaging).

2010 Chile tsunami (Morton et al., 2010, 2011; Fritz et al., 2011; Lario et al., in press): Tsunami triggered by an earthquake Mw 8.8. The maximum wave height was measured at 17.2m and maximum run-up at 29 m. The inundation reached up to 1 km in shoreline; and up to 3 km in river beds. Strong widespread erosion along beaches originating < 2 m depth scours. Strong erosion of littoral dune and lagoon-sand barrier systems, triggering significant morphological changes on river-mouths. Deposit of sand layers usually <30 cm thick. Occurrence of pebbles and boulders in near-shore areas. Maximum intensity in the coastal zones of the localities of the Peruvian Malue region affected by the earthquake about 90-100 km north and south of the epicentre was of VIII MM, but the earthquake was only located about 3 km offshore. The application of the ESI-07 Scale indicates that environmental damage reached intensity XI in the coastal epicentral area. The maximum environmental effect of this tsunami is proposed to be classified between *Intensity X (Very destructive)* and *Intensity XI (Devastating).*

From the studied events it is evident that the nature of the affected zones, especially relatively small islands or presence of coral-reefs, over- magnify the recorded intensities even for magnitudes of 7.7 Mw and epicentral distances of more than 200 km.

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