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Vulnerability Assessment of Highly Populated Buildings in the Face of Earthquake and Tsunami Actions: A Case Study of the AsiaWorld-Expo in Hong Kong

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Abstract

This paper presents a study of the vulnerability of highly populated buildings, using the AsiaWorld-Expo megastructure in Hong Kong as a case study. A 3D numerical model of the structure was developed using the OpenSees software to evaluate the building's vulnerability. Incremental dynamic analysis was conducted to analyse the seismic vulnerability of the structure, whereas a physics-based methodology was applied to determine the structure's tsunami response under various scenarios. The primary outcomes of the research include structural fragility curves, reflecting the building's damage potential in the face of seismic and tsunami hazards. It is found that the structure is more vulnerable along its shorter dimension (parallel to the roof trusses, the Y direction) with fewer shear walls. Moreover, the use of momentum flux was recommended as an intensity measure instead of flow depth for assessing tsunami-induced damages. The findings provide crucial insights for risk-informed design strategies in earthquake- and tsunami-prone areas.

Keywords: Vulnerability assessment, highly populated buildings, fragility curves

1 Introduction

Highly populated buildings, such as entertainment arenas, stadiums, and religious centres, play a critical role in urban environments, servicing thousands of people daily. These structures are categorised under high-importance buildings in many structural design codes due to the severe consequences of their failure, which can include significant casualties and substantial economic losses (ASCE7-22, 2022). Despite their importance, the seismic and tsunami vulnerabilities of such buildings have not been thoroughly investigated in the literature. The collapse of these structures during an earthquake or tsunami could lead to devastating outcomes, highlighting the need for detailed vulnerability analyses and resilient design strategies (Park et al., 2012).

In regions of low to moderate seismicity, the structural design often prioritises gravitational loads and wind forces over seismic considerations. However, as urban populations grow and cities expand, the risk of seismic events affecting these densely populated areas increases. Past earthquakes have shown that even in regions not traditionally considered seismically active, the damage to inadequately designed structures can be catastrophic. This is particularly concerning for buildings designed primarily for vertical loads without significant consideration for lateral forces induced by seismic or tsunami events.

The AsiaWorld-Expo in Hong Kong serves as an illustrative case study due to its location in a region with both seismic and tsunami risks (Beheshtian et al., 2023). This megastructure, designed under the Hong Kong Building Regulations and British Standards, provides a unique opportunity to explore the vulnerabilities of large-span and highly populated buildings. The detailed architectural and structural drawings available for this building facilitate a comprehensive analysis, making it an ideal subject for developing and validating advanced modelling techniques. Figure 1 illustrates some of the key geometrical features of this structure.

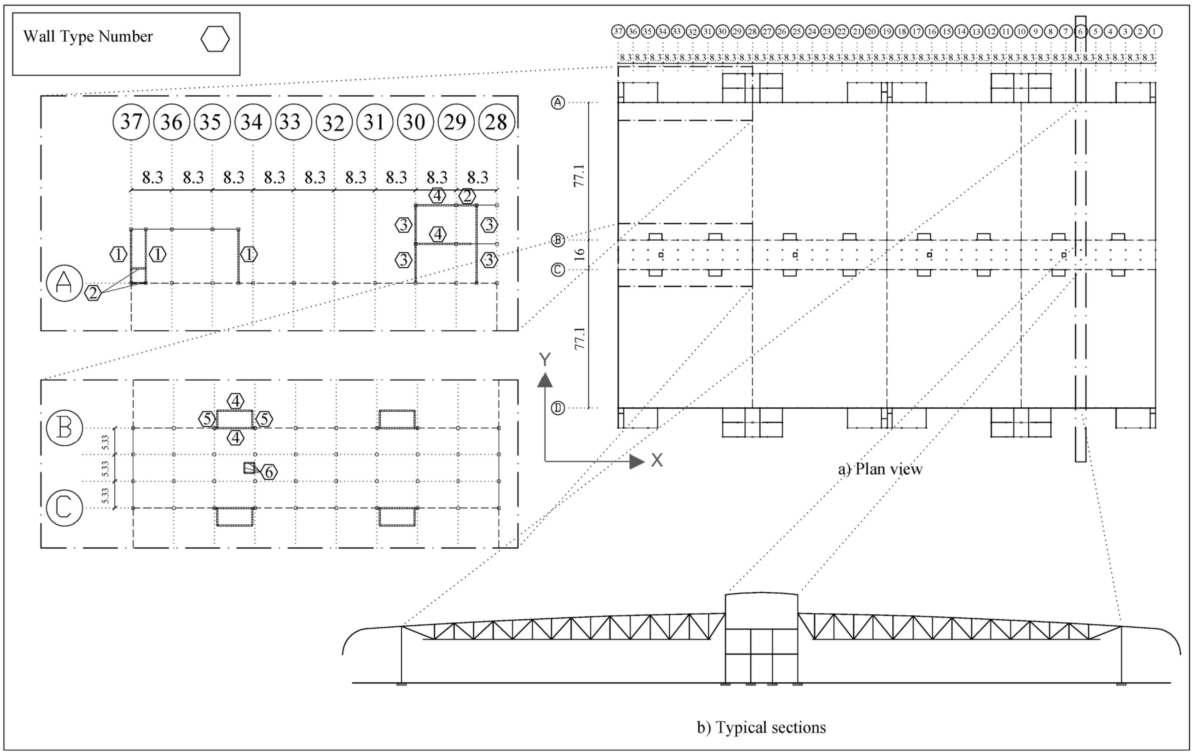

Figure 1: Plan and section view of the Typical Hall Building, including shear walls, beams, and columns.

2 Methodology

2.1 Seismic Vulnerability Assessment

To develop the seismic fragility curves, a 3D numerical model of the AsiaWorld-Expo was created using OpenSees software (Beheshtian et al., 2020). The model incorporated detailed architectural and structural drawings, ensuring an accurate representation of the building's geometry and material properties. Incremental Dynamic Analysis (IDA) was conducted to generate the seismic fragility curves (Vamvatsikos and Cornell, 2002).

To ensure computational efficiency, especially given the size and complexity of the building, a novel line element was used to model the shear walls. This approach leverages advanced computational optimisation techniques to precisely calibrate the non-linear behaviour of the shear walls, including material degradation and complex interaction effects. The SFI-MVLEM wall element and Ibarra-Medina-Krawinkler (IMK) spring models were integrated with an optimization-based calibration method, providing a practical means of performing detailed vulnerability assessments for large structures.

2.2 Tsunami Vulnerability Assessment

For tsunami vulnerability, a physics-based methodology was applied to determine the structure's response under various scenarios (Attary et al., 2017). A building-specific set of fragility curves was developed, carefully considering detailed wave-structure interactions. By incrementally varying the flow depths, with a maximum height of 9 meters—representing one of the most extreme scenarios observed in historical tsunamis, such as the 2004 Indian Ocean event—the study simulated a range of possible impacts on the structure. The tsunami forces for each scenario are calculated using the hydrodynamic force equation (Equation 1). These forces are then applied at various heights on the structure to evaluate its response. The structural response is analysed using a pushover analysis, which is schematically illustrated in Figure 2.

$$F_d = \frac{1}{2} \rho_s \, C_d \, B \, C_0 \, (hu^2)_{max} \qquad \text{Equation 1}$$

Equation 1 defines the hydrodynamic force F_d, where ρ_s represents the density of the fluid, $C_d$is the drag coefficient, B is the width of the structure, C_0 accounts for the shape and interaction effects, and $(hu^2)_{max}$ denotes the maximum dynamic pressure associated with the flow velocity and water height.

Traditionally, flow depth has been used as the intensity measure for tsunami-induced forces. However, this measure lacks sensitivity to flow velocity, which is a critical factor in the dynamic loading conditions of a tsunami. Therefore, the momentum flux was recommended as an alternative intensity measure, providing a more accurate representation of the tsunami forces acting on the structure.

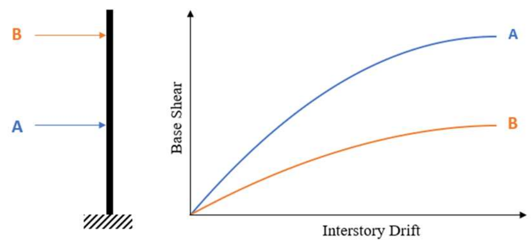

Figure 2: The schematic representation of the tsunami forces and the pushover analysis of the structure; illustrating the change of the inundation level from A to B

3 Results and Discussion

3.1 Seismic Fragility Curves

The seismic fragility curves developed for the AsiaWorld-Expo reveal distinct vulnerabilities in the structure (Figure 3). The analysis shows that the structure is particularly susceptible in the Y direction, which aligns with the building's shorter dimension, where the number of shear walls is less than in the X direction. This increased vulnerability is attributed to the reduced lateral stiffness and strength due to fewer shear walls, emphasising the importance of optimising shear wall placement and distribution to enhance the seismic resilience of such large-span and highly populated structures (Beheshtian et al., 2023).

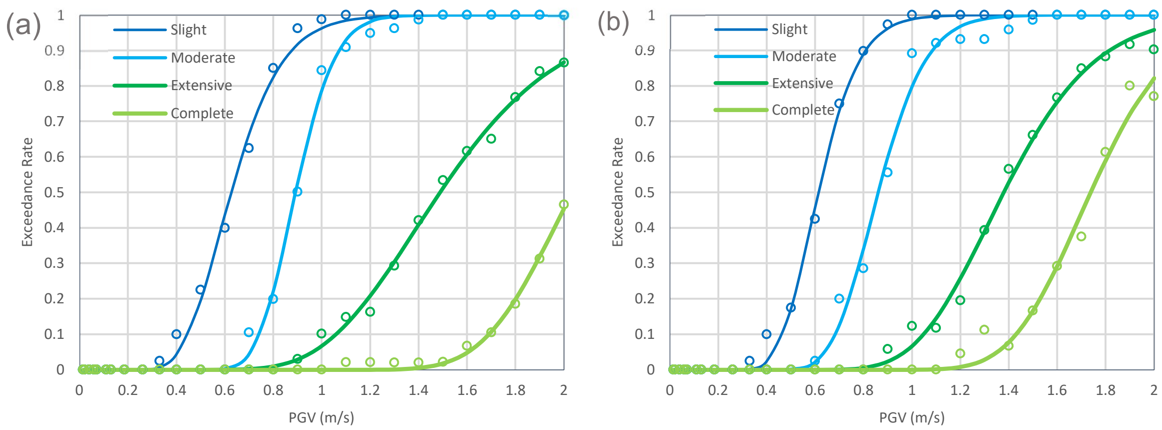

Figure 3: Seismic fragility curves based on ground motions with various magnitude-distance (M-R) combinations, (a) and (b) are respectively for X and Y directions.

The fragility curves indicate a higher probability of exceeding slight to moderate damage states at lower seismic intensities in the Y direction compared to the X direction. This suggests that under seismic events, the building is more likely to experience damage along its shorter dimension, potentially compromising its structural integrity and posing significant risks to occupants.

3.2 Tsunami Fragility Curves

The computed tsunami fragility curves are presented in Figure 4. Using the momentum flux as the intensity measure resulted in fragility curves with lower dispersion compared to those based on flow depth alone. This indicates a more accurate and reliable assessment of the building's vulnerability to tsunami forces.

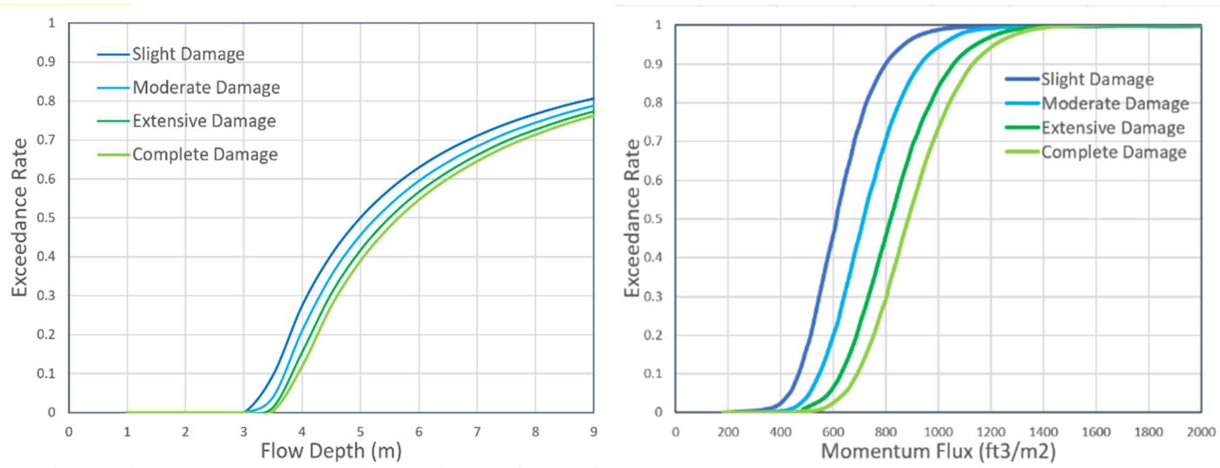

Figure 4: Fragility curves (a) and (b) for tsunamis are based on intensity measures of flow depth and momentum flux, respectively. These curves represent the exceedance rate of four damage states: slight, moderate, extensive, and complete.

The analysis demonstrates that the AsiaWorld-Expo is highly vulnerable to tsunami-induced damage, especially at higher flow depths and velocities. The fragility curves show a significant probability of exceeding extensive to complete damage states under extreme tsunami scenarios. These findings highlight the critical need for robust design and retrofitting strategies to enhance the tsunami resilience of coastal structures.

4 Conclusion

The study emphasises the critical role of context-specific analysis and robust modelling techniques in accurately assessing and mitigating multi-hazard risks, particularly in earthquake- and tsunami-prone regions. The developed fragility curves provide essential tools for evaluating the probabilistic performance of highly populated buildings under seismic and tsunami actions. The implications of this research extend beyond the AsiaWorld-Expo, offering valuable guidelines and setting a new benchmark for improving the resilience of similar high-importance structures worldwide.

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