International Journal of Disaster Risk Reduction 7 (2014) 28–38

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Assessing tsunami vulnerability of structures designed for seismic loading

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ARTICLE INFO

Article history:
Received 9 July 2013
Received in revised form
30 November 2013
Accepted 1 December 2013
Available online 11 December 2013

Keywords:
Earthquake
Tsunami
Coastal structures
Seismic resistant
Tsunami resilient

ABSTRACT

Wave movement with large velocity triggered by strong earthquake occurring at the sea bed is generally the primary cause of the tsunami. Occurrence of tsunami (like the one during the Sumatra earthquake in 2004 or the one during the Tohoku earthquake in Japan in 2011) causes devastating damages to the coastal structures and tremendous casualties. Seismic resistant design procedure is more popularly followed in various countries as per the relevant seismic codes. It is the need of the hour to see whether the lateral load-resisting capability attributed through seismic design is sufficient to resist tsunami loading. The present study using available design guidelines in various seismic codes and well accepted design literature for tsunami loading attempts to achieve this end in a limited form. The study may be helpful in providing a broad overview of tsunami vulnerability of coastal structures which are designed following the mandatory requirements of seismic codes. Such tsunami vulnerability is attempted to be recognized in terms of critical height that corresponds to maximum inundation depth of tsunami wave which the structure may withstand because of being aseismically designed. Thus, the results presented in this study may prove useful in assessing and reducing tsunami vulnerability of coastal structures.

1. Introduction

Earthquake and tsunami are the natural disasters, which cause huge loss of property in terms of lives and economy. The devastating damages of the present decade due to the Indian Ocean tsunami in 2004 and the tsunami in Japan in 2011, compelled the politicians, policy makers, economist and engineers to think deeply regarding tsunami resilient design. From the past experiences, it has been observed that most of the tsunamis are triggered by earthquakes. For example, Chile earthquake (1960), Alaska earthquake (1964), Indonesia earthquake (2004) and Tohoku earthquake (2011), triggered tsunamis. Strong earthquakes resulting in deformation of larger area lead~~s~~ to severe tsunamis than smaller earthquakes. Generally, earthquakes having focus deeper than 30 km, rarely cause tsunamis. But sometimes certain earthquakes like the Chile (1960) and the Indonesia (2004), which had a focal depth larger than 30 km also triggered tsunamis. Generally, tsunami possesses a lot of energy, move at high speed and can travel greater distances. For example in a typical ocean having depth of 4 km, the travel speed of tsunami is nearly equal to 700 kmph. However, after entering shallow water (less than a depth of 30 m) the tsunami waves travel at a speed of only 60 kmph. The speed of tsunami waves further diminishes as

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http://dx.doi.org/10.1016/j.ijdrr.2013.12.001

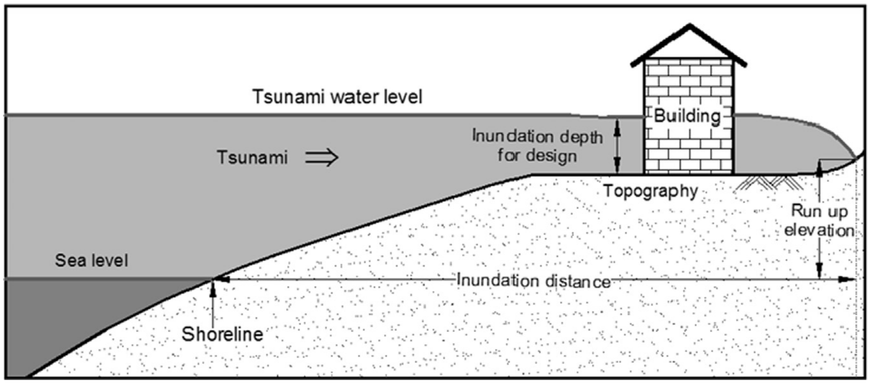

Fig. 1. Different terms related to tsunami [1,2].

it moves to shallower coastal water with increase in height. Such rise in height of tsunami waves to several meters near the coast is due to shoaling effect. As a result of this, when the tsunami reaches the coast it may develop into a rapidly rising or falling tide i.e., a series of breaking waves. So, while designing the structures along the coast, attention should be given towards tsunami loading in addition to earthquake loading in earthquake prone zones. But the analysis is very much complicated as both the forces are time dependent and the motion in each case is transient in nature. Some important parameters related to tsunami are presented in Fig. 1. Though tsunami is a low probability rarely occurring event but the devastating damage experienced during the last two tsunamis (the 2004 Indian Ocean tsunami and the 2011 Japan tsunami) compelled the human civilization to think about the tsunami resilient design of structures.

The important parameters considered during seismic design are seismic weight, stiffness, ductility and redundancy. On the other hand, the parameters like strength and rigidity of the structure (at lower level), velocity of the wave, inundation depth and the exposed area on the wave side of the structure are taken into account during tsunami resilient design. Well accepted detailed codal provisions [3–5] are available for seismic design of buildings. Though well-established design procedures for tsunami resilient buildings are not available but Federal Emergency Management Agency's Coastal and Construction Manual (FEMA 55) [6], City and County of Honolulu Building Code (CCH) [7] and Structural Design Method of Buildings for Tsunami Resistance (SMBTR) [8] (which is relevant Japanese design code), provides some guideline towards the design of tsunamis resilient buildings. During analysis of tsunami loading, most of the codes consider the following loads: (i) hydrostatic force (ii) buoyant force (iii) hydrodynamic force (iv) surge force (v) debris impact force and (vi) wave-breaking force. The limited study attempted in this paper makes an effort in establishing an equivalence between seismic loading and tsunami loading. In fact, it has been explored in this study what inundation depth of tsunami wave can be survived by a coastal structure which is designed for seismic load prescribed in that particular seismic zone. For evaluating seismic load, a few well known codes like IS 1893 (Part 1) [3], Eurocode 8 [4] and ASCE 7-05 [5] are used. On the other hand, for evaluating tsunami loads, the codes like FEMA 55 [6], CCH [7] and SMBTR [8] are used. This may be helpful to emerge a broader picture regarding such tsunami vulnerability. The outcome of the study may prove beneficial for the city planners and policy makers for disaster management and may also be helpful to the human civilization in reducing the risk of damage during natural disasters in a broad sense.

2. Literature review

For the design of tsunami resistant structure, the calculation of tsunami forces is necessary. So, many attempts have been made to calculate the Tsunami forces accurately. Thus, codes like FEMA 55 [6], CCH [7] and SMBTR [8] came up. FEMA 55 [6] provides the total flood load on a vertical wall (height $\geq 2.2H$) of a coastal residential building to be about 11 times the hydrostatic force with inundation depth (H). According to SMBTR [8], the force per unit length of the wall is taken as an equivalent hydrostatic load with three times the inundation depth (H), for a tsunami wave with no break-up. Total force is approximately 9 times as of static loading if the building height is more than 3 times inundation depth. The pressure diagram will be truncated if it is less than $3H$. A significant amount of research work on wave impact loading is being carried out experimentally as well as using physical modeling.

Mizutani and Imamura [9] conducted hydraulic experiments to measure the wave force of tsunami acting on the prevention structures along the coast such as seawalls and breakwaters. They used four types of wave pressures, namely dynamic, sustained, impact standing and overflowing. They proposed the formulation to estimate each type of wave forces for design of coastal structure. Yeh [10] proposed rational methodologies to determine design tsunami loads on onshore structures with finite breadth. Though the analytical solution proposed can be a useful tool for analysis but still it requires some simplifications and assumptions. Thusyanthan and Madabhushi [11] conducted model testing of new tsunami-resistant house design and a typical Sri Lankan coastal house in a wave tank. They observed the well performance of the new design under tsunami loading while the typical coastal house was destroyed. Fujima et al. [12] investigated tsunami forces on rectangular structures using a 7 m wide,