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DOI
10.64697/978-90-835589-7-4_41WC-P2072-cd

Publication date
2025

Document Version
Final published version

Published in
Proceedings of the 41st IAHR World Congress, 2025

Citation (APA)
Samadian, D., Eslamnia, H., Pregnolato, M., & Muhit, I. B. (2025). Sequential Nonlinear Analysis of Buildings Exposed to Flash Flooding and Earthquake. In A. Wing-Keung Law, & J. W. Er (Eds.), *Proceedings of the 41st IAHR World Congress, 2025* (pp. 1030-1033). Article 624 (Proceedings of the IAHR World Congress). IAHR. https://doi.org/10.64697/978-90-835589-7-4_41WC-P2072-cd

41ST IAHR WORLD CONGRESS SINGAPORE
22 – 27 JUNE 2025
INNOVATIVE WATER ENGINEERING FOR SUSTAINABLE DEVELOPMENT

Book of Extended Abstracts
41st IAHR World Congress
22-27 June 2025
Singapore

SEQUENTIAL NONLINEAR ANALYSIS OF BUILDINGS EXPOSED TO FLASH FLOODING AND EARTHQUAKE

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ABSTRACT

This paper introduces a novel computational framework that integrates a three-dimensional (3D) nonlinear time history analysis (NLTHA) of buildings subjected to combined flood and earthquake events. Unlike traditional single-hazard analyses, this research explores the complex interactions between hydrodynamic forces from flooding and seismic loads. Using steel special moment-resisting frames (SMRFs) of varying heights in Los Angeles (USA), the response to 13 earthquake hazard levels and four flood inundation depths is evaluated. The framework incorporates computational fluid dynamics (CFD) for hydrodynamic modelling and finite element (FE) analysis for structural response assessment. Results highlight a significant increase in engineering demand parameters (EDPs), such as inter-story drift, floor accelerations, base shear, and ductility in multi-hazard scenarios. These findings underscore the need for a re-evaluation of building resilience in flood-prone areas.

Keywords: Multi-hazard; resilience; flooding; earthquake; structural vulnerability; CFD; SMRF.

1. Introduction

Natural hazards, particularly floods and earthquakes, pose significant threats to structures worldwide. The frequency and intensity of these disasters are increasing due to climate change, urbanisation, and population growth in vulnerable regions. The Global Risk Report (2023) identifies climate-induced disasters as a growing concern, with floods and earthquakes alone causing billions of dollars in damage annually (Jonkman et al., 2024; EM-DAT., 2024). In this context, understanding how infrastructure responds to multiple hazards is essential for developing resilient systems. While extensive research has focused on either seismic or flood impacts individually (Asad et al., 2024; Harati and van de Lindt, 2024; Pregnolato et al., 2022; Samadian et al., 2019), there has been limited attention on their combined effects. In reality, structures often face sequential hazards where one event can weaken a building, making it more vulnerable to subsequent hazards. This paper addresses this gap by proposing an integrated framework for analysing building behaviour under combined earthquake and flood scenarios. The study focuses on low-to-high-rise steel special moment-resisting frame (SMRF) buildings in downtown Los Angeles (LADT), an area vulnerable to both earthquakes and flooding.

2. Methodology

As per Fig. 1, the integrated methodology involves three major components: hazard modelling (Step 1), structural vulnerability assessment (Step 2-5), and consequence evaluation (Step 6). This comprehensive approach allows for precise simulation of multi-hazard events and their impact on structures.

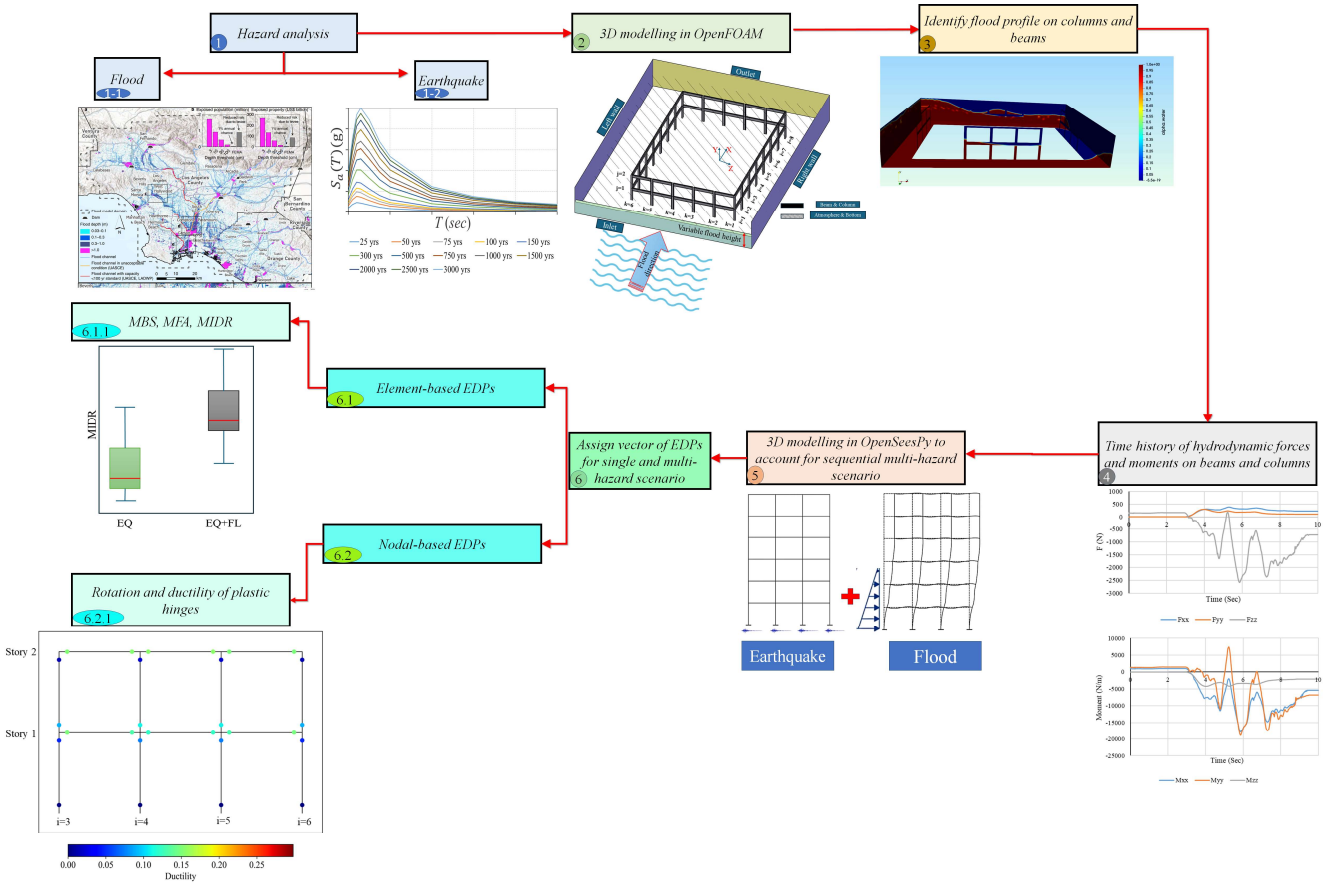


Fig. 1. Workflow of the research.

2.1 Hazard Modelling

2.1.1. Flood Scenario

The flood analysis is conducted using OpenFOAM, an open-source computational fluid dynamics (CFD) tool that simulates fluid-structure interaction, accounting for the dynamic forces exerted by water on buildings. The flood depths considered in this study are 0.3, 1, 2, and 4 meters, which represent varying flood intensities, including extreme events. The intensity of floods is extracted from flood hazard analysis conducted for LADT by Sanders et al. (2022). The CFD model uses the volume of fluid (VOF) method to track the air-water interface, simulating the interaction of water with structural elements. Initially, the water height is recorded on each column and beam (Step 3 in Fig. 1), enabling readers to discern which structural elements are impacted by the flood waves. Consequently, only these identified columns and beams will be subjected to flood loads. Hydrodynamic forces such as drag, lift, and moments are extracted from these simulations to assess their impact on the building's beams and columns (Step 4 in Fig. 1).

2.2.2. Earthquake Scenario:

For the seismic hazard, ground motions are selected via a modified conditional mean spectrum (CMS) (Samadian et al., 2024a) based on 13 return periods, ranging from 25 to 3000 years, ensuring a comprehensive range of earthquake intensities. The analysis uses OpenSeesPy for nonlinear time history analysis (NLTHA), capturing the building's response to seismic loads. The earthquake records include two horizontal ground motion components per event, scaled appropriately for the building's fundamental period.

2.2 Structural Vulnerability Assessment

The vulnerability model integrates the flood-induced hydrodynamic forces obtained from OpenFOAM into the FE models of the buildings in OpenSeesPy. The structural analysis simulates the sequence of events (Step 5 in Fig. 1), where an earthquake affects the building first, followed by a specific flood event (flood level). This sequence allows the model to capture the degradation in structural stiffness and strength caused by the seismic event before flooding.

The structural models represent low- (2-storey), mid-(8-storey), and high-rise (20-storey) SMRF buildings, designed per FEMA P695 (2009) guidelines. The buildings are modelled with 3D FE elements in OpenSeesPy to capture the complex interaction between lateral (seismic) and hydrodynamic (flood) loads. The OpenSeesPy models account for both material nonlinearity and geometric nonlinearity, with special attention to the plastic hinge formations in beams and columns. Key engineering demand parameters (EDPs) measured include:

- Maximum Inter-Story Drift Ratio (MIDR): an indicator of lateral deformation.
- Maximum Floor Acceleration (MFA): critical for evaluating non-structural damage.
- Maximum Base Shear (MBS): representing overall lateral forces.
- Plastic Hinge Ductility: measuring the rotation of plastic hinges in beams and columns.

2.3 Consequence Evaluation

The consequence phase evaluates the structural performance based on the EDPs. The results from the sequential hazard analysis (earthquake followed by flood) are compared to the baseline (earthquake-only) scenario. This comparison helps quantify the amplifying effect of floods on seismic vulnerability. Additionally, the framework segments each column into multiple sections, ensuring that the hydrodynamic forces are applied accurately at each structural node. A Python module is developed to automate the application of flood-induced forces and moments to the respective structural elements in OpenSeesPy. This process ensures that the forces vary dynamically with the flood's progression.

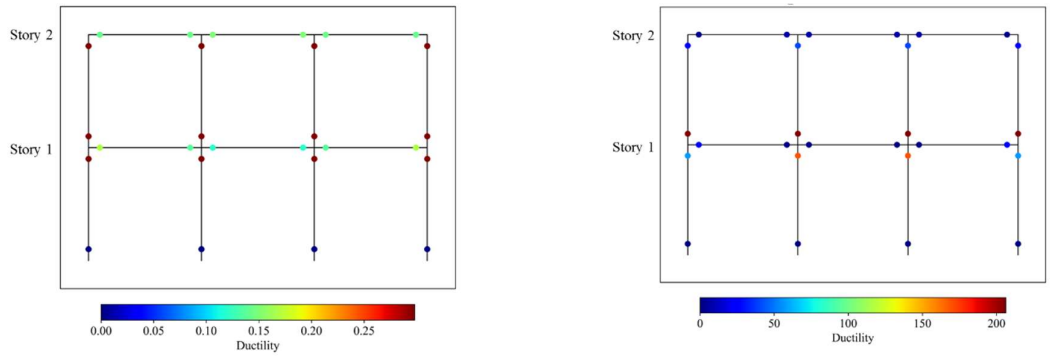
3. Results

3.1 Earthquake-Only Scenario

The earthquake-only analysis showed that the buildings performed within acceptable limits. For example, in the two-storey SMRF, the MIDR remained below 1%, in line with FEMA P-58 (2012) guidelines. The MFA was also within the expected range for seismic performance (Samadian et al., 2024b), with values between 0.10g and 0.3g for mid- and high-rise buildings.

3.2 Combined Earthquake and Flood Scenario

In the combined earthquake and flood (EQ+FL) scenario, structural responses were significantly amplified. For the two-storey SMRF building, with a 4-meter flood height, the first-storey MIDR increased from 0.0065 (EQ only) to 0.0739, a substantial escalation. Similarly, the MFA in the second storey increased from 0.24g to 0.83g when subjected to both hazards. Base shear forces saw a comparable rise due to the added hydrodynamic pressure from the flooding. The analysis of plastic hinge rotations revealed that, under the combined load (EQ+FL), many beams and columns exceeded their elastic limits as per Fig. 2, particularly those directly exposed to floodwaters. The ductility of plastic hinges in these elements increased significantly, indicating greater inelastic behaviour. Front-facing frames exposed to the flood flow experienced higher levels of yielding and plastic rotation compared to rear-facing frames, which experienced less direct impact from the flood.



(a) (b)

Fig. 2. Ductility of beams and columns for a front-facing frame: (a) EQ only; (b) EQ+FL.

4. Discussion

The results demonstrate that the combined effects of floods and earthquakes significantly increase the structural demands placed on buildings. The increased ductility in plastic hinges, especially for frames directly facing floodwaters, highlights the localised vulnerability in multi-hazard scenarios. These findings suggest that

traditional multi-hazard approaches, which often ignore complex nonlinear flood effects, may lead to an underestimation of structural failure risks in flood-prone areas. In addition, the significant increase in floor accelerations due to flooding suggests that non-structural components (such as equipment and interior elements) could face greater damage in a combined flood-earthquake scenario. This outcome points to the need for more integrated design strategies that consider both structural and non-structural resilience under multiple hazards.

5. Conclusion

This research presents a comprehensive framework for assessing the performance of SMRF buildings under combined earthquake and flood conditions. The results underscore the necessity of incorporating multi-hazard considerations into building design, particularly in flood-prone areas. The integration of 3D CFD for flood modelling with 3D NLTHA provides a more accurate assessment of structural performance compared to traditional methods.

Key conclusions include:

- Flooding significantly amplifies the structural demands imposed by seismic events, particularly on lower-storey elements.
- Plastic hinges in frames facing the flood flow experience higher levels of inelastic deformation.
- Maximum floor accelerations and base shear forces increase dramatically in combined hazard scenarios, suggesting that current design codes may underestimate these risks.

This framework offers a valuable tool for engineers to evaluate building resilience under multiple hazards, ultimately improving the safety and reliability of critical infrastructure.

References

Applied Technology Council. Seismic performance assessment of buildings (2012) volume 1 -methodology. Technical report FEMA P58-1. Washington, D.C.: Federal Emergency Management Agency

Asad M, Thamboo J, Zahra T, Thambiratnam DP (2024) Out of-plane failure analysis of masonry walls subjected to hydrostatic and hydrodynamic loads induced by flash floods. Eng Struct, 298:117041

EM-DAT, CRED/UCLouvain (2024) Brussels, Belgium. www.emdat.be. Accessed Sep 2024

Harati M, van de Lindt JW (2024) Methodology to generate earthquake-tsunami fragility surfaces for community resilience modeling. Eng Struct, 305:117700

Jonkman SN, Curran A, Bouwer LM (2024) Floods have become less deadly: an analysis of global flood fatalities 1975–2022. Nat Hazards, 120:6327–42

Pregnolato M, Winter AO, Mascarenas D, Sen AD, Bates P, Motley MR (2022) Assessing flooding impact to riverine bridges: an integrated analysis. Nat Hazards Earth Syst Sci, 22:1559–76

Samadian D, Muhit IB, Dawood N (2024a) Structural failure analysis with CMS-based ground motion selection using innovative cost function and weight factors. Earthq Eng Eng Vib, 23:899–918

Samadian D, Muhit IB, Occhipinti A, Dawood N (2024b) Surrogate models for seismic and pushover response prediction of steel special moment resisting frames. Eng Struct, 314:118307

Samadian D, Ghafory-Ashtiany M, Naderpour H, Eghbali M (2019) Seismic resilience evaluation based on vulnerability curves for existing and retrofitted typical RC school buildings. Soil Dyn Earthq Eng, 127:105844

Sanders BF, Schubert JE, Kahl DT, Mach KJ, Brady D, AghaKouchak A, et al (2022) Large and inequitable flood risks in Los Angeles, California. Nat Sustain, 6:47–57

World Economic Forum (2023) The global risks report 2023 18th Edition. World Economic Forum