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ORIGINAL PAPER

Classification of Tsunami and Evacuation Areas

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Abstract On March 11, 2011, a large earthquake that occurred offshore the north-east coast of Japan generated a large tsunami which devastated extensive areas of the Tohoku coastline. Despite Japan being considered a country well prepared for these types of disasters, large casualties were recorded, with numerous discussions amongst the Japanese coastal engineering community ensuing. As a result, two different levels of tsunamis have been proposed and now recognized in Japan, depending on the frequency of such extreme events. The idea that hard measures can protect the lives of inhabitants of coastal areas has been abandoned, and these measures are only considered to be effective in protecting properties against the more frequent but lower magnitude events. Soft measures should always be used to protect against the loss of lives, and to this respect, the authors of the paper propose the introduction of a Classification of Evacuation Areas, to show which of these should be prioritized by residents as they seek to evacuate.

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1 Introduction

On March 11, 2011, a large earthquake of magnitude 9.0 on the Richter scale occurred offshore the north-east coast of Japan. This very strong earthquake generated a major tsunami which devastated large parts of Japan's north-eastern coastline, inundating over 400 km^2 of land, and causing large numbers of casualties. On the Sendai Plain, the maximum inundation height was 19.5 m, and the tsunami propagated as a bore for around 4–5 km inland. The maximum run-up height was 40.4 m, making it the third world's large scale tsunami in the last 10 years (Tohoku Earthquake Tsunami Joint Survey Group 2011). Surveys in Tohoku region began on March 25, after the completion of major search and rescue operations (Mori et al. 2012), though the entire length of the affected coastline was eventually covered, including Hokkaido (Watanabe et al. 2012), Iwate Prefecture (Ogasawara et al. 2012; Shimozono et al. 2012), and Miyagi Prefecture (Suppasri et al. 2012; Kakinuma et al. 2012; Mikami et al. 2012). From these surveys, many kinds of destruction patterns were identified. Buildings, including many well-engineered reinforced concrete structures, were washed away or suffered extensive damage, while numerous ships, as well as large boats, were left stranded inland. Coastal protection works such as dikes, tsunami walls, breakwaters, and coastal forests also suffered heavy damage. Historically, this was one of the worst tsunamis that affected Japan since records began. Past tsunamis which affected the Sanriku Coast have been recorded in Japanese history for over 1,000 years, and five major destructive ones are all well documented in this region (Watanabe 1985). These are known as the Jogan (869), Keicho (1611), Meiji-Sanriku (1896), Showa-Sanriku (1933), and Chile (1960) tsunamis and will be referred to in this way in the present article.

In fact, the 2011 *Great Eastern Japan Earthquake and Tsunami* has been described as a one in 1,000 years event, resembling thus the Jogan Tsunami which occurred in A.D. 869 (Sawai et al. 2006). The description of the Jogan Tsunami only appears on a historical document known as the Sandai-Jitsuroku. The Jogan Tsunami flooded a wide swath of the coastal area of Tohoku, and approximately 1,000 people were reported to have drowned. There is no other record about the Jogan Tsunami, and hence, information regarding this event is rather limited. However, some tsunami deposits found in sediment layers in the Sendai Plain, as well as along the Sanriku Coast, have allowed researchers to gradually identify the area inundated by this tsunami (Minoura et al. 2001). Since the Edo Era (1603∼), the number of tsunami records increased substantially. The Keicho Tsunami (1611), which attacked a wide swath of the coastal area from Hokkaido to Sanriku, was one of the most destructive tsunamis in the Edo Era. In Tohoku, waves travelled up to 4 km inland and caused significant damage to the region (Sawai et al. 2006). Since the Meiji Era (1868∼), the Sanriku Coast experienced three major tsunamis. Two of them were near-shore generated tsunamis, while the other was a tsunami generated by a distant source. The first of these three tsunamis is known as the Meiji-Sanriku Tsunami, which caused the loss of 22,000 lives. Although the magnitude of the generating earthquake was not extreme, the maximum tsunami height reached up to 20 m. The second tsunami is called Showa-Sanriku Tsunami and caused 3,000 deaths along the Sanriku coastline. The third event is the 1960 Chile Tsunami, which was triggered by an earthquake in Chile with a 9.5

magnitude on the Richter scale. This tsunami caused heavy damage all around the Pacific Rim, including the Sanriku Coast of Japan, where over 100 casualties were reported.

As a consequence of the *Great Eastern Japan Earthquake and Tsunami*, it is necessary that the Coastal Disaster Management in Japan be revised to take into account the lessons learned from this, as well as other past disasters. These lessons will affect the theoretical, philosophical, and moral underpinning of the Japanese coastal disaster management framework. In this article, the authors attempt to describe how, following this event, a number of new ideas related to the classification of tsunami events and Evacuation Areas have started to enter the coastal engineering terminology. This tsunami classification in fact is not the authors' own, but the product of many intensive discussions amongst the coastal engineering community in Japan, including not only academics and engineers but also government officials. While some of these concepts might not be without their problems, they do represent a terminology widely employed by a majority of stakeholders in the Japanese coastal management and risk disaster management community. The authors thus feel that it is important to share these concepts with the wider international management communities. These ideas, while simple, have profound implications to the development of risk management strategies in Japan. Indeed, the 2011 *Great Eastern Japan Earthquake and Tsunami* was the first time when modern and well-developed tsunami countermeasures faced an extreme event (Tohoku Earthquake Tsunami Joint Survey Group 2011). The fact that many lives were lost makes it imperative that tsunami disaster management attempts to move forward and develop new strategies to deal with these events in the future.

2 The 2011 Great Eastern Japan Earthquake and Tsunami

Buildings, including reinforced concrete buildings, were washed away or suffered extensive damage as a consequence of the tsunami inundation. The tsunami also significantly damaged breakwaters, coastal dikes, seawalls, quay walls, and coastal forests (Mikami et al. 2012). Even breakwaters specifically designed to protect against tsunami were either damaged or completely destroyed, such as those in Kamaishi or Ofunato. In order to comprehensively record tsunami inundation and impacts along the coastal regions affected, the 2011 Tohoku Earthquake Tsunami Joint Survey Group was immediately organized following this disaster. This survey group constituted probably the largest ever assembled tsunami survey team, composed of academics, engineers, and government officials from various institutions throughout Japan. Forty-eight different teams were assembled from the Japanese Coastal Engineering Committee, totalling almost 300 individuals from 64 different universities/institutes (Tohoku Earthquake Tsunami Joint Survey Group 2011). However, survey groups were also formed in cooperation with prefectural and local authorities such that it can be concluded that more data has been collected for this event than for any other one such event in the history of Japan. Much of this information can be accessed on the Tohoku Earthquake Tsunami Joint Survey Group website (2011).

As a part of the larger 2011 Tohoku Earthquake Tsunami Joint Survey Group, the authors of this article conducted several field surveys in Iwate, Miyagi, Fukushima, Ibaraki and Chiba Prefectures. The inundation heights measured were found to be in the range of more than 10 m in the northern part of Miyagi Prefecture, 5–10 m along the coast of Sendai Bay and around 5 m along the shores of Ibaraki and Chiba Prefectures. Figure 1 shows the points that were surveyed along the coast by the authors and the Joint Survey Group, along with the inundation and run-up heights at each location.

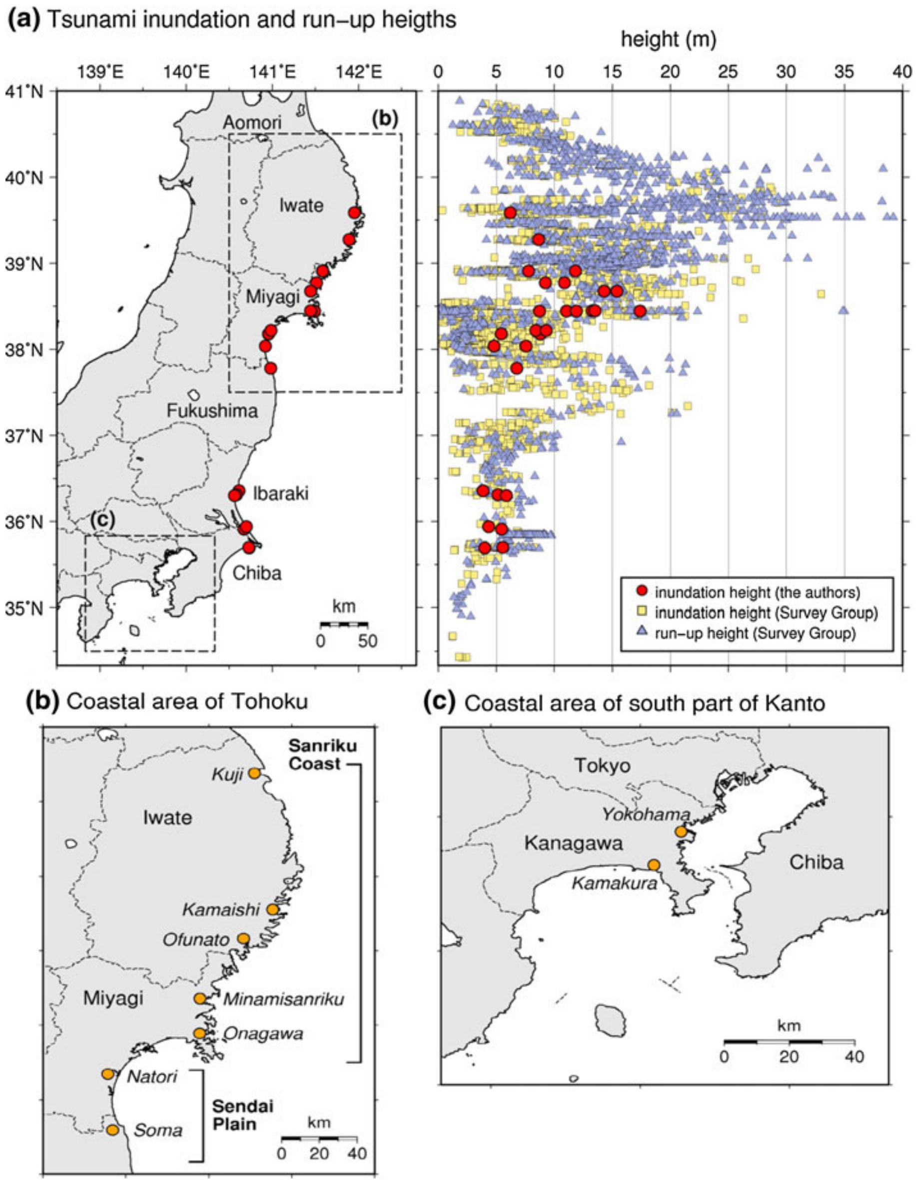

Fig. 1 Tsunami inundation and run-up height at different points along the coast surveyed by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (release 20120330, http://www.coastal.jp/ttjt/) and the location of the places mentioned in this paper

3 Classification of Tsunami Events

The recent distinction between different levels of tsunami events actually has its origin in discussions that have taken place within the Japanese disaster management community for a number of years. Indeed prior to the 2011 *Great Eastern Japan Earthquake and Tsunami,* there was already much debate amongst the Japanese coastal engineering and coastal zone management community of whether hard measures (such as breakwaters or dikes) are preferable over soft measures (such as tsunami warning systems and evacuation plans). The March 2011 event re-ignited this debate, which is obviously still ongoing. Nevertheless, some consensus has already emerged from this debate, centred around the idea that tsunamis should be classified into two different levels, and this terminology has entered into widespread use by the coastal engineering community in Japan after March 2011. This was evident during the Coastal Structures Conference in October 2011 in Yokohama, where these terms were widely used by Japanese coastal engineers, yet they were unknown until then by engineers in other countries. It is important to note that this classification is based on the frequency of these extreme events, and that the exact period of return of each of the events has yet to be fixed. The two proposed levels would be

- Level 1 Events (Tsunami Protection level). These would represent events with a return period of several decades to 100+ years—literally the Japanese expression which has been used in coastal engineering discussions would translate as a return period from 50–60 to 150–160 years. These tsunamis would generate relatively low inundation depths, typically less than 7–10 m.
- Level 2 Events (Tsunami Evacuation level). These, on the other hand, would be far rarer events, typically taking place at intervals between every few hundred and a few thousand years apart. The tsunami inundation depths would be much bigger, typically over 10 m, but would encompass inundations of up to 20–30 m. It is clear that both the 2004 Indian Ocean and the 2011 *Great Eastern Japan Earthquake and Tsunami* would fall within this category.

It is important to understand that a certain event might constitute a Level 2 events for a certain area or country, yet only a Level 1 events for others. For example, the March 2011 Tsunami could be catalogued as a Level 2 events for most of the areas it hit in Japan, though the waves that reached Chile would have represented only a Level 1 events. Exactly what tsunami wave height would constitute each of the levels would also depend on the local geographical characteristics of the area. For the case of the Ria coastline in Tohoku, for example, many of the tsunami defences had been built with a 2–10 m tsunami inundation depths in mind, and it is clear that for that coastline, a tsunami lower than that height would have been a Level 1 events. However, certain areas in Japan (such as the coast of Sanriku or parts of Iwate Prefecture) appear to be prone to hits by large tsunami waves, and hence, even large waves would only constitute a Level 1 events due to the frequency with which they occur. Hence, the classification of a Level 1 or 2 events would be different even for the north or south parts of the Tohoku coastline. Thus, this classification into Level 1 or 2 events is not without its problems. Also, this classification includes the far rarer events (such as large meteorite impacts or underwater landslides) as Level 2 events. These events are of course much rarer and occur 1 in 100,000 years or more, but can cause devastating inundations. Nevertheless, somehow these fall outside the scope of coastal engineering and would be better dealt using satellite or telescope technologies to predict them days in advance so that the population can evacuate to higher areas. Though it could be argued that these events should be included under a different category (a Level 3-type event?) in the present paper, the authors would not like to deviate from the consensus classification so far agreed in Japan, as it has already taken significant time and extensive discussions amongst many specialists in the field.

The debate on hard and soft measures has used these concepts to try to understand when it would be advisable to use each type of measure: in this respect, experts in Japan appear also to be reaching consensus on many points. Essentially, the idea that hard measures can *always* protect against the loss of life has been discarded. The function of coastal structures would thus be to attempt to protect property against Level 1 events. Soft measures, on the other hand, would be used to protect lives and be designed with Level 2 events in mind. The cost of using hard measures for tsunami protection is often significant, and their effectiveness is not clear and seems to have been relatively low for massive tsunamis that exceed the design height of the structures, such as the 2011 *Great Eastern Japan Earthquake and Tsunami*. Future construction of hard measures should only proceed after it has been established that they make sense from a cost-benefit point of view, especially considering that they will only be expected to prevent damage to property and coastal infrastructure and help the evacuation process. At present, it is unclear to what extent hard measures contributed to the alleviation of the effect of the tsunami, particularly given the extensive (often catastrophic) damage that they suffered. A preliminary assessment carried out in front and behind of the Kamaishi Bay mouth breakwater appears to show that the structure could have contributed to reducing inundation depths by around 40–50 %, though much more research is needed to ascertain this with accuracy [using data from the Tohoku Earthquake Tsunami Joint Survey Group and PARI (2011)]. For the more extreme tsunami events, however, hard measures would be completely meaningless and would not contribute to any alleviation of the tsunami impact, and the sole means to protect the population would be to evacuate them to very high areas inland. A summary of the philosophy of how evacuation points should be used is given in Table 1, together with how these interact with hard measures and the warning system.

At the heart of this debate of hard versus soft measures, one important aspect is also whether coastal areas can be considered areas of recreation or a source of potential threats. Should the beauty of these areas be preserved, or should they be protected from potential hazards? Japan is a country that periodically experiences natural disasters in the form of earthquakes, tsunamis, or typhoons. The regular occurrence of typhoons and tsunamis requires the construction of not only of coastal defences but also of river embankments, and other engineering structures needed to protect against additional hazards posed by these disasters, such as landslides. Thus, the aesthetic and engineering considerations pertinent to the case of Japan do not necessarily resemble those of other countries. This in itself reflects on the psyche of the Japanese population and its civil engineers, who often associate coastal problems with ideas of danger and the need to protect from such hazards. For example, the area around the Sanriku Coast is heavily dependent on fishing and industries related to fishing. For the population that live in these areas, aesthetic considerations are probably secondary to the preservation of not only their lives and livelihoods,

Table 1 Framework of hard and soft measures for various tsunami Levels

Tsunami level	Soft measures	Hard measures	Warning system
1	Residents to evacuate to for Cat. A preferably, otherwise Cat. B. Cat. C only as last resort	Primary function: protect property. Secondary function: help in the protection of lives	Tsunami early warning system
2	Residents to evacuate to for Cat. A preferably, otherwise Cat. B. Cat. C only as last resort	Possibly give residents some extra time to evacuate the area. Generally ineffective	Tsunami early warning system

but also their way of life. For this reason, the implementation of hard measures would be essential for the continued habitation of the area and would allow the inhabitants to live in relative peace with the ocean. This feeling in Japan is substantially different to that of other countries in Europe or North America, where the implementation of such structures would be difficult due opposition from the local population, who would strongly resent the impact that such hard structures would have on their local scenery and environment. The *Great Eastern Japan Earthquake and Tsunami* of 2011 will undoubtedly challenge many existing concepts and accepted practices in tsunami risk management in Japan and possibly worldwide. The extent of the damage and the number of casualties in a country which considered itself well prepared against a tsunami attack will no doubt encourage debate amongst coastal engineers, coastal zone managers, and local and government policy makers. Events such as this one, despite their tragic consequences, also present opportunities to shape the utilization and protection of the coastline and improve the resilience of communities against future damaging events. One cannot claim that past mistakes are being repeated, as the timescales at which such catastrophic events occur clearly outline their uniqueness. Nevertheless, such events will remain forever recorded in history of humankind, as they will serve as examples of good practice for other threatened regions in Japan or elsewhere.

4 Classification of Evacuation Areas

One of the cornerstones of disaster prevention philosophy is the need to train local residents to escape to higher ground after the issue of a tsunami warning and/or alert. Where high ground cannot be easily reached, residents are instructed to move to tall structures in the event of such an emergency. These structures can be either purpose-built constructions, whose sole function is for residents to escape the incoming wave (which will be referred to as “Tsunami Shelters”), or tall, robust buildings (which generally serve other purposes also, such as hospitals, fire stations, or apartment blocks, which will be referred to as “Evacuation Buildings”). The distinction between these two types of structures is important in the context of Japanese Disaster Management terminology and hence will be kept in the present article. Both of them are typically designed against the worst-case scenario that was predicted or anticipated using available scientific and historic information. Collectively, both “Evacuation Buildings”, “Tsunami Shelters”, and high ground areas will be referred to as “Evacuation Areas”.

4.1 High loss of life due to *The Great Eastern Japan Earthquake and Tsunami*

The Great Eastern Japan Earthquake and Tsunami of March 2011 caused 19,868 casualties (between dead and disappeared). This is a fairly large number of people, especially for a country such as Japan that prides itself on its disaster management and preparedness. Previous disasters such as the Meiji-Sanriku Tsunami in 1896 that caused 21,959 casualties (dead and disappeared) or the Showa-Sanriku Tsunami in 1933 that resulted in 3,066 casualties (1,522 dead and 1,542 disappeared) show that the area frequently suffers and will most probably suffer from such devastating tsunamis in the future. In terms of magnitude, the Meiji-Sanriku Tsunami of 1896 generated inundation depths that reached up to 38.2 m at Ryori and could be compared in magnitude to the 2011 event.

For the case of the *Great Eastern Japan Earthquake and Tsunami* of March 2011, some of the designated Evacuation Buildings were below the tsunami inundation level. An example of this was the case of Minamisanriku, where a tsunami warning was issued by the local authorities. During this alarm, the person in charge of emitting the actual evacuation message heroically stayed at her post until the tsunami ripped her building apart. Additionally, the tsunami reached the top of one of the Evacuation Buildings, shown in Fig. 2. During one of our field surveys, a local resident explained how he had to take his child in his arms so that he was not soaked by the incoming wave, while he took refuge on the top of the 4-story building (Mikami et al. 2012). Some other designated tsunami Evacuation Buildings were less than 4 stories high, and whoever took refuge there would have been overwhelmed by the incoming coastal inundation.

4.2 New Classification of Evacuation Areas

In the light of the events of March 2011, it is imperative that the philosophy behind the design of Evacuation Areas is re-assessed. The construction of tall, robust buildings that would complementary serve as Evacuation Buildings during tsunamis is clearly both financially and technologically feasible in Japan. It appears that these buildings, if correctly designed, are able to resist tsunami forces, although more research is needed in this sense, as will be highlighted later.

In the future, Evacuation Buildings should be designed against the highest envisaged tsunami inundation level within a certain return period, regardless of whether it has taken place in recorded history or not. How the return period should be selected has not yet been established at present, but the 2011 *Great Eastern Japan Earthquake and Tsunami* reinforces the need to construct Evacuation Buildings that are designed against the highest

Fig. 2 Surviving Evacuation Building in Minamisanriku. The tsunami inundation reached the top of the building. Generally, the building was well constructed and suffered little structural damage, aside from scouring at the sides

tsunami that took place in the past (taking into account both historical records of tsunami and geological deposits of events that happened before history started in a certain area). It is important to emphasize that this represents a major deviation from traditional tsunami disaster risk management. Before the *Great Eastern Japan Earthquake and Tsunami,* the scenarios used in tsunami risk management were based on historical data or expected earthquakes, not on the worst-case scenarios. The study of worst-case scenarios was often dismissed as something unlikely to happen, and such research was often not taken seriously. The events of March 2011 demonstrated that such events, unfortunately, do occur, and it is imperative that evacuation strategies are designed against these worst-case scenarios.

The authors believe that this move to protect against the higher-order events will actually represent a major shift in the design philosophy and will require extensive re-assessment of the hazards associated with each particular stretch of the Japanese coast. Fortunately, for the case of Japan, a number of major universities and research centres carry out tsunami research, and such assessments do not represent a major logistical problem due to the large pool of available expertise. In addition, it will be necessary to consider the type of shelter required according to the topographical features of each area, as places in the Sanriku Coast (e.g. Kamaishi or Onagawa) and Sendai Planes (e.g. Natori or Soma) should actually have different strategies for sheltering people.

Research into more extreme tsunami scenarios has in fact already started, and engineers in Japan have begun to re-assess what would happen if traditionally accepted earthquake scenarios were more intense than expected, or if the fault lines were at slightly different position than those expected by seismologists.

The authors are currently arguing for the Classification of Evacuation Areas in Japan into three separate categories:

- Category A This category would include hills (higher terrain) that are adjacent to the coast but continue to increase in elevation for a long distance. Preferably, these would not be isolated low hills, but would include those that form part of larger geographical features and have a large hinterland region. A good example would be Akanumayama in the Taro area, already designated as an Evacuation Area.
- Category B This would include robust buildings that have 7 or more floors, or small hills that are more than 20 m in height. Such buildings would generally ensure the safety of anybody taking shelter in them and could be considered "critical lifeline" structures. This category would have the inherent risk of being isolated during the worst tsunami, but would likely be safe for most events. All new Evacuation Buildings should be at least Category B.
- Category C This would include robust buildings that are over 4 floors high. This category, however, would have the risk of being overtopped during the worst tsunami events, as described earlier. The use of such a category is not recommended, but in areas where Category B or A do not exist they could be used while better evacuation points are not available. No new Evacuation Buildings should be built in this category.

Thus, local residents would be trained to always attempt to reach the highest category Evacuation Areas (A) and proceed only to other locations in the case that better evacuation points cannot be reached. Currently, the lead author (Shibayama) is working with the local government authorities of Kanagawa Prefecture for the implementation of such a system. However, it has become apparent that in some areas, even Category C Evacuation Buildings do not exist (for example, in some dockland areas with a high concentration of low-elevation warehouses, which typically have a large workforce during the daytime but are almost deserted at night). This presents a significant problem, and careful consideration must be given to how to deal with such areas.

4.3 Design considerations regarding Evacuation Buildings

Many buildings were partially or completely destroyed due to *2011 The Great Eastern Japan Earthquake and Tsunami*. While extensive damage to wooden buildings was to be expected given the magnitude of coastal inundation, many concrete buildings also suffered extensive damage. Particularly, interesting was the case of a number of buildings in Onagawa, which failed due to overturning, as shown in Fig. 3. These building were built on pile foundations and, as a consequence of the earthquake, the upper end of the piles (at the point where they were joined to the bottom of the building itself) were sheared off and, subsequently, lateral loading combined with buoyancy forces overturned the structure. Liquefaction of the foundation due to the earthquake is likely to have also played a part in this, as well as serious corrosion of the steel reinforcement used in the foundation piles. Most of the buildings that failed were built decades ago and were designed using design codes that did not include the effect of strong earthquakes and tsunami loading.

In fact, even at present, no building design incorporates mandatory and consistent provisions for the design of tsunami-resistant buildings (neither in Japan nor anywhere else in the world). Few current engineering design documents provide prescriptive measures on estimating tsunami-induced forces. To improve this lack of guidance, tsunami forces are currently estimated using formulations that were initially intended for river floods or storm surges. Recent tsunami events have highlighted that this approach is inadequate, mainly due to the significantly higher bore velocities generated by tsunamis relative to other events such as river floods.

The only document available in Japan is the "Tsunami Rescue Building Design Manual" which has so far only been used for the design of a limited number of structures, such as the Evacuation Building in Minamisanriku shown in Fig. 2, and which survived the tsunami loading with almost no structural damage except for some scour on the sides of the building. This design manual, however, does not have the status of a mandatory engineering design code. It is interesting to note, however, that the new earthquake design code for buildings in Japan,[1] although not taking tsunami explicitly into account, contains provisions to estimate lateral loading due to earthquake acceleration, and buildings designed under it would be far more resilient to tsunami attack than structures designed under previous codes. For the case of the USA, some documents make provisions for tsunami loadings (such as the CCH-2000 of FEMAP646), though none of them are mandatory codes.

Of particular interest is the fact that considerable discrepancies exist between the limited number of available building codes and design guidelines that contain some provisions or make some recommendations on how to calculate the tsunami design loads as a function of the tsunami inundation height and the beach slope. Some of these documents include The City and County of Honolulu Building Code (CCH 2000), American Society of Civil Engineers Code (ASCE07/2005), the Federal Emergency Management Agency FEMA55 Coastal Construction Manual (2005), and the Federal Emergency Management Agency Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

[1] The "Building Standards Law Enforcement Ordinance", originally issued in 1950, has been frequently revised. The latest modifications were made on the March 30, 2011. This ordinance does not have any section that indicated that tsunami loads shall be considered when designing normal buildings.

Fig. 3 Reinforced concrete building damaged due to overturning in Onagawa. The piles on which the building was anchored failed in shear

(known as FEMA P646). Other researchers, such as Nistor et al. (2009), have presented new loading schemes for tsunami loading and proposed a methodology for the estimation of tsunami loading for buildings. However, there are significant differences and inconsistencies between the provisions and recommendations of the different design documents: some of them (such as FEMA 55) do not really account for tsunami loading or, certain parameters, such as the bore velocity, or debris impact characteristics, are estimated quite differently from document to document (Nistor et al. 2010). In fact, the complex interaction between tsunami-induced hydrodynamic forces and structures located in tsunami areas is still poorly understood, and efforts are currently being made to advance this area of knowledge and improve current design code guidelines. Work is under way by the Tsunami Loads and Effects Subcommittee—in which one of the authors of the present paper (Nistor) is a member—of the ASCE/SEI 7 Standards Committee for developing a new Chapter 6—Tsunami Loads and Effects, with Commentary for the 2016 edition of the ASCE 7 Standard. At the same time, ongoing efforts have been initiated in Japan in order to revise the current design provisions for buildings located in tsunami-prone areas.

A review of engineering documents that contain flood-loading expressions and the effects of tsunami waves propagating inland is presented below.

4.3.1 The City and County of Honolulu Building Code (CCH)

The City and County of Honolulu Building Code (CCH) Article 11 provides regulations for areas prone to flood hazard (Department of Planning and Permitting of Honolulu Hawaii 2000). Flood-proofing and structural requirements are provided for the design of structures against coastal flooding, including the effects of tsunami. Bore velocity is assumed equal to the bore depth, while scour around foundations is empirically based on the distance from the shoreline and the type of soil at the location of the structure. This code provides formulas to estimate the forces affecting buildings due to coastal flooding including buoyant, surge, drag, and hydrostatic forces, in addition to impact force caused by waterborne debris.

4.3.2 American Society of Civil Engineers Standard ASCE/SEI 24-05

The American Society of Civil Engineers/Structural Engineering Institute Standard ASCE/SEI 24-05 Flood Resistant Design and Construction Standard (ASCE ASCE 2006a) provides minimum requirements for flood-resistant design and construction of structures located in flood hazard areas. This standard complies with the US Federal Emergency Management Agency (FEMA) and National Flood Insurance Program (NFIP) flood plain management requirements. This standard was referenced by the 2006 edition of the International Building Code (International Code Council 2006). ASCE/SEI 24–05 refers to the American Society of Civil Engineers Standard ASCE 7–05 Minimum Design Loads for Buildings and other structures (ASCE ASCE 2006b) for flood loads, which includes hydrostatic, hydrodynamic, wave, and debris loads, as well as load combinations.

4.3.3 Federal Emergency Management Agency (FEMA) 55

The Federal Emergency Management Agency (FEMA) issued the Coastal Construction Manual known as FEMA 55 (FEMA 2000). This manual contains instructions on how to design and construct structures located in coastal regions and under the threat of damage due to a natural disaster (e.g. hurricane, earthquake, flood…). Chapter 11 includes formulations related to site-specific loads, including snow, floods, tsunamis, wind, tornados, and earthquakes, in addition to load combinations. The flood loads include estimates for flood depth, wave set-up, wave height, flood velocity, hydrostatic loads, breaking wave loads on piles and walls, and debris impact loads. This document suggests that tsunami loads can be calculated similarly to other flood loads given that certain physical characteristics of the tsunami-induced coastal flooding bear resemblance to regular floods. However, many of these characteristics such as scale, spatial extent, and flow pattern are significantly different in the case of tsunami-induced coastal flooding comparing to regular floods.

4.3.4 Structural Design Method of Buildings for Tsunami Resistance (SMBTR)

In 2005, the Building Center of Japan proposed a Structural Design Method of Buildings for Tsunami Resistance (SMBTR) (Okada et al. 2005). This document includes formulations for loads applied to inland structures resulting from tsunami flooding. The maximum tsunami force is calculated from a hydrostatic pressure distribution extending 3 h from the base of the structure, where h is the inundation depth at the structure. The magnitude of the resulting base shear force at the base of the wall is 9 times the equivalent hydrostatic force for the same inundation depth (Nouri et al. 2010). SMBTR also provides guidance on the effect of buoyancy and load combinations with other types of forces.

4.3.5 American Society of Civil Engineers Standard ASCE/SEI 7–10

The American Society of Civil Engineers Standard ASCE 7–10 Minimum Design Loads for Buildings and Other Structures (ASCE 2006) provides requirements for structural design, including the calculation of forces arising from floods and waves on specific types of structural elements. This standard also covers definitions that relate to flood areas or coastal high-hazard areas associated with tides, storm surges, riverine flooding, seiches, and tsunamis. Chapter 5 of ASCE 7–10 provides formulas to calculate wave loads and breaking wave loads on piles and walls. The formulas simply convert hydrodynamic loads into equivalent hydrostatic forces, when flow velocity does not exceed 3.05 m/s; otherwise, basic concepts of fluid dynamics must be used. Guidance on debris impact forces is based on imposing concentrated loads at the most critical location of a structure but no debris loading formulas are prescribed. This document, however, did not specifically contain formulas for tsunami loading.

4.3.6 Federal Emergency Management Agency (FEMA) P646

The Federal Emergency Management Agency (FEMA) published the Guidelines for Design of Structures for Vertical Evacuation from Tsunamis, known as FEMA P646 (FEMA 2006). This document is the most recent engineering document that provides formulations to calculate tsunami loads on structures. Chapter 6 contains prescriptions for tsunami-induced force components and structural design criteria. The force components include hydrostatic forces resulting from standing water or slow moving flow around the structure; buoyant forces due to displaced volume of water; hydrodynamic forces arising from moderate-to-high-velocity water flow around the structure; impulsive forces caused by the leading edge of the water impacting the structure; debris impact forces generated by floating debris colliding with the structure; and damming of waterborne debris due to the accumulation of debris on the upstream side of the structure, which results in an increase in the hydrodynamic force. In addition, uplift forces on elevated floors of a structure that are submerged during tsunami inundation are also considered.

4.4 Case Study of Tsunami Evacuation Plans: Kanagawa Prefecture

In order to understand the profound changes in the coastal risk management mentality that have taken place since the 2011 *Great Eastern Japan Earthquake and Tsunami*, it is worth analysing at least one case study. For this, the authors have chosen Kamakura City in Kanagawa Prefecture, as the lead author is the Chair of the Committee for Tsunami Studies of the prefectural government, and can thus provide accurate and relevant information of the current thoughts on disaster risk management at this location. The city is a former seat of the Shogunate and Regency during the Kamakura Period (1192–1333AD) and is renown both for its temples and for suffering tsunami attacks a number of times in the past, one of which reached its famous bronze Buddha statue (See Fig. 4). In fact, Kamakura City is considered to be one of the most vulnerable settlements in Kanagawa Prefecture and thus concentrates much of the attention of the prefectural government when it comes to tsunami risk management.

In the analysis of possible tsunamis that could take place in the prefecture (and more specifically in Kamakura city), three different approaches were employed:

1) Analysis of records provided by historical documents.
2) Geotechnical investigations to investigate layers of historical and pre-historical (i.e. paleotsunami) tsunami sediments.
3) Numerical simulations of historical tsunamis.

Fig. 4 Kamakura bronze Buddha statue (Daibutsu). Famously, the 1498 tsunami reached the statue

Based on the results of (1) and (2), the numerical simulations focused on the scenarios provided by the historical Genroku Kanto Earthquake of 1703, the Keicho Earthquake of 1605, and the Meiou Tokai Earthquake of 1498. The Genroku Kanto Earthquake has an estimated recurrence interval of around 2,300 years, though after the Tohoku Earthquake seismologists are trying to re-analyse this interval. The Keicho and Meiou events are related to the Suruga through and have recurrence intervals of 120 years (Headquarters for Earthquake Research Promotion 2012). All of these earthquakes generated large tsunamis that caused strong damage to the coastal area of Kamakura, also affecting the cities of Yokohama and Tokyo. Based on these numerical simulations, new tsunami inundation maps were presented to the residents of the coastal area of Kamakura City in November 2011, with more precise information issued further in April 2012. These maps provide larger inundation areas and heights than previous maps and thus represent a “worst-case scenario”, as opposed to previous maps which presented a lower threat level to Kamakura.

In order to use the tsunami hazard map for evacuation planning, it is necessary to know both the height and the arrival time of tsunami waves. For Kamakura area, the tsunami resulting from the Keicho Earthquake would have an inundation height of 10 m and take 80 min to reach the Kamakura coastline, according to the simulation results. However, for the case of the 1703 Genroku Kanto Earthquake, it would only take 51 min, though it would have a lower height (around 6.5 m). The Minami Kanto Earthquake would produce the quickest tsunami that would reach Kamakura, a 5-m wave that would hit after only around 32 min. Thus, two different types of risks can be identified: one where a high tsunami wave strikes the area, yet there is ample time for evacuation, and another one where the wave is smaller but the time for evacuation is limited.

In Kamakura City, there are small-scale town organizations for each district in the city (of approximately 1,000–1,500 inhabitants), where discussions for possible evacuation plans are conducted by the residents themselves. These organizations carry out their own training activities for evacuation and are thus a central part of the disaster management process.

In Kamakura, hills are located close to the coastline, which would thus designate them as Category A Evacuation Areas, though the road system to access these hills is not adequate and needs improvement. Thus, residents in large areas of the city can potentially easily evacuate to areas that are high enough even for the case of a Level 2 tsunami. The main exception to this is the Zaimokuza area, which would be isolated from the hills by the coastline and Nameri River in the event of a tsunami, and where it would take residents in excess of 30 min to reach the hills by foot (for the case of healthy adults). For this case, a scenario based on the 1703 Genroku Kanto Tsunami would pose significant problems since the tsunami wave arrival time is estimated to be only 51 min after the earthquake. The Minami Kanto tsunami would represent an even worse scenario, as residents would hardly have any time to evacuate.

For the case of Zaimokuza, the problem is compounded by the fact that the number of buildings that have more than 4 stories is limited due to house construction code in this district. This code attempts to keep good living conditions in the area by restricting building height to a maximum of 10 m for houses and 15 m for commercial buildings. However, these would only be classified as Category C Evacuation Buildings, which could be lower than a potential Level 2 tsunami. Consideration is now been given to this matter by designating additional tsunami Evacuation Buildings and by planning to build higher structures in the future.

5 Coastal protection structures

5.1 Structural damage to coastal dykes

Numerous coastal dikes suffered significant, often irreparable, damage as a result of the 2011 *Great Eastern Japan Earthquake and Tsunami* waves, which were much higher than what they were originally designed for. For the case of Japan, these structures were designed against either storms or tsunami waves. Although a structure designed against storm waves can also offer some protection against tsunami, there are specific problems associated with each type of structure. The area that concentrates almost all the tsunami protection structures in Japan is that of Sanriku Coast, due to the frequency of tsunami attacks in recent history (i.e. Meiji-Sanriku in 1896, Showa-Sanriku in 1933, and the Chile Tsunami in 1960, as previously explained in this chapter). On the other hand, areas to the south of Sanriku (on the Sendai Plain) were protected mainly by structures designed for storm surge conditions.

For the case of dikes designed against storm waves, the high loading generated by the overtopping tsunami waves often resulted in scour either to the front or at the back of these structures and often led to the destruction of many sections, as shown in Figs. 5 and 6. Many were constructed with a central core of coarse sand and gravel, which was then lined with often weak or non-reinforced concrete. These structures were particularly vulnerable to the effect of overtopping by tsunami waves, as the scouring exposed the central sand and gravel core to the rapid flow of the water, leading thus to the rapid erosion of the core, and subsequent collapse of the structure (see Fig. 5). Essentially, most of the cores of these dikes appeared to be unprotected by geotextile membranes, and some observations of river embankments (such as that at the mouth of Natori River) showed that areas protected by geotextiles generally suffered less scouring than areas that had no such membrane protection. In order for dykes and embankments to perform better during future tsunami events, the authors would recommend the possible inclusion of geotextile membranes into the design in order to protect the sand core. The use of geotextiles is actually pretty common in Japan nowadays, although they are normally only used at the front toe of the dykes. Based on the experience of this tsunami event, it would be probably better to install them also at the back of the structure.

The effect of concrete armour units placed in front of coastal dikes was also studied. In areas such as Soma City, it could be observed that such units were indeed successful in protecting the dike behind them. Placing these units on the beach next to the sea, however, greatly diminishes the visual appeal of the beach. Therefore, it appears difficult to strike a balance between the need to protect using hard structures and the desire to preserve the aesthetics and unspoilt local coastal environment.

5.2 Structural damage to breakwaters

A great number of breakwaters have been built in the Tohoku coastal areas, and they can be broadly divided into two categories, depending on whether they were built primarily to protect against (1) storm waves or (2) tsunami waves.

5.2.1 Tsunami breakwaters

A large portion of the Tohoku coastline, especially the Sanriku Coast, is made up of rias, which are fjord-like inundated deep former river valleys that are especially vulnerable to tsunami attack as they concentrate much of the incoming tsunami wave energy along their longitudinal axis, as experienced also during the 1960 Chile Tsunami. After the aforementioned tsunami, the Japanese government decided to build massive breakwaters at the entrance of some of the rias to protect the

Fig. 5 Extensive failure due to overtopping of coastal dikes in Soma City, Fukushima Prefecture. The parts of the structure that survived had armour units placed in front of them

Fig. 6 Failure of coastal dikes in Watari. Note how scouring of the back of the dike can then result in the exposure of the core soil, which can then lead to the failure of the unsupported concrete superstructure of the dike

area behind them against tsunami waves, in places such as Kamaishi, Ofunato, and Kuji. These breakwaters were built at great expense, due to the significant depths in which they were constructed (the breakwater at Kamaishi is actually the world's deepest breakwater, in 63 m of water depth). However, for the 2011 *Great Eastern Japan Earthquake and Tsunami*, they were not able to survive intact the peak of the tsunami impact. The breakwater at Ofunato completely disappeared and that located offshore Kamaishi was significantly damaged, according to visual inspections carried out during the tsunami survey. Arguably, neither of them had been designed against the tsunami wave height that actually occurred during this event, as they had been originally only conceived with a 6 m height from the lowest sea level to the crest of the breakwater (Takahashi et al 2011). However, what is interesting to mention is that the breakwaters at Kamaishi and Ofunato behaved differently, with one of them completely disappearing (Ofunato—catastrophic failure), while the other one (Kamaishi) suffered significant damage (in one of its sections, at least) but still remained visible above the water line after the tsunami. Obviously, these breakwaters have different dimensions, and it is thus normal that they behaved differently. However, more research is needed into the failure mechanism under extreme tsunami waves. It is essential that future tsunami breakwater design should attempt to design structures that do not fail catastrophically and that would have some level of built-in resilience. However, considering the present experience with such structures, it is not clear the level of protection that these structures may provide. There is some evidence that inundation heights behind these structures were lower than in their front (PARI 2011), though much more research will be needed to accurately model the behaviour of the breakwater–structure interaction. Also, at present, the failure mode of breakwaters under tsunami wave attack or even wind wave (Esteban et al. 2008) is poorly understood, and this will undoubtedly also have an effect on the propagation of the tsunami waves inside a bay.

5.2.2 Storm protection breakwaters

Other breakwaters that were designed to protect against wind waves and storm attack suffered extensive damage and in some cases resulted in their complete destruction, such as that located at the entrance of Onagawa Port, as shown in Fig. 7. Generally speaking, composite breakwaters (those protected by armour units such as Tetrapods) were far more resilient than simple caisson breakwaters. It appears that the armour behaved as designed at dissipating the impact of the tsunami wave forces on the seaward side of the caisson, although damage to armour units was also recorded for several composite breakwaters. For some of these breakwaters, armour units of different sizes and types were used for the same breakwater, and it appears that damage is dependent on the weight of the units (as can be expected from formulas such as that of Van der Meer 1987). At present, few formulas have been derived for the design of armour units against tsunami attack (Sakakiyama 2012; Hanzawa et al. 2012; Esteban et al. 2012; Kato et al. 2012), and these have not been verified to accurately predict real case failures. Although many of these structures are designed primarily against storm waves, it would be advisable to develop a formula to check this type of effect, in order to ensure added protection against tsunami waves. Significantly, more research is needed in this area, but as composite breakwaters appear to be more resilient against tsunami attack, these structures could be better suited in areas where their cost does not become prohibitive (Esteban et al. 2013).

6 Future research

In view of the severe damage generated by recent tsunamis in different regions around the world, tsunami research must be intensified in the future. Prior to the 2004 Indian Ocean Tsunami, little effort was placed on tsunami research, and although following this event research efforts around the world intensified considerably, researchers' interest gradually subsided as subsequent tsunamis did not cause damage in a similar trans-national scale (such as the 2009 Mentawai or the 2010 Chile Tsunamis). It is obvious that much is still not properly understood particularly with respect to the tsunami frequency and the destruction potential in various areas around the world. In a similar manner, the effect of bathymetry on tsunami propagation in coastal regions such as submarine canyons needs to be better understood (A-ranguiz 2012). It is hence important to continue research into a number of areas particularly related to tsunami generation, propagation, transformation in the nearshore area, and impact on the coastline and associated infrastructure.

Fig. 7 Breakwater at Onagawa town before (*left*) and after the tsunami. Not that the tsunami completely destroyed the breakwater, with the caissons being scattered by the incoming and outgoing wave

6.1 Paleotsunami research

One of the major problems of tsunami risk management is that researchers often use only recorded historical events to assess future threats. Human history, however, spans several millennia: while a few countries have longer records, they do not necessarily always provide much information about the magnitude of events. It is absolutely necessary to investigate past events, and historical records are often not sufficient. A field of research that has thus emerged in recent decades, and gathered increased attention recently is that of paleotsunami research, where events older than humankind history or that have not been recorded are confirmed through geological investigations.

Following the 2011 *Great Eastern Japan Earthquake and Tsunami,* it appears that Japanese authorities have increased their efforts to try to better understand the nature of past tsunami threats. For example, the authors recently took part in geotechnical investigations organized by Kanagawa Prefecture in the Kamakura City, which is known to have been affected by tsunamis in the past (see Fig. 8). Paleotsunami investigations are, however, difficult to conduct in built-up areas, and much wider surveys will probably be necessary before detailed conclusions can be obtained. This field, however, is of great importance to establish what the likelihood of future events may be. Moreover, engineers need to understand what is the magnitude of the worst possible event in combination with a carefully selected return period that could be used to design infrastructure and protective structures. While it is virtually impossible to design against all possible tsunami events, understanding past events and their impacts can help better define risk management strategies.

6.2 Structural and propagation research

Currently, the proper estimation of forces exerted by tsunamis on coastal dykes and breakwaters, as well as on buildings, is not well understood. Physical modelling such events in laboratory is not always accurate, and despite the existence of some large wave flumes fitted with tsunami waves generating equipment (such as those at the Ports and Airports Research Institute in Yokosuka, Japan), there is still considerable debate about how well tsunamis can be reproduced in laboratory. Additionally, it is difficult to confirm if such models can actually provide a good indication of the true forces and loads associated with tsunami loading. It is thus imperative that a better understanding of tsunami waves is achieved, in order to formulate better design codes for structures located in tsunami-prone areas, and hence research and engineering efforts should intensify in this field. As the economy and population of many countries around the world continue to grow, it is likely that the number of buildings in tsunami-prone areas (such as the coastal areas of Indonesia, for example) will continue to increase. It is therefore important for these structures to be properly designed.

Numerical models are also used to simulate tsunamis, but the results of the propagation models can be incorrect sometimes by a factor around a factor of two. It is often only the first of the waves of a tsunami that can be well simulated, due to issues of reflection, inundation over land, and uncertainties in the selection of the generation fault parameters. Thus, the uncertainties in the tsunami generation, which depend on the displacement of the ground at the fault location, are essential in the accurate initiation of the tsunami wave. As these earthquakes occur under water there are always considerable uncertainties involved, and the estimation of the initial tsunami height is difficult.

Fig. 8 Taking core samples of the soil in Kamakura City (Kanagawa Prefecture, Japan) to find traces of historical tsunami events

Being able to correctly forecast the spatial and temporal behaviour of tsunami impact based on a certain earthquake scenario is extremely important in disaster management and mitigation. This is an ongoing area of research, where the tools available must be improved.

7 Conclusions

In the present study the authors proposed new concepts on tsunami and Evacuation Area classification. Some of these concepts, such as that of the Level 1 and 2 tsunamis, are currently widely used by the Japanese coastal engineering community and are increasingly known to members of the international community.

Soft measures, such as evacuation plans, require the residents to be able to access higher ground, and if this is located too far, they need to proceed to tsunami shelters or Evacuation Buildings, which must be correctly designed. One of the main lessons is that it is necessary to augment and improve the training of local residents and make them aware of how both hard and soft measures interact and complement each other. Additionally, residents must be informed of how the establishment of hard measures still means that it is necessary to evacuate, should the event be greater than what was expected. Hard measures, if properly designed, can provide valuable time for residents to evacuate. The present consensus amongst tsunami researchers in Japan is that hard measures cannot prevent the loss of life against Level 2 events. Hard measures can protect property against Level 1 events and might have a role in protecting lives for the weaker events. This last point is still the object of intense debate, with government officials and coastal engineers still debating the topic. The protection of lives, however, should ultimately always rely on soft measures, and residents should be instructed also to evacuate after a tsunami evacuation order is issued. The 2011 *Great Eastern Japan Earthquake and Tsunami* was unanimously categorized as a Level 2, and residents should be always trained to expect such events.

It is also necessary to establish a hierarchy of the Evacuation Areas that would provide the residents with a sense of which are the safest places to seek shelter once a tsunami warning has been issued. In the event of an impending tsunami arrival, residents should proceed to the safest points, and only if they judge that they do not have sufficient time to reach such points should they go to Evacuation Areas which are considered less safe. There is a chance that coastal areas in the future will experience a more drastic differentiation in the land use of such areas. Some researchers and government officials are arguing for the amalgamation of some small fishery villages into bigger settlements with housing located in higher ground, thus relatively separating them from the fishery port itself. If this will be implemented, then careful consideration should also be given to the evacuation of workers from the areas located closer to the water.

The present paper attempted to highlight that much is still not properly understood about tsunami waves and their destructive potential. Increases in research effort typically follow these events, but this effort unfortunately diminishes a few years following the event. It is therefore important to maintain the research efforts until such natural disasters are better understood, and adequate mitigation measures are proposed and implemented.

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