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4 authors:

Efthymis Lekkas
National and Kapodistrian University of Athens

Andreadakis Emmanuel
National and Kapodistrian University of Athens

Irene Kostaki
National and Kapodistrian University of Athens

Eleni Kapourani
National and Kapodistrian University of Athens

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A Proposal for a New Integrated Tsunami Intensity Scale (ITIS-2012)

by Efthymis L. Lekkas, Emmanuel Andreadakis, Irene Kostaki, and Eleni Kapourani

Abstract The implementation of a new Tsunami Intensity Scale is proposed because a vast amount of data has been collected from the two megatsunamis that took place in the Indian Ocean in 2004 and northeast Japan in 2011. The newly proposed scale is 12-grade and is based on the assessment of a large number of objective criteria that are easily accessible and incorporated into six groups. As a result, it does not saturate as six-grade scales do. More specifically, the estimation of intensity values 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 new scale is compatible with the widely used EMS_{1998} and ESI_{2007} scales and has a reliable horizontal correspondence throughout the groups of criteria. It is easily and directly applicable to all environments, and particularly useful for the outlining of microzones of different intensities in any tsunami-affected area. It can be implemented for any land use/cover type, such as urban, rural, industrial, touristic, and so on, and at the same time, morphologic diversity of affected areas is not an obstacle to application.

Online Material: Photos and satellite images of tsunami damage and associated intensity values.

Introduction

Many tsunamis have been recorded in both historical and recent times as a result of great offshore earthquakes, volcanic eruptions, or marine landslides. Many of these events have caused great damage along coastal areas, as well as hecatombs of victims. During the pre-instrumentation era great events were recorded, for example, the prehistoric tsunami in the Mediterranean during the eruption of Santorini (fifteenth century B.C.) volcano, the tsunami of Lisbon (eighteenth century A.D.) or the Krakatau eruption (nineteenth century A.D.).

In recent times, before 2004, a series of major events had occurred, such as the tsunami that hit Pololu valley and Hilo in Hawaii (Aleutian islands, 7.8 earthquake, 1946), the Alaska tsunami (Prince William Sound, 9.2 earthquake, 1964), and the Chile tsunami (Valdivia, 9.5 earthquake, 1960). These events, however, have occurred in rather underdeveloped and/or sparsely inhabited areas. Consequently, the impact on structures, infrastructure, and people was not comparable to the latest tsunami disasters of 2004 and 2011.

In fact, 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 that opened a new era in the study of these phenomena in every aspect, because for the first time it was possible to observe, measure, monitor, and record phenomena and impact frame-by-frame.

Both tsunami events struck wide and widely diverse geographical areas from urban zones under development or developed 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, and port constructions.

Through event studies, both tsunamis' large-scale impact provided the opportunity to outline a complete picture of the disasters themselves, as well as concluded a more accurate assessment of the critical factors leading to disastrous outcomes. These events offered an amount of evidence, not available for past events, regarding the vulnerability of systems so that the type and grade of damage covered all vulnerability classes of substantially diverse systems. In addition, data from great contemporary (e.g., Maule, Chile, 2010) and historical events (Santorini volcanic eruption, Greece, ~1464 B.C.; Lisbon, Portugal, 1755) were taken into account.

Recording the type and grade of impact permitted reclassification of tsunami intensity into a new 12-grade intensity scale on the basis of a large amount of data and a variety of supplementary criteria.

History

Sieberg (1927) introduced the first six-grade tsunami intensity scale, pro rata to the earthquake intensity scale. The Sieberg scale was based on the description of tsunami macroscopic effects, such as damage. Ambraseys (1962) published

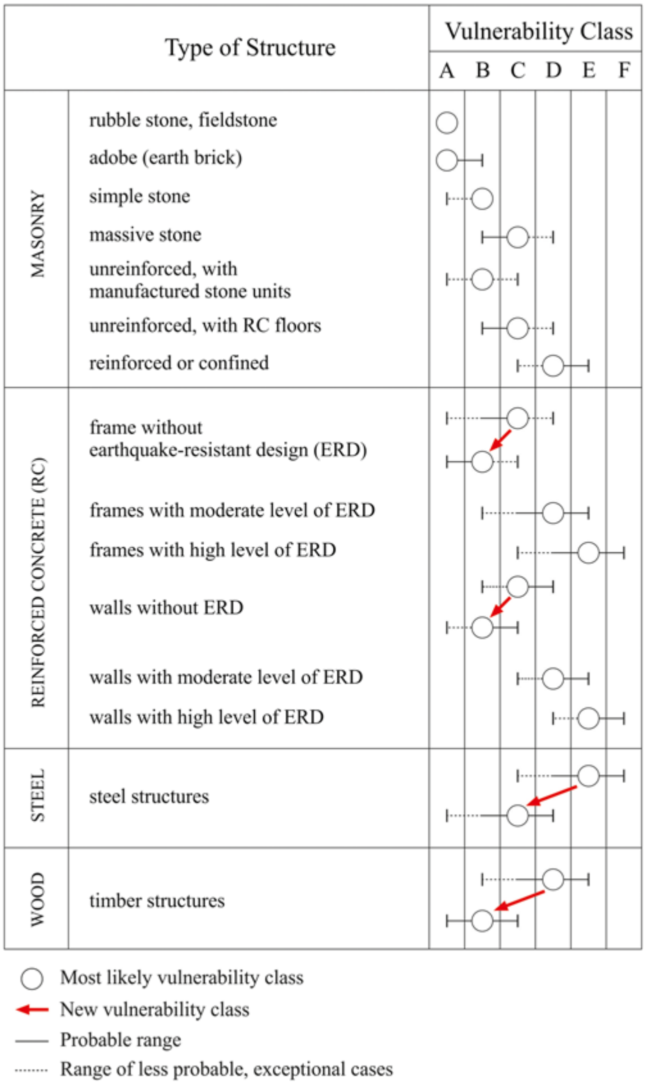

Figure 1. Vulnerability table. Differentiation of structure (building) into vulnerability classes based on the EMS-1998 (Grünthal, 1998). Differentiations to the Vulnerability Class for certain types of structures are shown. The color version of this figure is available only in the electronic edition.

a new version of the Sieberg scale, modified by Sieberg–Ambraseys, which is, however, considered too crude by many researchers today.

Imamura (1942, 1949) introduced the concept of tsunami magnitude, m, and Iida (1956, 1970) and Iida *et al.* (1967) further developed it. Magnitude, m, was defined by $m = \log_2 H_{\max}$, where $H_{\max}$ is the maximum tsunami wave height (in m) observed at the coastline or measured by tide gauges. The so-called Imamura–Iida scale is practically a six-grade scale ranging from -1 to 4. Soloviev (1970) proposed the tsunami intensity i_s, expressed as $i_s = \log 2\sqrt{2H}$, where H (in m) is the mean tsunami height. Shuto (1993) introduced a tsunami intensity scale in the form $i = \log_2 H$, where H is the local tsunami height (in m), be it the tsunami crest height above the ground level or the inundation height. Apparently, both $H_{\max}$ and H are physical quantities. Therefore, Papadopoulos and Imamura (2001) remarked that this is a magnitude rather than an intensity scale. Later, Abe (1979, 1981, 1985, and 1989) and Hatori (1986) proposed the tsunami magnitude, M_t, defined by

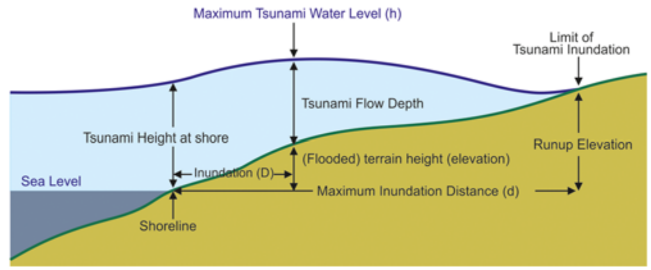

Figure 2. The anatomy and the main characteristics of tsunami. The color version of this figure is available only in the electronic edition.

$$M_t = a \log H + b \log \Delta + D.$$

In the Hatori (1986) equation, H (in m) is the maximum amplitude of tsunami waves measured by tide gauges, Δ is distance (in km) from the epicenter to the tidal station along the shortest oceanic part, and a, b, and D are constants.

Murty and Loomis (1980) introduced a different approach for the calculation of tsunami magnitude, M_L, defined by

$$M_L = 2(\log E - 19),$$

where E is tsunami potential energy (in ergs).

Even though the Shuto (1993) tsunami scale is by definition a magnitude scale, its description for tsunami impact has finally been classified into a six-grade tsunami scale, ranging from 0 to 5 depending on H. More recently, 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. Finally, they obtained a 12-point scale of tsunami intensity analogous to earthquake intensity scales like the EMS_{1998} or Mercalli. EMS_{1998} is a 12-grade scale referring to earthquake effects in several structure types, in particular in: (a) the Timber type, (b) Steel type, (c) Masonry type, and (d) Reinforced concrete (RC) type (Fig. 1). Both 12-grade EMS_{1998} and ESI_{2007} scales are complementary and link contemporary and historical earthquakes (Lekkas, 2010), as well as earthquake effects that are observed in completely different environments, such as urban and semi-urban (Papanikolaou *et al.*, 2009; Lekkas, 2010).

What is New in the New Scale

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

Table 1

Structural Classification of Tsunami Damage

Grade	Timber Structures	Steel Structures	Masonry Structures	Reinforced Concrete Structures
Grade 1	Slight damage. Perimetrical imprints of water level. Slight abrasions. Light objects overturn.	Slight damage. Perimetrical imprints of water level. Slight abrasions. Light objects overturn.	Slight damage. Perimetrical imprints of water level. Slight abrasions on walls. Light objects overturn outwards.	Slight damage. Perimetrical imprints of water level. Slight abrasions on walls. Light objects overturn outwards.
Grade 2	Moderate damage. Extensive external abrasions. Windows break. Decorative elements detachment.	Moderate damage. Extensive external abrasions. Windows break. Decorative elements detachment.	Moderate damage. External erosion. Extensive external abrasions. Windows break. Decorative elements detachment.	Moderate damage. Extensive perimetrical abrasions. Windows break. Decorative elements detachment.
Grade 3	Heavy damage. Walls fracture, roof damage. Doors break. Small deformations.	Heavy damage. Deformation and detachment of frame elements. Doors break.	Heavy damage. Partial wall collapse. Roof damage, tiles are detached, or extensive wall damage from object impact. Doors and shutters break.	Heavy damage. Masonry wall damage. Masonry wall damage due to object impact.
Grade 4	Very heavy damage. Extensive fracture on walls and roof. Detachment and small movement of the construction.	Very heavy damage. Extensive detachment of wall elements. Load bearing structure exposure.	Very heavy damage. Partial building collapse. Partial—total roof collapse.	Very heavy damage. Extensive damage on masonry walls, masonry walls blow up. Reinforced masonry walls suffer damage. Load bearing elements are destroyed, few building collapse.
Grade 5	Destruction. Total fracture and collapse of the construction. Detachment of whole construction and transportation at sufficient distance.	Destruction. Extensive load bearing structure deformation. Buildings are possible to be detached and carried away at great distances.	Destruction. Total collapse of most of the buildings. Debris is carried away. Buildings disappear. Buildings are uprooted.	Destruction. Total destruction of most of buildings. Construction elements are carried away.

1. Physical quantities of the phenomenon (Fig. 2), such as tsunami height on shoreline, inundation, extent of inundated areas, tsunami run-up, tsunami flow depth, and maximum tsunami water level (Bruce *et al.*, 2006; Lekkas, Andreadakis, Alexoudi, *et al.*, 2011; Lekkas, Andreadakis, Kostaki, *et al.*, 2011).
2. Impact on humans, especially on human perception and on human behavior—reaction and human loss. For this category, the criteria of Papadopoulos and Imamura (2001) were mostly used (for intensities I–X), examining perception of the phenomenon for the lower intensities, human reaction and/or loss for the intermediate intensities, and extent of human loss for the higher intensities.
3. Effects on mobile objects, such as vessels, boats, heavy objects, cars and means of transport (Bruce *et al.*, 2006;

Table 2

Relationship between Tsunami Height and Damage Grading of On-land Structures and Buildings

		Maximum Grade of Damage by Vulnerability Class					
$ITIS_{2012}$	Tsunami Height/Tsunami Flow Depth	A	B	C	D	E	F
I	—						
II	—						
III	—						
IV	< 0.5						
V	0.5–1	1	1				
VI	< 1	2	2	1			
VII	1–2	4	3	2	1		
VIII	2–5	5	4	3	2		
IX	5–7	5	5	4	3	2	
X	7–10	5	5	5	4	3	2
XI	< 10	5	5	5	5	4	3
XII	> 10				5	5	5

Figure 3. Estimation of run-up approximately 28 m (tsunami flow depth > 10 m), in the area of Onagawa (Japan, 2011). The area has been totally destroyed and intensity values reached $XII_{ITIS-2012}$. The color version of this figure is available only in the electronic edition.

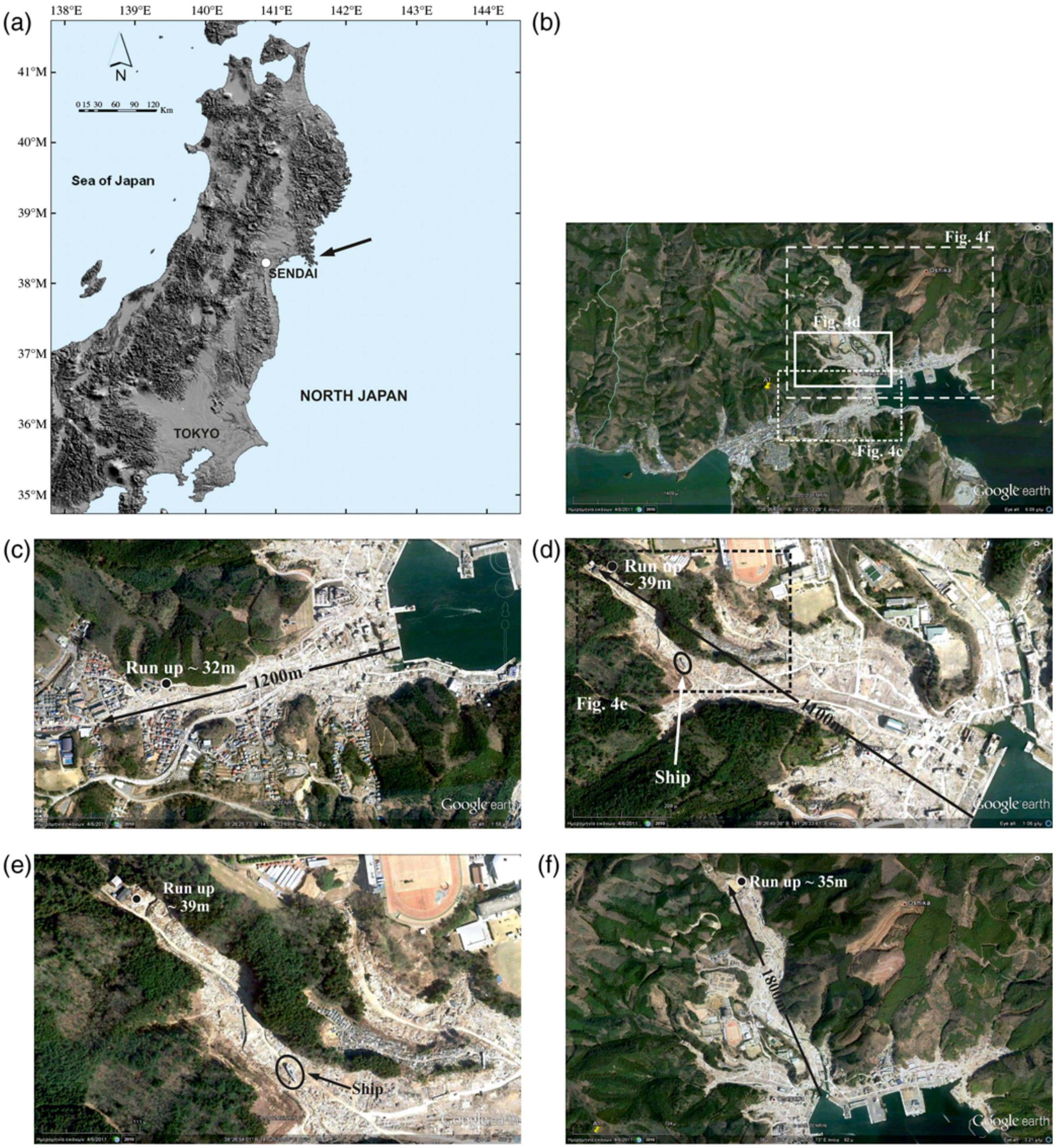

Figure 4. Satellite images of the wider area of Onagawa (northeast Japan). In each image run-up and inundation distances are shown for individual parts of the affected area. The urban area has been totally destroyed and values of intensity reached $XII_{ITIS-2012}$ (Source: Google™Earth). The color version of this figure is available only in the electronic edition.

Rai *et al.*, 2006; Lekkas, Andreadakis, Alexoudi, *et al.*, 2011; Lekkas, Andreadakis, Kostaki, *et al.*, 2011).

4. 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, and industrial installations.
5. Geoenvironmental effects (Parcharidis *et al.*, 2005; Bruce *et al.*, 2006; Andreadakis *et al.*, 2011). In order to classify geoenvironmental effects, ESI_{2007} scale (Michetti *et al.*,

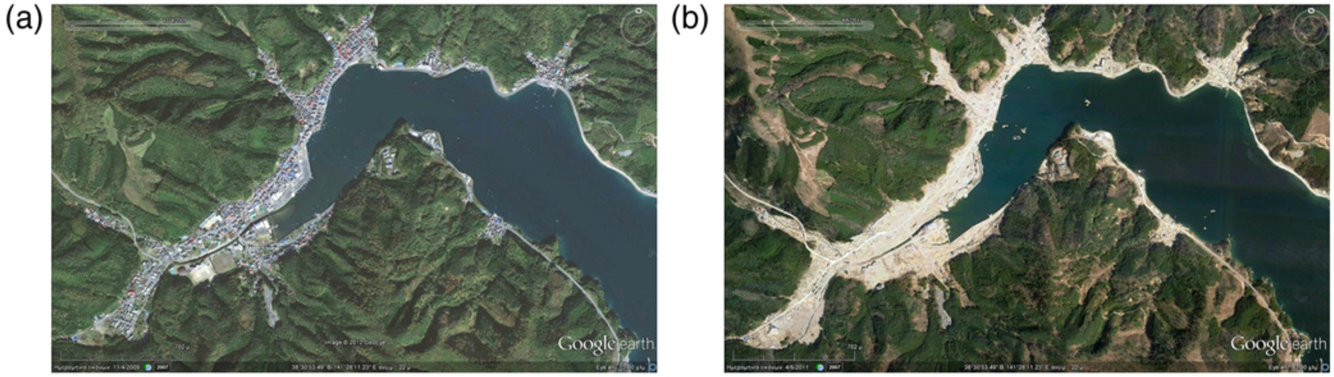

Figure 5. Satellite images showing the Ogatsu bay area (a) before and (b) after the tsunami impact. Values of intensity in the specific area reached $XII_{ITIS\text{-}2012}$. Total destruction of all structures with only a few exceptions of class F buildings is observed. Street layout is hardly visible, apart from main arteries. Despite the relatively high relief, zones of deforestation are very clear around the settlement, up to the run-up elevation. Coastal infrastructure is totally destroyed along zones of the northwest shoreline and all mobile objects are carried away, with many of the boats washed ashore along several hundreds of meters. The color version of this figure is available only in the electronic edition.

2007) was used. Some aspects of ESI_{2007} were used in this particular criteria category, such as uplift or subsidence, morphological alterations, material transport, effects on trees, and so on, whereas other elements, such as tsunami height, were transferred to the physical quantities category of criteria (1). This type of impact can be reliably observed on satellite imagery and especially in comparison to imagery of the affected areas before the event (Andreadakis *et al.*, 2011), which by the way is greatly facilitated by the widely available Google™Earth software. Deforestation, leveling of urban areas, debris accumulation, remnants of street layout, shoreline erosion, and so forth, are all characteristic features of high intensities (especially VIII and higher). Moreover, remote sensing can help processing large areas and define intensity based on the criteria of this category.

6. Effects on structured environment (Ghobarah *et al.*, 2005; Lekkas *et al.*, 2005; Saatcioglou *et al.*, 2006a,b; Scawthorn *et al.*, 2006; Lekkas, Andreadakis, Alexoudi, *et al.*, 2011; Lekkas, Andreadakis, Kostaki, *et al.*, 2011). EMS_{1998} scale (Grünthal, 1998) was used as a basis on which to grade effects on the structured environment. Additionally, classification of damage is referred (Grade 1–5) for each structure type (Table 1). The type and grade of damage, recorded as earthquake effects, were adjusted to the damage observed at the two great tsunami events of 2004 and 2011, in which a very great number of cases of damage of every building type were observed. In addition, in some cases, vulnerability grading was altered (Fig. 1). For example, vulnerability of steel-type structures was downgraded, as this particular type has proven 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 three definition levels of quantity (few, many, or most). In Table 2, maximum grade of damage by vulnerability class is shown for all intensity values and respective tsunami heights. Tsunami intensities I to IV cause very little or no damage to all vulnerability-class structures. Maximum grade, at least for some buildings, is observed at intensity VIII (tsunami height 2–5 m) for class A, at intensity IX

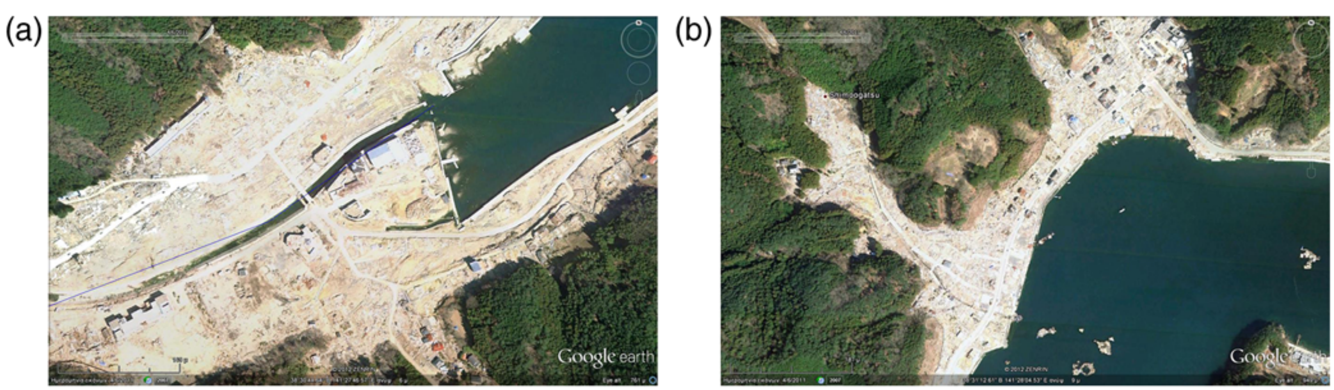

Figure 6. Parts of the Ogatsu bay area after the tsunami impact where details of the grade of impact, as described previously, are more clearly visible. Values of intensity in the specific area reached $XII_{ITIS-2012}$. The color version of this figure is available only in the electronic edition.

Table 3
The New Tsunami Intensity Scale (ITIS-2012)

	Quantities	Impact on Human	Impact on Mobile Objects	Infrastructure	Environment	Structures
I—Not felt	No effect	Not felt, even under the most favorable circumstances	No effect	No effect	No effect	No damage
II—Slightly felt	No effect	Felt only by few people on board small vessels. Not noticed onshore.	No effect	No effect	No effect	No damage
III—Weak	No effect	Felt by many people on board on small vessels. Noticed by a few people onshore.	No effect	No effect	No effect	No damage
IV—Largely observed	Tsunami height or tsunami flow depth of a few cm.	Felt by most people on board small vessels. Felt only by few people on board large vessels and by many people onshore.	Some small vessels wiggle or move towards the coast.	No effect	No effect	No damage
V—Strong	Tsunami height or tsunami flow depth of several cm to dm (0.5 m). Limited onshore areas inundated.	Felt by most on board big vessels and people onshore. Some people panic and run for higher ground.	Many small vessels get washed on the shore and many offshore collide with one another.	No effect	No effect	Damage of grade 1 to a few buildings of vulnerability classes A and B
VI—Slightly damaging	Tsunami height or tsunami flow depth of some dm (<1 m). Small onshore areas are flooded.	Many people panic and run for higher ground.	Many small vessels are washed out violently or collide with each other or are overturned along the shoreline. Cars are uplifted and moved.	No effect	Marginal turbulence in coastal sediments.	Damage of grade 1 is sustained by many buildings of vulnerability classes A and B; a few of classes A and B suffer damage of grade 2; a few of class C suffer damage of grade 1
VII—Damaging	Tsunami height or tsunami flow depth usually higher than 1 m. Small onshore areas are flooded.	Most people panic and run for higher ground.	Many small vessels suffer damage. Bigger vessels are shaken violently or collide with one another. Most cars are carried away.	A few makeshift facilities on coastline are washed away.	Garbage and debris on parts of the shoreline. Limited erosion. Deposition of sand and pebbles in coastal areas.	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.

(*continued*)

Table 3 (*Continued*)

	Quantities	Impact on Human	Impact on Mobile Objects	Infrastructure	Environment	Structures
VIII—Heavily damaging	Tsunami height or tsunami flow depth higher than 2 m. Limited onshore areas are flooded. Limited inundation along coastline.	Most people run for higher ground. Many are washed away.	Many small vessels suffer damage. Bigger vessels are washed out or collide with each other. Heavy objects are moved. Cars are washed away.	Many makeshift facilities along the coastline are washed away.	Erosion, garbage, and debris along the shoreline. Some bushes or trees are uprooted and get carried away small distances.	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.
IX—Destructive	Tsunami height or tsunami flow depth of a few m (<5). Wide areas are inundated along the shoreline. Tsunami run-up or maximum tsunami water level of some m, whereas maximum inundation distance reaches some hundreds of m, depending on coastal morphology.	Many people are washed away.	Most vessels are destroyed or sunk. Many bigger vessels are washed out and some are destroyed. Cars are being washed away. Fires break out along the shore.	Most makeshift facilities along the coastline are washed away. Little damage on offshore backfilling.	Depending on the topography and the kind of coastal formations, limited coastal profile changes with erosion and material deposition take place. Garbage and debris deposition along the shoreline. Uprooting of bushes and some trees.	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.
X—Very destructive	Tsunami height or tsunami flow depth of many m (<7). Tsunami run-up or maximum tsunami water level reaches or exceeds 10 m, whereas maximum inundation distance reaches some hundreds of m, depending on coastal morphology.	General panic. Most people are washed away.	Most big vessels are washed out and many are destroyed due to impact on the shoreline and buildings. Cars overturn and are washed away.	Little damage to quays and port facilities. Damage to objects at port facilities. Small failures to anti-erosional works on the shoreline.	Depending on the profile of offshore and onshore area, notable changes on 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 out.	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.

(*continued*)

Table 3 (*Continued*)

	Quantities	Impact on Human	Impact on Mobile Objects	Infrastructure	Environment	Structures
XI—Devastating	Tsunami height or tsunami flow depth of many m (<10 m). Tsunami run-up or maximum tsunami water level exceeds 15 m, whereas maximum inundation distance exceeds 1 km, depending on coastal morphology.	Extensive human loss.	Extensive fires break out. Heavy objects are washed away. Boats are washed hundreds of m onshore. Most cars are washed away or destroyed.	Breakwaters are damaged. Failures of anti-erosion works on the shoreline. Damage on the roads near the coastline. Great damage to onshore lifelines. Damage to cranes and other port facilities. Tanks in port facilities are moved. Railways suffer damage. Many riprap boulders are detached and moved. Some industrial facilities are damaged.	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 out.	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—Completely devastating	Tsunami height or tsunami flow depth exceeds 10 m. Run-up or maximum tsunami water level reaches many tens of m and maximum inundation distance some km. Areas of some tens of km^2 are inundated.	Extensive human loss in wide areas.	Boats are moved to high elevation. Cars, trains, etc., are washed away or destroyed.	Great damage in all port works such as jetties, marine breakwaters, port facilities, cranes, onshore lifelines. Riprap blocks are detached and moved great distances.	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 to great distances. Massive pollution from oil and chemicals. Extensive fires break out.	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.

(tsunami height 5–7 m) for class B, and at intensity X (tsunami height 7–10 m) for class C. Grade 5 is only observed at intensity XII (tsunami height >10 m) for classes D, E, and F, whereas all other buildings (classes A, B, and C) are totally destroyed.

Description of the New Scale

The newly proposed scale is 12-grade and it is based on the assessment of numerous and more objective criteria evaluating easily accessible data that are classified in six categories. For every grade, the six categories of criteria are described accordingly (1–6):

1. Quantities of the phenomenon (wave height, inundation, run-up, etc.; Figs. 3 and 4; Ⓔ Fig. S1, available in the electronic supplement to this article).
2. Impact on human environment (human perception, reaction, and behavior in general).
3. Impact on moving objects (small vessels, boats, heavy objects, cars, etc.; Ⓔ Figs. S2, S3, S4, S5, and S6, available in the electronic supplement to this article).
4. Impact on infrastructure (marine installations, anti-erosion works, ports, industry, etc.; Fig. 5; Ⓔ Figs. S7, S18, and S22, available in the electronic supplement to this article).
5. 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; Figs. 5 and 6; Ⓔ Figs. S18, S19, S20, S21, and S22, available in the electronic supplement to this article).
6. Impact on structured (e.g., urban) environment (all sorts of structures) on the basis of the EMS_{1998} scale classification (Ⓔ Figs. S8, S9, S10, S11, S12, S13, S14, S15, S16, and S17, available in the electronic supplement to this article).

The characteristics for each of the twelve grades of the new scale are described in Table 3.

Conclusions

The main characteristics of the new tsunami intensity scale are:

1. The scale is based on six different criteria, more than any other existing scale and allows for horizontal correlation between criteria in every intensity grade.
2. There is a gradual increase of the intensity grades, which is observable in all six criteria categories with concurrent clear boundaries between grades.
3. Quantities are easily measured. Objective criteria outnumber subjective criteria.
4. Evidence and grading is based on field work data and particular damage types and not on theoretical data. In addition, photographic evidence and satellite imagery allow for easy data assessment.
5. The new intensity scale is fully compatible with EMS_{1998} and ESI_{2007} seismic intensity scales.
6. Covers all diverse land use type areas, such as agricultural, natural, ports, urban, and a variety of different infrastructure and protection facilities/works.
7. Application of the scale and area microzonation in smaller areas is easier with the use of remote sensing techniques.
8. A 12-grade scale is more accurate and does not saturate, as six-grade scales do.

Data and Resources

All data used in this paper came either from field work and processing by the authors for both 2004 and 2011 tsunami events, or from published sources listed in the references and imagery from Google™Earth.

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Professor of Dynamic Tectonic Applied Geology
Faculty of Geology and Geoenvironment
University of Athens, Greece
Panepistimioupoli Zografou
Athens 15784, Greece
elekkas@geol.uoa.gr
(E.L.L.)

Geologist, MSc Faculty of Geology and Geoenvironment
University of Athens, Greece
Panepistimioupoli Zografou
Athens 15784, Greece
eandreadk@geol.uoa.gr
kostakirene@gmail.com
elkap@geol.uoa.gr
(E.A., I.K., E.K.)

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