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Performance-Based Tsunami Engineering methodology for risk assessment of structures

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ABSTRACT

Tsunamis are rare destructive phenomena caused by the sudden displacement of a large amount of water in the ocean and can result in enormous losses to coastal communities. The resilience of coastal communities to tsunamis can be improved through the use of risk-informed decision making tools. Performance-Based Engineering (PBE) approaches have been developed for different natural hazards including earthquake, fire, hurricane, and wind to perform probabilistic risk assessment for structures. In this study, a probabilistic Performance-Based Tsunami Engineering (PBTE) framework based on the total probability theorem is proposed for the risk assessment of structures subject to tsunamis. The proposed framework can be disaggregated into the different basic analysis phases of hazard analysis, foundation and structure characterization, interaction analysis, structural analysis, damage analysis, and loss analysis. An application example consisting of the risk assessment of a three-story steel moment frame structure was performed using the proposed framework. The probability of exceedance of the total replacement cost including structural, nonstructural, and content losses were computed.

1. Introduction

Tsunamis are a series of large sea waves caused by the displacement of a large volume of water caused mostly by submarine earthquakes, but can also include landslides, volcanic eruptions, and meteor impacts. Tsunamis are a high-impact, low-probability event that, although rare, are extremely destructive, resulting in high casualty rates and billions of dollars of economic loss (e.g., Indian Ocean, 2004; Samoa, 2009; Chile, 2010 and Japan, 2011). To improve the resilience of coastal communities to tsunamis, decision makers can benefit from tools that would enable them to make risk-informed decisions. In recent years, probabilistic approaches, such as Performance-Based Engineering (PBE), have gained significant attention and are being used in many specialty areas of civil engineering. The major benefit of a PBE approach is the articulation of performance metrics, which are applicable in the decision making process for hazard risk mitigation [1]. Performance-based earthquake engineering (PBEE) has been at the frontier among natural hazards, starting approximately two decades ago [1–4]. The PBEE framework, implemented by Pacific earthquake engineering research (PEER) center, intended to provide a tool for seismic risk-informed decisions for stake-holders, allowing for a more informative and scientific based approach. This framework is based on the total probability theorem and can be disaggregated into different analysis phases that include hazard analysis, structural analysis, damage analysis and loss analysis [1]. These phases must be carried out in sequence, resulting in an estimation of the frequency for which different levels of decision variables would be exceeded.

Following the PBEE framework and along with its recent applications (e.g. [5–8]), the PBE approach was used in dealing with other hazards such as performance-based fire engineering (PBFE) [9,10], performance-based wind engineering (PBWE) [11,12] and performance-based hurricane engineering (PBHE), [13]. One major difference between PBEE and the PBE for hazards which deal with fluids, such as PBWE, is the interaction analysis phase that should be performed before the structural analysis phase, accounting for the physical interaction between the structure and the environment [11] [13].

Design guidelines considering tsunami forces are currently very limited in the literature. Cross [14], described tsunami surge forces and predicted the forces occurring when a bore strikes a vertical wall, which were further validated using experimental data. Camfield [15] discussed different methods of predicting tsunami flooding and proposed generating mechanisms of tsunamis and the

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method of determining the probability of occurrence. Dames and Moore [16] presented different loading requirements that should be considered for tsunami resistant design of residential buildings. Later, the Japan Cabinet Office guideline [17], City and County of Honolulu Building Code [18] and FEMA P646 [19], proposed guidelines for designing vertical tsunami evacuation structures. ASCE 7-16 [20] now has a chapter dedicated to tsunami design, which relies on probabilistic tsunami hazard analysis (PTHA) to provide tsunami inundation hazard maps for the design of structures.

Preliminary efforts to develop PTHA by Lin and Tung [21], Rikitake [22], and Downes and Stirling [23] used the same approach as Probabilistic Seismic Hazard Analysis (PSHA) [24], to calculate wave heights using a simple source specification and attenuation relationships. Due to lack of historical data for tsunamis, Geist and Parsons [25], proposed another approach for PTHA by combining computational methods and empirical analysis of historical tsunami data. Burbidge et al. [26] used a Green's function summation to perform PTHA, running full probabilistic analyses over a much wider area. This approach was then used by Thio et al. [27] to perform PTHA for California in a PEER report, in which, tsunami hazard maps are used to compute the tsunami inundation hazard for California [28]. Park and Cox [29] conducted a probabilistic tsunami hazard analysis conditioned on a full rupture Cascadia Subduction Zone event to estimate the annual exceedance probability of five intensity measures closely related to loss of life, immediate response and recover, and damage to the built and natural environment. These intensity measures were the inundation depth, velocity, momentum flux, arrival time, and duration, and were computed throughout the inundation zone. As mentioned earlier, these types of PTHA would be the first step in a fully probabilistic tsunami risk assessment methodology.

The need for Performance-Based Tsunami Engineering (PBTE) has been recognized by researchers for several years (e.g., [30,31]) and is finding its way to codes and standards such as ASCE 7-16 [20]. However, currently there is no comprehensive PBTE framework in the literature. In this study, a probabilistic framework for PBTE based on the total probability theorem is proposed. Similar to other performance-based approaches (PBHE, PBWE, etc.), the proposed methodology can be disaggregated into different analysis phases each of which is presented herein. The proposed methodology is illustrated by performing a risk assessment of a three-story moment frame steel structure subjected to a tsunami.

2. Tsunami loads and effects

Depending on the distance between the origin and the point of interest, tsunamis can be classified into near-field and far-field tsunamis. For the case of far-field tsunamis, the mechanism by which the tsunami is generated, such as a large earthquake, is far enough from the point of interest so that the triggering mechanism itself does not have a direct impact on the structure. For near-field tsunamis, on the other hand, the triggering mechanism is close to the point of interest as is the case when an earthquake occurs offshore of the structure. In this case, the structure experiences the earthquake before being impacted by the tsunami water waves. Near-field tsunamis should be treated as a multi-hazard event (cascading effects) requiring successive analysis; however, the focus of this paper is limited to the tsunami itself.

Tsunami effects on structures are broadly classified as hydrostatic forces, hydrodynamic forces, waterborne debris impact forces and scour effects [16,19,32]. Horizontal hydrostatic forces are typically imposed on the structure when standing water encounters can be calculated as:

$$F_h = \frac{1}{2} \cdot \rho_s \cdot g \cdot B \cdot h_{max}^2 \tag{1}$$

where ρ_s is the fluid density including sediment, g is the gravitational acceleration, B is the breadth of the building, and h_{max} is the maximum water height above the base of the wall at structure location. The vertical hydrostatic force (buoyant force) is equal to the weight of water displaced. Buoyant forces are resisted mostly through the weight of the structure and are calculated using the following equation:

$$F_b = \rho_s \cdot g \cdot V \tag{2}$$

in which V is the volume of water displaced by the structure. The capacity of the structure to resist lateral loads may be reduced by buoyancy forces [33]. Hydrodynamic forces are caused by the flow of water and can be computed as:

$$F_d = \frac{1}{2} \cdot \rho_s \cdot C_d \cdot C_o \cdot B \cdot (hu^2)_{max} \tag{3}$$

where C_d is the drag coefficient, B is the breadth of the building in the plane normal to the direction of flow, h is flow depth, and u is the depth-uniform flow velocity. C_o is a coefficient to account for openings and wall/window failure/breakage [34] and is generally less than unity. The term hu^2 is the specific momentum flux per unit mass and $(hu^2)_{max}$ is the maximum specific momentum flux per unit mass at any time during the tsunami inundation at the point of interest. Impulsive forces are caused by the leading edge of a surge of water impacting a structure, which is estimated using the following equation:

$$F_{imp} = \alpha \cdot F_d \tag{4}$$

where α is an amplification factor [35,36].

The debris impact forces depend on the density of the debris in the region and the maximum flow velocity, and can be estimated as:

$$F_{deb} = u_{max} \cdot \sqrt{k \cdot m_d} \tag{5}$$

where u_{max} is the maximum flow velocity carrying the debris, m_d is the mass of the debris, and k is the effective stiffness of the impacting debris or the lateral stiffness of the impacted structural element (s). The other important aspect that should be considered regarding waterborne debris is the damming effect caused by accumulation of debris. To account for this effect, hydrodynamic force calculated using Eq. (3) can be modified using the breadth of the debris dam (B_d). Other effects of tsunamis on structures that should be accounted for in the analysis are the scour and erosion effects along with soil-foundation-structure interactions.

3. Proposed PBTE methodology

The proposed PBTE methodology, similar to other PBE frameworks, should involve defining the following:

- An Intensity Measure (*IM*) in probabilistic form, which is a key parameter of the hazard intensity and has a strong correlation with structural response and damage.
- Foundation Structure Parameters (*FSP*), accounting for the relevant properties of the foundation structural system.
- Interaction Parameters (*IP*), describing interaction between the environment and structure.
- An Engineering Demand Parameter (*EDP*), providing a measurable quantity from the structural response subjected to the hazard.
- Damage Measures (*DM*), presenting structural behavior and capacity, including damage based on the *EDPs*.