A proposal for a new tsunami intensity scale

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Abstract. Since the introduction of a primitive tsunami intensity scale by Sieberg (1927) several further attempts were made to quantify tsunamis, like those of Imamura (1942), Iida (1956), and Ambraseys (1962). However, the proposed scales suffered either from lack of detailed description of the intensity grades or from confusion between real intensity or magnitude scales, a problem discussed by Soloviev (1970) and Murty and Loomis (1980) and examined in more detail by Shuto (1993). The lack of a detailed, real tsunami intensity scale creates serious problems in the standardization of descriptions of tsunami effects and their comparison from site to site and from case to case. Following the long seismological tradition we propose the establishment of a new, 12-grade tsunami intensity scale based on the following principles: (a) *independence* from physical parameters like wave amplitude (or height) in the source and in the coast; (b) *sensitivity*, that is, incorporation of an adequate number of grades to describe even small differences in tsunami effects; and (c) a *detailed description* of each intensity grade by considering all possible impacts on the human and natural environment and vulnerability of structures.

1. Introduction

Efforts toward a quantification of tsunamis started about 75 years ago by the pioneering work of Sieberg (1927). However, tsunami quantification is still a puzzling aspect in tsunami research since the several scales proposed to measure tsunami size often are confusing regarding the quantity they represent: intensity, magnitude, or a mixture of them? In fact, from a short review that we present in the next section, it results that only very few of the proposed scales are real tsunami intensity scales. Others have been considered as being intensity scales while they are either magnitude scales or a mixture of intensity and magnitude. We show the general need to construct pure tsunami intensity scales, established on standard principles and on modern well-elaborated criteria. Then we proceed first with the description of the basic principles and second with the proposal of a new twelve-grade tsunami intensity scale which is open for further discussion.

2. Quantification of Tsunamis: A Review

2.1 Intensity and magnitude of earthquakes

Results from seismological experience (e.g., see Bullen and Bolt, 1985) show that field investigations of earthquakes yield macroseismic data that supplement the data obtained from seismographs. The macroseismic data reveal broad features of the variation in the intensity of an earthquake over the

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affected area. This "intensity" is not capable of simple quantitative definition, and is estimated by reference to "intensity scales" that describe the effects in qualitative terms. On the other hand, the Richter scale as well as other earthquake magnitude scales are completely independent from any kind of macroseismic effects being quantitatively defined solely on the basis of physical parameters like the amplitude and duration of the recorded seismic motion or the seismic moment in the source of the earthquake event. Efforts have been made to associate the divisions in the seismic intensity scales with accelerations of the local ground shaking or even with earthquake magnitudes. However, such associations are not included by definition in the concept of seismic intensity.

As a conclusion, the earthquake magnitude is an objective physical parameter that measures either energy radiated by, or moment released in, the earthquake source and does not reflect macroseismic effects. On the contrary, the earthquake intensity is a rather subjective estimate of the macroseismic effects. In every earthquake event only one magnitude on a particular scale corresponds. However, every earthquake is characterized by different intensities in different locations of the affected area. Okal (1988) showed that source depth and focal geometry play only a limited role in controlling the amplitude of the tsunami, and that more important are the effects of directivity due to rupture propagation along the fault and the possibility of enhanced tsunami excitation in material with weaker elastic properties, such as sedimentary layers. Therefore, a tsunami can be considered as a particular case of seismic wave and problems related to tsunami quantification could be approached in analogy to seismology.

2.2 Proposed scales of tsunami intensity and magnitude

Sieberg (1927) is very likely the first to present a six-grade tsunami intensity scale which, in analogy to earthquake intensity scales, was based not on the measurement or estimation of a physical parameter, e.g., wave height, but it was established on the description of tsunami macroscopic effects, like damage, etc. Ambraseys (1962) published a modified version of Sieberg's scale. In the Japanese tsunami literature one may find a long tradition of effort toward tsunami quantification. Imamura (1942, 1949) introduced and Iida (1956, 1970) and Iida *et al.* (1967) developed further the concept of tsunami magnitude, m, defined as

$$m = \log_2 H_{\max} \tag{1}$$

where H is the maximum tsunami wave height (in m) observed in the coast or measured in the tide gages. Practically, the so-called Imamura-Iida scale is a six-grade scale ranging from –1 to 4, giving the impression of intensity rather than a magnitude scale. In fact, Soloviev (1970, p. 152) stated that "*If seismological terminology is applied to description of tsunamis, the grades of the Imamura-Iida scale must be designated as the intensity of the tsunami and not the magnitude of it... If the seismological terminology is not desired, then the term 'magnitude' for grades of this scale is quite acceptable,*" and finally he adopted the term "*intensity of tsunamis*" for the tsunami size measured by the Imamura-Iida scale. However, the quantity defined by the Imamura-Iida scale represents magnitude because it does not estimate effects but by definition it measures $H_{\max}$, that is, a physical quantity. In his attempt to improve Imamura-Iida's definition, Soloviev (1970) proposed to define tsunami intensity, i_s, by

$$i_s = \log 2\sqrt{2}(H) \tag{2}$$

where H (in m) is the mean tsunami height in the coast. However, this is still a magnitude scale since it is also based on a physical quantity like H. Tsunami magnitude $\mathrm{M_t}$ (Abe, 1979, 1981, 1985, 1989) or m (Hatori, 1986) was defined by the general form

$$\mathrm{M_t} = a \log H + b \log \Delta + D \tag{3}$$

where H = maximum single (crest or trough) amplitude of tsunami waves (in m) measured by tide gages, Δ is the distance (in km) from the earthquake epicenter to the tide station along the shortest oceanic path (in km), and a, b, and D are constants. Equation (3) is similar to that used since the 1960s in seismology for the measurement of the surface-wave earthquake magnitude. A different approach for the calculation of the tsunami magnitude was introduced by Murty and Loomis (1980). Their tsunami magnitude, ML, is defined by

$$\mathrm{ML} = 2(\log E - 19) \tag{4}$$

where E is the tsunami potential energy (in ergs).

A particular case of scale measuring tsunami size is that proposed by Shuto (1993) who considered it as an intensity scale:

$$i = \log_2 H \tag{5}$$

where H is the local tsunami height (in m). Obviously it is still a magnitude scale. However, in order to use it as an intensity scale for tsunami damage description, Shuto (1993) proposed to define H according to its possible impact; in this sense H is taken as the tsunami crest height above the ground level at the shoreline for the tsunami profile and damage to fishing boats, H is the inundation height for damage to an individual house and effectiveness of the tsunami control forest, and H is the maximum tsunami crest height above m.s.w. level at the raft location for damage to an aquaculture raft. Finally, a six-grade classification of tsunami effects ranging from 0 to 5 is tabulated for the description of the expected damage or destruction as a function of H.

The tsunami intensity scale proposed by Sieberg (1927) and modified by Ambraseys (1962) is a six-grade scale constructed in such a way that its divisions are not detailed enough and certainly do not incorporate the experience gained from the impact of large destructive tsunamis occurring in the last decades. Shuto (1991) reviewed more completely and effectively the possible tsunami disasters including impact on human lives, damage to houses and coastal structures, traffic hindrance, lifelines, fishery, commerce and industry, agriculture, forest, fire, oil spill, and topography changes. Shuto's (1993) tsunami scale based on (5) is by definition a magnitude scale because H is simply a physical parameter. On the other hand, its description of tsunami impact is a six-grade tsunami intensity scale, ranging from 0 to 5, the divisions of which, however, is a function of H, that is, the overall approach is an unusual mixture of magnitude and intensity. Apparently, Shuto (1993) tried to produce a predictive tool that describes expected tsunami impact as a function of H, rather than to create a new tsunami intensity scale describing tsunami effects independently from physical parameters that control the type and extent of the effects.

3. Basic Principles for the Establishment of a New Tsunami Intensity Scale

The lack of a pure tsunami intensity scale with a detailed description of its divisions that incorporate recent experience from large, catastrophic tsunamis of the Pacific Ocean creates serious problems in the standardization of the estimation of the tsunami effects, as well as in the comparisons of the effects from site to site for a given tsunami and from case to case for different tsunami events. Following the long seismological experience we propose the establishment of a new tsunami intensity scale based on the following basic principles: (a) *independence* from any physical parameter, like the measured or macroscopically observed wave amplitude (or height) in both the tsunami source and the coast affected, or the duration of the seawater disturbance in any observation point; (b) *sensitivity*, that is, incorporation of an adequate number of divisions (or grades) in order to describe even small differences in tsunami effects; and (c) a *detailed description* of each intensity division by taking into account all possible tsunami impacts on the human and natural environment, the vulnerability of structures, etc., on the basis of recent experiences from large, catastrophic tsunamis from the Pacific Ocean.

4. A New Tsunami Intensity Scale

The new tsunami intensity scale proposed here incorporates twelve divisions and is consistent with the several twelve-grade seismic intensity scales established and extensively used in Europe and North America in about the last 100 years. The new scale is arranged according to (a) the effects on humans; (b) the effects on objects, including vessels of variable size, and on nature; and (c) damage to buildings.

I. Not felt

(a) Not felt even under the most favorable circumstances.

(b) No effect.

(c) No damage.

II. Scarcely felt

(a) Felt by few people onboard small vessels. Not observed on the coast.

(b) No effect.

(c) No damage.

III. Weak

(a) Felt by most people onboard small vessels. Observed by few people on the coast.

(b) No effect.

(c) No damage.

IV. Largely observed

(a) Felt by all onboard small vessels and by few people onboard large vessels. Observed by most people on the coast.

(b) Few small vessels move slightly onshore.

(c) No damage.

V. Strong

(a) Felt by all onboard large vessels and observed by all on the coast. Few people are frightened and run to higher ground.

(b) Many small vessels move strongly onshore, few of them crash into each other or overturn. Traces of sand layer are left behind on ground with favorable conditions. Limited flooding of cultivated land.

(c) Limited flooding of outdoor facilities (e.g., gardens) of near-shore structures.

VI. Slightly damaging

(a) Many people are frightened and run to higher ground.

(b) Most small vessels move violently onshore, crash strongly into each other, or overturn.

(c) Damage and flooding in a few wooden structures. Most masonry buildings withstand.

VII. Damaging

(a) Most people are frightened and try to run to higher ground.

(b) Many small vessels damaged. Few large vessels oscillate violently. Objects of variable size and stability overturn and drift. Sand layer and accumulations of pebbles are left behind. Few aquaculture rafts washed away.

(c) Many wooden structures damaged, few are demolished or washed away. Damage of grade 1 and flooding in a few masonry buildings.

VIII. Heavily damaging

(a) All people escape to higher ground, a few are washed away.

(b) Most of the small vessels are damaged, many are washed away. Few large vessels are moved ashore or crash into each other. Big objects are drifted away. Erosion and littering in the beach. Extensive flooding. Slight damage in tsunami control forest, stop drifts. Many aquaculture rafts washed away, few partially damaged.

(c) Most wooden structures are washed away or demolished. Damage of grade 2 in a few masonry buildings. Most RC buildings sustain damage, in a few damage of grade 1 and flooding is observed.

IX. Destructive

(a) Many people are washed away.

(b) Most small vessels are destroyed or washed away. Many large vessels are moved violently ashore, few are destroyed. Extensive erosion and littering of the beach. Local ground subsidence. Partial destruction in tsunami control forest, stop drifts. Most aquaculture rafts washed away, many partially damaged.

(c) Damage of grade 3 in many masonry buildings, few RC buildings suffer from damage grade 2.

X. Very destructive

(a) General panic. Most people are washed away.

(b) Most large vessels are moved violently ashore, many are destroyed or collide with buildings. Small boulders from the sea bottom are moved inland. Cars overturned and drifted. Oil spills, fires start. Extensive ground subsidence.

(c) Damage of grade 4 in many masonry buildings, few RC buildings suffer from damage grade 3. Artificial embankments collapse, port water breaks damaged.

XI. Devastating

(b) Lifelines interrupted. Extensive fires. Water backwash drifts cars and other objects in the sea. Big boulders from the sea bottom are moved inland.

(c) Damage of grade 5 in many masonry buildings. Few RC buildings suffer from damage grade 4, many suffer from damage grade 3.

XII. Completely devastating

(c) Practically all masonry buildings demolished. Most RC buildings suffer from at least damage grade 3.

5. Correlation Between Intensity and Wave Height

As already explained, the definition of an intensity scale does not rely on physical parameters of the natural event but only on observations regarding the degree of impact of the event. For example, earthquake intensity scales are not arranged on the basis of ground velocities or accelerations or other physical characteristics of the earthquake. It is of interest, however, to correlate intensity degrees (or domains) with parameters like ground acceleration. In this sense it is of interest to establish possible correlations between the domains of a tsunami intensity scale with physical parmeters like the single wave height. Such correlations, however, are meaningless under particular conditions. For example, even the highest tsunami wave that attacks a uninhabited coastal region produces the lowest intensity. On the contrary, the tsunami intensity may reach a high degree in a vulnerable coastal region even with a moderate tsunami. Therefore, in Table 1 we use formula (5) of Shuto (1993) and provide a rough correlation between the domains, I, of the intensity scale proposed with the tsunami height, H, keeping in mind that it could be practically useful only under certain conditions. For reasons of comparison we also list the quantity, i, proposed by Shuto (1993) as it calculated from (5).

6. Conclusions and Perspectives for Future Research

From the existing scales for the quantification of tsunamis only a very few are real intensity scales. However, they do not incorporate an adequate number of divisions and a detailed description of the several types of tsunami damages and other effects. Therefore, we propose a new tsunami intensity scale. The scale proposed is new in that it is detailed enough by incorporating twelve divisions, it is arranged by taking into account the several types of damages and other effects caused by several large tsunamis occurring in the

Table 1: Possible correlation between the intensity domains, I, proposed here and the quantities H and i introduced in formula (5) by Shuto (1993).

I **(intensity proposed)**	***H*** **(m)**	***i***
I–V	<1.0	0
VI	2.0	1
VII–VIII	4.0	2
IX–X	8.0	3
XI	16.0	4
XII	32.0	5

last decades, and it is constructed following the long seismological experience gained in about the last 100 years according to which intensity scales are constructed solely on the basis of the damages and other effects, that is, independently from any kind of physical parameter that may control the damages.

The new tsunami intensity scale is certainly open for discussion and improvement. Even in its present version, however, it yields possibilities to reexamine the fields of impact of past characteristic tsunamis, to draw tsunami intensity maps, to compare maps for different tsunamis, and to try to correlate tsunami intensity distributions with a number of physical parameters that may control the tsunami impact. Moreover, a very good opportunity emerges for the impact of the next tsunamis to strike to be described by maps based on the new intensity scale, thus testing the efficiency of the scale and possible aspects for its improvement.

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