A New Tsunami Intensity Scale proposed after the Tsunamis of 11 Mar. 2011, Japan & 26 Dec. 2004, Indian Ocean

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SUMMARY:
The tsunami events caused by mega-earthquakes in the Indian Ocean (9.0, 12-26-04) and NE Japan (9.0, 03-11-11) had dramatic impact over extended areas and various distances from the source area, providing a huge amount of data, during unprecedented situations. The records of magnitude and grade of impact allowed a more precise specification of a more objective, 12-grade intensity scale of tsunamis, covering a full range of intensities, situations and environments. The proposed scale is based on 6 groups of criteria linking quantities, impact on all environments and human response.

Key Words: new scale, tsunami, intensity

1. INTRODUCTION

Tsunamis have occurred many times in both historical and recent times, as a result of great marine earthquakes, volcanic eruptions or marine landslides. Many of these events have caused great damages along coastal areas, as well as a great number of victims. In the historical times (before instrumental observations) great events were recorded, such as for example the tsunami in the Mediterranean during the eruption of Santorini (17th century BC), the tsunami of Lisbon (18th century) or the Krakatau eruption (19th century).

In recent times, before 2004, a series of relatively minor – in the global scale **-** events have occurred, for instance the Hawaii tsunami (1940), the Alaska tsunami (1961) and the Chile tsunami (1964). These events have occurred in rather underdeveloped and/or sparsely inhabited areas, and the impact on structures, infrastructure and people was not comparable to the more recent tsunami disasters.

On the contrary, the Indian Ocean tsunami of 2004 caused by the 9.1 earthquake and the 2011 tsunami in Japan caused by the 9.0 earthquake were two global scale catastrophic events which opened a new era in the study of these phenomena in all their dimensions, due to the fact that for the first time it was possible to observe, monitor and record all aspects frame by frame.

Both tsunami events stroke wide geographical areas corresponding to under development urban areas or developed areas with structures of any kind, rural areas with no residential cover, touristic areas, industrial zones, developed infrastructure, port facility areas, areas protected against tsunami waves, port constructions, etc.

Both tsunamis' large scale effects and event study give us the opportunity to outline a more complete picture for the disasters themselves as well as to conclude to a more accurate assessment of the factors responsible for the disasters' occurrence. The two big events offer an amount of evidence, not present for past events, regarding the vulnerability of systems, resulting to a more accurate picture with a great extent of the type and grade of disasters. In addition, data from great contemporary (e.g. Maule, Chile 2010) and historical events (Santorini Island, Greece ~1464 B.C., Lisbon, Portugal 1755) were taken into account.

The structure of the new tsunami intensity scale is based on 6 categories of criteria:

a. Physical quantities of the phenomenon itself, such as tsunami height, inundation depth, the extent of inundated areas, tsunami runup, etc. (Jaffe et al. 2006, Lekkas et al. 2011).
b. Impact on human environment, especially on human perception, but also on human behaviour - reaction and human loss.
c. Effects in mobile objects, such as vessels, boats, heavy objects, cars and means of transport (Bruce et al. 2006, Lekkas et al. 2011, Rai et al. 2006).
d. Impact on infrastructure, especially on offshore constructions, anti-erosion and anti-tsunami sea walls, port constructions, onshore infrastructure, lifelines, port structures and equipment such as cranes, tanks etc and industrial installations.
e. Geoenvironmental effects (Bruce et al. 2006, Parcharidis et al. 2005). In order to classify geoenvironmental effects, ESI_{2007} scale (Michetti et al. 2007) was used. Both 12 grade EMS_{1998} and ESI_{2007} scales complete one another and link contemporary and historical earthquakes (Lekkas, 2010) as well as earthquake effects that are observed in completely different environments, eg: urban, semi-urban etc (Lekkas 2010, Papanikolaou et al. 2009). Some aspects of ESI_{2007} were used in this particular criteria category, such as uplift - subsidence, morphological alterations, material transport, effects on trees etc, whereas other elements were transferred to physical quantities category of criteria (a category) as tsunami wave features for example.
f. Effects in structured environment (Ghobarah et al. 2005, Lekkas et al. 2005, Saatcioglou et al. 2006a, Saatcioglou et al. 2006b, Scawthorn et al. 2006) EMS_{1998} scale (Grünthal et al. 1998) were used as a basis, in order to grade effects in structured environment. EMS_{1998} is a 12-grade scale referring to earthquake effects in several structure types, in particular at: (i) Masonry type, (ii) Reinforced concrete type, (iii) Steel type and (iv) Timber type. Additionally, classification damage is referred (Grade 1-5) in any structure type. The type and grade of damage recorded as earthquake effects were adjusted to the damage observed at the 2 great tsunami events of 2004 and 2011, where a really great number of cases of damage in every building type were observed. In addition, at some cases, vulnerability grading was altered. For example, vulnerability of steel type structures was downgraded, as this particular type was proved to be particularly vulnerable to tsunami risk, as opposed to seismic risk. Likewise, vulnerability grade of wooden structures was altered as well. The final valuation of the intensity levels follows the same methodology as EMS_{1998}, using 3 definition levels of quantity, few - many - most.

2. DESCRIPTION OF THE NEW SCALE

For every grade, the six categories of criteria are described accordingly (a to f):

a. Quantities of the phenomenon (wave height, inundation, runup, etc) (Fig. 2, 5)
b. Impact on human environment (human perception, reaction and behavior in general)
c. Impact on moving objects (small vessels, boats, heavy objects, cars, etc) (Fig. 4)
d. Impact on infrastructure (marine installations, anti-erosion works, ports, industry, etc) (Fig. 3)
e. Impact on geoenvironment, on the basis of the 12-grade ESI_{2007} (uplift and subsidence, morphological alterations, debris transport and deposition are taken into account)
f. Impact on urban environment (all sorts of structures) on the basis of the EMS_{1998} scale classification (Fig. 1).

$I_{ITIS\text{-}2012}$, Not felt

a. No effect
b. Not felt, even under the most favorable circumstances
c. No effect
d. No effect

e. No effect
f. No damage

$II_{ITIS-2012}$, Slightly felt

a. No effect
b. Felt only by few people on board small vessels. Not being noticed onshore.
c. No effect
d. No effect
e. No effect
f. No damage

$III_{ITIS-2012}$, Weak

a. No effect
b. Felt only by many people on board on small vessels. Being noticed by a few people onshore.
c. No effect
d. No effect
e. No effect
f. No damage

$IV_{ITIS-2012}$, Largely observed

a. Tsunami height of a few cm.
b. Felt only by all people on board on small vessels. Felt only by few people on board on large vessels and by many people onshore.
c. Some small vessels wiggle or move towards the coast.
d. No effect
e. No effect
f. No damage

$V_{ITIS-2012}$, Strong

a. Tsunami height of several cm to dm (0,5m). Limited onshore areas inundated.
b. Felt by all on board on big vessels and people onshore. Some people panic and run for higher ground.
c. Many small vessels get washed on the shore and many offshore collide with each other.
d. No effect
e. No effect
f. Damage of grade 1 to a few buildings of vulnerability class A and B

$VI_{ITIS-2012}$, Slightly damaging

a. Tsunami height of some dm (<1m). Small onshore areas are flooded.
b. Many people panic and run for higher ground.
c. Many small vessels are washed out violently or collide with each other or are overturned along the shoreline. Cars are uplifted and moved.
d. No effect
e. Marginal turbulence at coastal sediments.
f. Damage of grade 1 is sustained by many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1

$VII_{ITIS-2012}$, Damaging

a. Tsunami height usually higher than 1m. Small onshore areas are flooded.
b. All people panic and run for higher ground.
c. Many small vessels suffer damage. Bigger vessels are shaken violently or collide with each other. All cars are carried away.

d. Few makeshift facilities on coastline are washed away.
e. Garbage - debris at parts of the shoreline. Limited erosion – deposition of sand and pebble at coastal areas.
f. Many buildings of vulnerability class A suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class B suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class C sustain damage of grade 2. A few buildings of vulnerability class D sustain damage of grade 1.

$\mathrm{VIII}_{\mathrm{ITIS\text{-}2012}}$, Heavily damaging

a. Tsunami height higher than 2m. Limited onshore areas are flooded. Limited inundation along coastline.
b. All people run for higher ground. Many are washed away.
c. Many small vessels suffer damage. Bigger vessels are washed out or collide with each other. Heavy objects are moved. Cars are washed away.
d. Many makeshift facilities along the coastline are washed away.
e. Erosion and garbage - debris along the shoreline. Some bushes or trees are uprooted and get carried away in small distance.
f. Many buildings of vulnerability class A suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class B suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class C suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class D sustain damage of grade 2.

$\mathrm{IX}_{\mathrm{ITIS\text{-}2012}}$, Destructive

a. Tsunami height of a few m (<5). Wide areas are inundated along the shoreline. Tsunami run up of some m, whereas inundation depth reaches some hundreds of m, depending on coastal morphology.
b. Many people are washed away.
c. Most vessels are destroyed or sunk. Many bigger vessels are washed out and some are destroyed. Cars are being washed away. Fires break along the shore.
d. Most makeshift facilities along the coastline are washed away. Little damage on offshore backfilling.
e. Depending on the topography and the kind of coastal formations, limited coastal profile changes with erosion and material deposition takes place. Garbage - debris deposition along the shoreline. Uprooting of bushes and some trees.
f. Many buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class C suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class D suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class E sustain damage of grade 2.

$\mathrm{X}_{\mathrm{ITIS\text{-}2012}}$, Very destructive

a. Tsunami height of many m (<7). Tsunami run up reaches or exceeds 10 m, whereas inundation depth reaches some hundreds of m, depending on coastal morphology.
b. General panic. Most people are washed away.
c. Most big vessels are washed out and many are destroyed due to impact on the shoreline and buildings. Cars overturn and are washed away.
d. Few damage on quays and port facilities. Damage on objects at port facilities. Small failures on anti-erosion works on the shoreline.
e. Depending on the profile of offshore and onshore area, notable changes at the coastal profile take place due to erosion and deposition. Trees are uprooted and washed away, small boulders move. Extensive pollution from oil and chemicals. Fires break.
f. Most buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B sustain damage of grade 5. Many buildings of vulnerability class C suffer damage of grade

4; a few of grade 5. Many buildings of vulnerability class D suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class E suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class F sustain damage of grade 2.

$XI_{ITIS-2012}$, Devastating

a. Tsunami height of many m (<10m). Tsunami run up exceeds 15 m, whereas inundation depth exceeds 1km, depending on coastal morphology.
b. Extensive human loss.
c. Extensive fires break. Heavy objects are washed away. Extensive erosion. Boats are washed off for hundreds of m onshore. Most cars are washed away or destroyed.
d. Breakwaters are damaged. Failures at anti-erosion works on the shoreline. Damage on the roads near the coastline. Great damage at onshore lifelines. Damage on cranes and other port facilities. Tanks on port facilities are moved. Rail lines suffer damage. Many riprap boulders are detached and moved. Some industrial facilities are damaged.
e. Depending on the profile of offshore and onshore area and probable uplift or subsidence, changes at the coastal profile take place due to erosion deposition and deep erosion. Many trees are uprooted and washed away, small boulders are washed away. Great pollution from oil and chemicals. Many fires break.
f. Most buildings of vulnerability class B sustain damage of grade 5. Most buildings of vulnerability class C suffer damage of grade 4; many of grade 5. Many buildings of vulnerability class D suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class E suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class F suffer damage of grade 2; a few of grade 3.

$XII_{ITIS-2012}$, Completely devastating

a. Tsunami height exceeds 10m run up reaches many tens of m and inundation some km. Areas of some tens km^2 are inundated.
b. Extended human loss in wide areas.
c. Boats are moved in high altitude. Cars, trains etc are washed away or destroyed.
d. Great damage in all port works such as jetties, marine breakwaters, port facilities, cranes, onshore lifelines. Riprap blocks are detached and moved in great distances.
e. Depending on the profile of offshore and onshore area and probable uplift or subsidence, extended changes at the coastal profile take place in wide areas, due to erosion deposition and deep erosion. Great changes on coastline topography. Almost all trees are uprooted and washed away. Big boulders are washed away on great distance. Massive pollution from oil and chemicals. Extensive fires break.
f. All buildings of vulnerability class A, B and practically all of vulnerability class C are destroyed. Most buildings of vulnerability class D, E and F are destroyed. The earthquake effects have reached the maximum conceivable effects.

Figure 1. Total destruction, deformation and movement of steel structures in Onagawa town, Japan 2011 (Vulnerability Class C, Grade 5) (Intensity: XII).

Figure 2. Runup evaluation (about 29m) in Onagawa area, Japan 2011 (Intensity: XII).

Figure 3. Damaged coastal infrastructures in Batong, Thailand 2004 (Intensity: IX) and in Ogatsu, Japan 2011 (Intensity: XII).

Figure 4. Tsunami induced transport and deposition of vessels in Thailand 2004 (Intensity: VIII-IX) and Japan 2011 (Intensity: XI-XII).

3. CONCLUSIONS

The main characteristics of the new tsunami intensity scale are:

1. The scale is based on 6 different criteria, more than any other existing scale (e.g. Papadopoulos & Imamura, 2001) and offers horizontal correlation between criteria in every intensity grade.
2. There is a gradual increase of the intensity grades, which is observable in all 6 criteria categories with clear boundaries between grades, at the same time.
3. Quantities are easily measured. Objective criteria are more than subjective criteria.
4. Evidence and grading is based at fieldwork data and particular damage types and not in theoretical data. In addition, photographic material documentation is available.
5. The new intensity scale is fully compatible with EMS_{1998} and ESI_{2007} seismic intensity scales.
6. Covers a wide span of land use type areas, such as agricultural, natural, ports, and a variety of different infrastructure and protection facilities/works.
7. Application of the scale and area microzonation in smaller areas is easier via the use of remote sensing techniques.
8. A 12-grade scale is more accurate and does not saturate, as 6-grade scales do.

Figure 5. Satellite imagery before and after the 2011 Tsunami, showing the effects on coastal areas, about 5km of Miyako town, in Onatsube area. Inundation was estimated at 750m and Runup at 37m. Damage in port facilities, infrastructure, houses and industrial facilities etc., are visible, as well as effects in natural environment (Intensity: XII).

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