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Fragility assessment of a RC structure under tsunami actions via nonlinear static and dynamic analyses

Crescenzo Petrone [a],*, Tiziana Rossetto [a], Katsuichiro Goda [b]

[a] Department of Civil, Environmental & Geomatic Engineering, University College London, London, United Kingdom
[b] Department of Civil Engineering, University of Bristol, University Walk, Bristol, United Kingdom

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ABSTRACT

Current guidelines for design and assessment of buildings under tsunami actions do not explicitly state how to apply tsunami loads to buildings and which analysis methods to use in order to assess the structural response to the tsunami loads. In this paper, a reinforced concrete (RC) moment-resisting frame, which is designed as a tsunami evacuation building, is selected as a case study and subjected to simulated 2011 Tohoku tsunami waves. To assess tsunami impact on the model building, different nonlinear static analyses, i.e. constant-height pushover (CHPO) and variable-height pushover (VHPO), are compared with nonlinear dynamic analysis. The results of VHPO provide a good prediction of engineering demand parameters and collapse fragility curves obtained from the dynamic analysis under a wide range of tsunami loading. On the other hand, CHPO tends to overestimate interstorey drift ratio (IDR) and underestimate column shear by about 5–20%. It provides a larger fragility, i.e. about 10% in median value, for global failure and a smaller fragility for local shear failure. On the basis of these results, it is recommended that VHPO be used in future fragility analysis of buildings subjected to tsunami. However, pushover methods might not be adequate in cases where the tsunami inundation force time-histories are characterised by a "double-peak", which subjects the structure to a two-cycle load. Finally, it is found that tsunami peak force is better correlated to IDR than flow velocity and inundation depth for the considered structure. This suggests that the peak force would be a more efficient intensity measure than the other two in the development of tsunami fragility curves.

1. Introduction

Recent tsunami events (e.g. 2004 Indian Ocean tsunami and 2011 Great East Japan tsunami) have caused numerous deaths and widespread damage. The 2004 Indian Ocean tsunami caused 230,000 deaths [1], whereas the 2011 Great East Japan (Tohoku) earthquake-tsunami caused 19,000 fatalities as well as US$211 billion direct economic loss [2]. It is worth noting that such a loss does not include costs related to the Fukushima Daiichi nuclear power plant crisis nor indirect losses, such as supply-chain disruptions and retail trade and tourism reduction due to restrained consumption and radiation fears.

These observed consequences from tsunami can only be reduced through the development of comprehensive risk mitigation plans based on tsunami impact scenarios and risk assessments. An important component in the evaluation of tsunami risk is the estimation of building fragility due to tsunami onshore flow. This has recently been recognised by researchers worldwide [3–5]. To date the majority of this research has focussed on the development of fragility functions based on observational post-tsunami damage data, in particular after the 2004 Indian Ocean tsunami (e.g. [6,7]) and the 2011 Japan tsunami (e.g.[3]). Empirical tsunami fragility functions are by their nature specific to the event represented in the post-event damage data as well as the local building stock, and suffer from absence of locally recorded tsunami intensity measures (IMs). Tsunami inundation depths can be obtained from the inspection of water marks on standing buildings, whereas other IMs, such as flow velocity, are difficult to assess after the event. It is important to recognise that the building damage observation data have been affected by both earthquake and tsunami loads, and implicitly include the response of buildings to the combined hazards. As post-tsunami reconnaissance cannot distinguish damage due to the two hazards, it is difficult to determine whether the preceding damage due to the earthquake has affected the structural response to the tsunami inundation. The assessment of structural performance through numerical analyses is therefore

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* Corresponding author.
E-mail addresses: c.petrone@ucl.ac.uk (C. Petrone), t.rossetto@ucl.ac.uk (T. Rossetto), Katsu.Goda@bristol.ac.uk (K. Goda).

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essential to overcome the mentioned limitations of empirical fragility functions. Analytical fragility functions can also be used together with empirical assessments to provide a deeper understanding of structural behaviour under tsunami actions.

1.1. Previous studies on analytical fragility functions and structural assessment to tsunamis

Very few studies concerning analytical fragility of structures to tsunami are available in the literature. Macabuag et al. [8] presented a preliminary study where they considered different building codes in assessing the tsunami force on a simple reinforced concrete (RC) frame building based on a pushover-based method. investigated the behaviour of RC buildings under tsunami loads by means of both experimental and numerical analyses and assessed the contribution of infill walls on the response of the structure. A set of tsunami pushover curves for a single-storey RC structure was produced assuming a constant inundation height. It was found that shear failure in columns leads the structure to failure before the full structural capacity is exploited. Nanayakkara and Dias [9] proposed analytical fragility curves for different structural typologies. A probabilistic model based on Monte Carlo simulation was used to artificially produce fragility curves for simplified masonry and RC structural models assuming that inundation depth is uniformly distributed for different inundation depth ranges. A good match with empirical fragility curves was observed. In addition, preliminary studies on the behaviour of structures under ground motion and subsequent tsunami inundation are available in the literature. For instance, Park et al. [10] proposed an approach to consider the successive seismic and tsunami risk to buildings. The structure was modelled as an equivalent single-degree-of-freedom system and was subjected first to an acceleration time-history and then a tsunami force calculated from FEMA P646 [11]. Latcharote and Kai [12] implemented a sequential earthquake and tsunami simulation in an Integrated Earthquake Simulation to assess the expected damage for a three-storey RC structure in Kochi, Japan.

All these existing tsunami analytical fragility approaches are associated with a number of issues that affect their accuracy. Firstly, the tsunami action is typically modelled with an equivalent force according to design prescriptions, without taking into account realistic tsunami inundation time-histories. Current design building codes might be inadequate in assessing tsunami force; in particular, conservative assumptions are typically made for design purposes. Secondly, gross assumptions are made regarding the pressure distribution along the height of the structure resulting from the tsunami actions, without consideration of the potential sensitivity of the structural response to variations in the pressure distribution or how the load is discretised and applied to the structural model. Furthermore, almost none of the approaches consider the fact that tsunami forces are applied at the rear of the structure as the tsunami wave flows past the building. Thirdly, available studies typically consider only nonlinear static analyses pushing the structure up to the structural peak strength, where the structure cannot be considered to have failed. It is clear that there is a gap in knowledge in determining how tsunami loads should be applied to a building and which analysis methodology is most suitable for the estimation of building response to realistic tsunami.

1.2. Objectives of the study

This paper takes a first step to address the above mentioned issues by assessing different nonlinear static analyses and comparing them with dynamic analyses performed considering realistic tsunami inundation time-histories. The assessment is performed in terms of the ability of each nonlinear static method to predict the peak structural response observed in the dynamic analyses and to reproduce the tsunami fragility curves developed from the dynamic analyses. The peak structural response, e.g. maximum interstorey drift ratio (IDR), is referred to as "demand" in the following, whereas the tsunami peak intensity is expressed in terms of IM, e.g. inundation depth. The study takes advantages of the numerical-experimental studies developed at UCL and HR Wallingford for the assessment of tsunami forces on structures [13,14] and the extensive tsunami simulations for generating realistic tsunami wave traces [15]. The paper is divided into different sections. First, a case study building, a Japanese tsunami evacuation building, is described and then its modelling is discussed. Particular attention is paid to the definition of tsunami load through the adoption and modification of the formulation of Qi et al. [13]. A tsunami inundation simulation of the 2011 Tohoku tsunami is presented in order to define numerous tsunami wave traces in terms of inundation depth and flow velocity, for use in the dynamic analyses of the structural model. Different non-linear static analysis methodologies for the assessment of the building response are defined and a sensitivity analysis is performed to assess the influence of applied load distribution on the structural response under tsunami actions. The demand on the building, in terms of maximum IDR and shear, is then evaluated using the defined nonlinear static analysis methods and compared to the results of the nonlinear dynamic analysis, with the aim of identifying the bias induced by adopting the former simpler analyses. Such a bias is finally estimated in terms of tsunami fragility curve, and recommendations are made as to which nonlinear static analysis and load distribution approach are the most suitable for use in the study of building fragility to tsunami. It is highlighted that the fragility functions presented in this paper are specific to the case study building and should not be adopted in the assessment of other RC building types.

2. Methodology

2.1. Case study building

The case study building selected is an ideal tsunami evacuation building, consisting of 10 storeys and RC frames in both horizontal directions (Fig. 1). Building plan dimensions are 36 × 23 m, with a constant 3.9 m interstorey height for all storeys except for the ground storey, which is 4.5 m high. Six and three bays can be identified along the longitudinal and transverse directions, respectively. The tsunami evacuation building is taken from the design example 3-1 of the "structural design and members section case studies" [16]. This structure is an ideal tsunami evacuation building, designed according to both earthquake and tsunami actions. It should not be considered as representative of a typical midrise RC building in Japan, e.g. the apartment building in Rikuzentakada [17] and other RC frame buildings that were surveyed after the 2011 Japan tsunami [18–20]. The example structure is designed assuming an earthquake zone coefficient $Z = 1.0$, soil type 2, fundamental vibration period 0.796 s, characteristic vibration coefficient $Rt = 0.979$ and base shear coefficient $C_0 = 0.2$. The structure is also designed to resist tsunami loads, assuming a 10 m inundation depth and coefficient a equal to 2.0, yielding an effective inundation depth equal to 20 m in calculating the wave forces action the building. Only minor modifications from the seismic design result are made for the tsunami design of the structure, particularly concerning the building foundations. However, the tsunami design is conducted assuming that the first two floors are "pilotis", i.e. do not have infills. This study neglects the presence of openings; it is assumed that water flow is obstructed in all bays for the whole height of the structure. Such an assumption