

# Comparative Dynamic Analysis of Tsunami-Induced Loads on Regular and Irregular Reinforced Concrete Buildings in Coastal Regions

Omkar Anil Mirkale<sup>1</sup>, Guide- Prof. J. M. Chavan<sup>2</sup>, Dr. V. S. Rajamanya<sup>3</sup>

<sup>1</sup>Student, Department of Civil Engineering, M.B.E.S. College of Engineering, Ambajogai

<sup>2</sup>Research Guide, Department of Civil Engineering, M.B.E.S. College of Engineering, Ambajogai

<sup>3</sup>HOD, Department of Civil Engineering, M.B.E.S. College of Engineering, Ambajogai

## Abstract

Tsunami-induced actions produce complex transient demands on coastal reinforced concrete (RC) buildings because hydrostatic pressure, hydrodynamic drag force, impulsive bore impact, debris impact, uplift pressure and overturning effects act in a combined and time-varying manner. The present research paper converts an ETABS-based analytical project report into a journal-style study on the comparative dynamic response of regular and irregular RC buildings located in the Chennai coastal region. Four G+6 RC moment-resisting frame configurations were investigated: a Regular Building, a Plan-Irregular A Building, a Plan-Irregular B Building and a Vertical-Irregular Building. The tsunami propagation direction was considered along the global Y-direction. Tsunami loading was developed using FEMA P-646 based recommendations and associated tsunami engineering procedures. Separate normalized time-history functions for hydrostatic force, hydrodynamic drag force, impulsive bore force, debris impact force and uplift force were prepared in Microsoft Excel and imported into ETABS through TXT files. A combined tsunami load case named TS\_FINAL was analysed using linear direct integration time-history analysis with Hilber-Hughes-Taylor integration, 5% damping, 300 s total duration and 0.05 s time step. Structural performance was evaluated using peak overturning moment, roof joint displacement and maximum storey drift. The results show that the Plan-Irregular A Building had the highest roof displacement and storey drift, indicating greater flexibility and deformation concentration. The Plan-Irregular B Building showed the lowest roof displacement and drift, indicating better deformation control under the considered tsunami loading.

**Keywords:** Tsunami loading; RC buildings; ETABS; Time-history analysis; FEMA P-646; Irregular buildings; Overturning moment; Storey drift; Roof displacement.

## 1. Introduction

Tsunamis are low-frequency but extremely high-consequence coastal hazards capable of producing severe inundation, high-velocity flow, impact pressures and long-duration hydrodynamic loading on coastal infrastructure. Unlike ordinary wind or earthquake actions, tsunami effects arise from the movement of a large water mass and therefore include water pressure, flow drag, impact, buoyancy and debris collision. These actions are particularly critical for reinforced concrete buildings located close to the shoreline, where lower storeys and exposed structural components directly interact with the incoming water front.

The Indian coastal belt has extensive urban and economic development, and the east coast facing the Bay of Bengal is vulnerable to tsunami events generated in the Indian Ocean region. The 26 December 2004 Indian Ocean Tsunami demonstrated the vulnerability of Tamil Nadu and other eastern coastal areas. Chennai is especially important because of its dense coastal population, rapid urbanisation and presence of residential, commercial and public infrastructure near vulnerable coastal zones. For such areas, tsunami-resistant planning and structural evaluation are essential for reducing casualties, damage and post-disaster disruption.

In conventional Indian building design practice, RC buildings are commonly designed for gravity, wind and earthquake loads using IS 456, IS 875 and IS 1893 provisions. Dedicated tsunami-specific design procedures are not explicitly covered for ordinary RC buildings in the same way that seismic and wind design are covered. International recommendations such as FEMA P-646 and ASCE/SEI 7-22 provide a more detailed basis for estimating tsunami actions. Therefore, there is a need to apply these procedures to representative Indian coastal building configurations and to evaluate their dynamic response using appropriate time-history analysis.

A further concern is the influence of structural irregularity. Regular buildings generally have uniform load paths and balanced stiffness distribution, while plan-irregular and vertical-irregular buildings may experience uneven force transfer, torsional tendency, local deformation concentration and altered dynamic behaviour. The present study compares the tsunami response of regular, plan-irregular and vertical-irregular RC buildings under identical loading and modelling assumptions, so that the effect of configuration can be evaluated in a consistent technical framework.

## 2. Literature Review

Aranguiz et al. (2020) discussed tsunami evacuation and structural resilience of coastal buildings and emphasized that structural planning in tsunami-prone zones must consider both human safety and building survivability. Klapp et al. (2021) used real-scale Smoothed Particle Hydrodynamics simulation to estimate tsunami hydrodynamic force on buildings and showed that detailed topography and flow velocity strongly affect force estimation. Park et al. (2021) experimentally studied tsunami-driven debris transport and found that debris density, obstacle arrangement and collision probability significantly influence impact hazard on structures. Bhoi et al. (2022) analysed reinforced concrete buildings subjected to earthquake and tsunami forces and reported that structural configuration affects displacement and dynamic response. Cortez et al. (2022) investigated an RC building under sequential seismic and tsunami loading with soil–structure interaction and concluded that dynamic analysis gives a more realistic estimate of structural demand than simplified static methods. These studies are directly relevant because the present work also evaluates RC building response under transient tsunami loading using dynamic time-history analysis.

Tun et al. (2022) studied mitigation of tsunami debris impact on reinforced concrete buildings using fender structures and highlighted that shipping-container-type debris may generate severe concentrated impact forces. Till, Stephens and Toma (2022) reviewed international guidance for tsunami loading on buildings and noted that tsunami loading remains less understood compared with wind and earthquake loading. Del Zoppo et al. (2023) examined buoyancy effects on tsunami fragility of existing RC buildings and showed that uplift loads can significantly affect damage assessment, especially in mid-rise and high-rise structures. Joynt et al. (2024) presented analytical and numerical modelling of debris impact on columns and highlighted the need for improved prediction of debris loading on vertical structural members. Kaida et al. (2024) reviewed tsunami-induced debris collision evaluation and emphasized that debris impact assessment is essential for tsunami-resistant structural design. These studies support the inclusion of debris impact, uplift pressure and combined tsunami load components in the present research methodology.

Recent 2025 studies further show the growing importance of fragility-based and performance-based tsunami assessment. Biswas et al. (2025) evaluated tsunami fragility of open-ground-storey RC buildings with stepped column configurations and used ANN-based response prediction with Monte Carlo simulation. Oddo and Cavaleri (2025) developed earthquake–tsunami combined fragility curves for coastal masonry buildings, showing the importance of sequential hazard assessment. Rafi et al. (2025) developed tsunami fragility functions for low-rise RC buildings to support coastal resilience and disaster planning. Del Zoppo et al. (2025) proposed a time-dependent tsunami fragility framework for RC residential building stock and showed that aging and marine deterioration affect tsunami vulnerability. Dignan et al. (2025) applied real-scale SPH tsunami runup modelling to three-dimensional urban tsunami flow, demonstrating that realistic urban geometry is important for estimating wave elevation, velocity and forces. These recent works strongly justify the present study's focus on dynamic tsunami response, RC building vulnerability, time-history loading and comparison of regular and irregular building configurations.

### 2.1. Research Gap

The reviewed studies indicate that considerable work is available on tsunami hydrodynamics, tsunami force estimation and post-event damage assessment. However, comparatively fewer studies are available on ETABS-based dynamic tsunami analysis of regular, plan-irregular and vertical-irregular multistorey RC buildings using transient load functions. Many practical analyses simplify tsunami demand as an equivalent static lateral load, which cannot represent inundation rise, sustained peak water depth, impulsive bore impact and recession behaviour. The time-dependent nature of tsunami action is therefore often underrepresented in ordinary structural modelling.

Another gap is the comparative assessment of plan and vertical irregularity under tsunami-specific loading. Most irregular building studies focus on seismic response, whereas tsunami loading produces different response characteristics

because the applied forces are concentrated near lower storeys and depend on exposed interaction area. The present work addresses this gap by analysing four RC building configurations using a common tsunami time-history load case and by comparing overturning moment, roof joint displacement and storey drift.

## 2.2 Study Area

The Chennai coastal region along the southeastern coast of India was selected as the study area. Chennai faces the Bay of Bengal and is exposed to tsunami hazards generated by seismic disturbances in the Indian Ocean region. During the 2004 Indian Ocean Tsunami, several coastal areas of Tamil Nadu and Chennai experienced inundation, infrastructure damage and disruption. The city also has a high concentration of coastal buildings, transportation links and public infrastructure, making structural safety under tsunami loading an important engineering concern.

Chennai was selected because it represents a practical Indian coastal urban setting where conventional gravity and seismic design may not fully address tsunami-induced actions. The study therefore provides a relevant analytical framework for understanding how common RC building configurations may respond to severe inundation conditions. The adopted tsunami parameters were selected to represent severe coastal interaction conditions reported for the Chennai region in the project report.

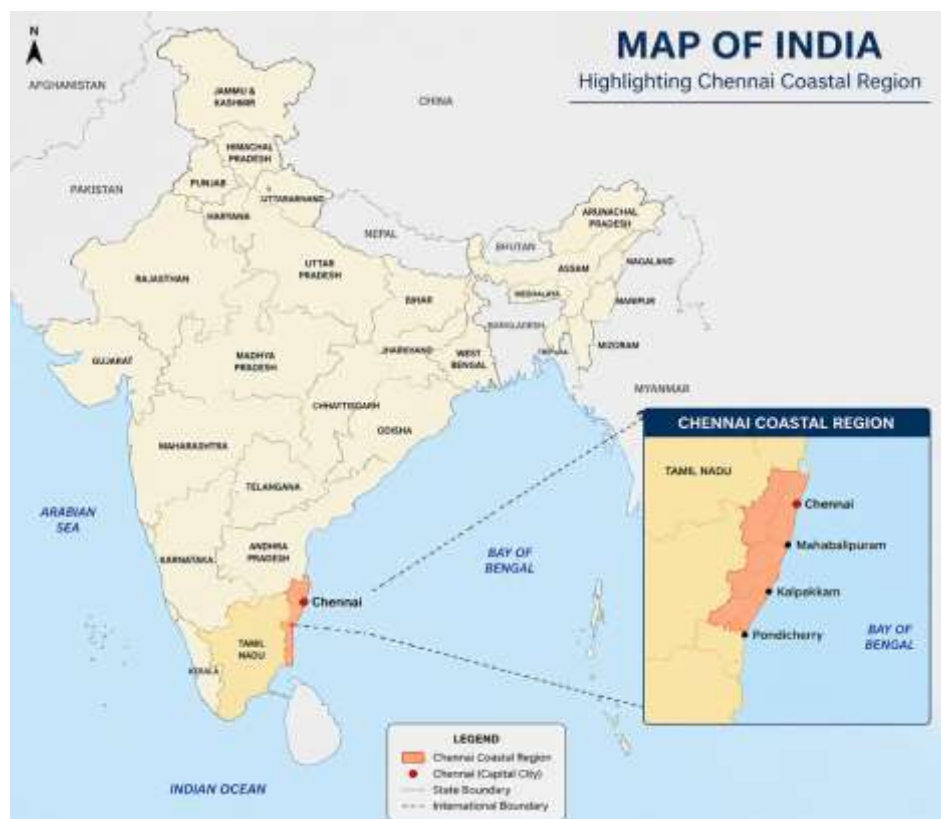


**Figure 1. Chennai coastal region selected as the tsunami-vulnerable study area.**

## 3. Methodology

The present study adopted an analytical and numerical methodology to evaluate the dynamic response of regular and irregular reinforced concrete buildings subjected to tsunami-induced loading. The complete methodology was developed to simulate realistic tsunami load behaviour on coastal RC buildings using ETABS-based linear time-history analysis. The study focused on comparing the structural performance of Regular, Plan-Irregular A, Plan-Irregular B and Vertical-Irregular building models under identical tsunami loading conditions. The response was evaluated mainly in terms of overturning moment, roof joint displacement and storey drift, as these parameters directly indicate global stability, lateral deformation and inter-storey performance of the structures under transient hydrodynamic action. The report states that tsunami loading components such as hydrostatic, drag, impulsive, debris impact and uplift forces were calculated based on FEMA P-646 recommendations and applied as transient time-varying loads in ETABS.

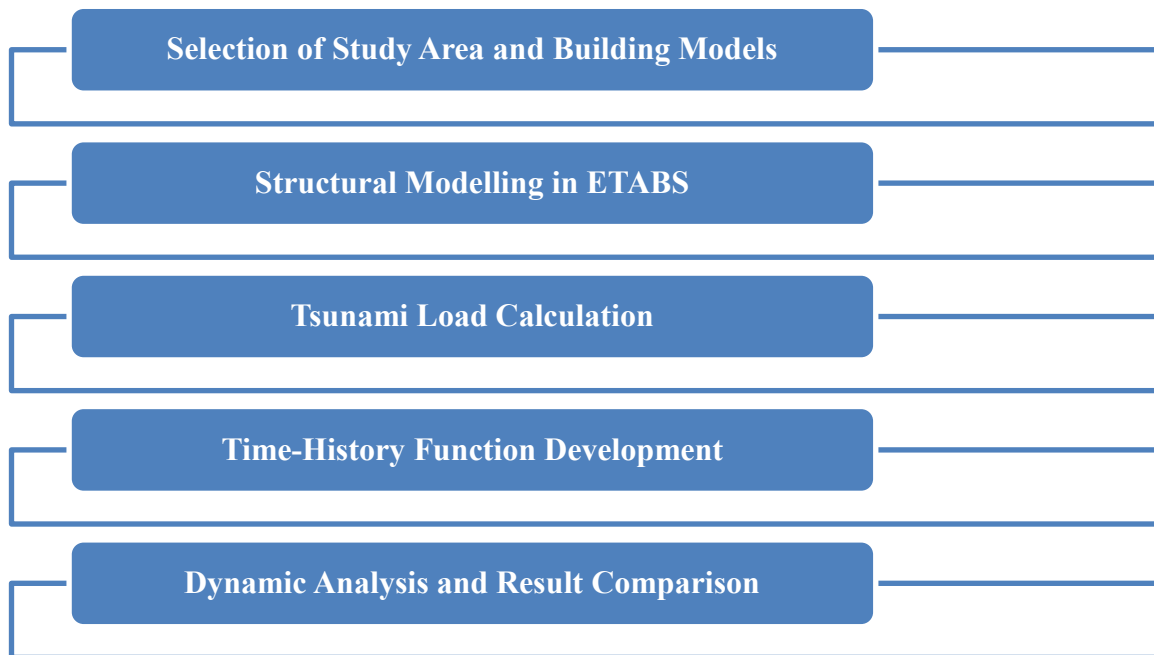


**Figure 3.1: Methodology Flowchart**

### 3.1. Selection of Study Area and Building Models

The present study was carried out for the Chennai coastal region, which is vulnerable to tsunami hazards from the Bay of Bengal. Four G+6 reinforced concrete building models were developed in ETABS: Regular Building, Plan-Irregular A, Plan-Irregular B and Vertical-Irregular Building. All models were assigned the same material properties, storey height, bay spacing, member dimensions and loading conditions to maintain a uniform basis for comparison. The tsunami flow direction was considered along the global Y-direction, and the ground storey was assumed open for tsunami flow passage.

### 3.2. Structural Modelling in ETABS

The buildings were modelled as reinforced concrete moment-resisting frame structures. Beams, columns and slabs were assigned as per the selected geometry. Fixed supports were provided at the base, and rigid diaphragm action was considered at floor levels. The building models included regular geometry, plan irregularity and vertical irregularity so that the effect of stiffness distribution and structural configuration on tsunami response could be studied properly.

### 3.3. Tsunami Load Calculation

Tsunami loads were calculated using FEMA P-646-based procedures. The major load components considered were hydrostatic pressure, hydrodynamic drag force, impulsive bore force, debris impact force and uplift pressure. These loads were calculated using tsunami parameters such as inundation depth, flow velocity, water density, drag coefficient, debris mass and impact duration. The calculated forces were applied on exposed columns, wall regions and slab elements according to the nature of loading.

### 3.4. Time-History Function Development

To represent realistic tsunami action, time-history functions were prepared in Microsoft Excel. The tsunami loading was divided into three stages: gradual inundation rise, sustained peak flow and gradual recession. Separate normalized functions were developed for hydrostatic, drag, impulsive, debris impact and uplift loads. These functions were exported as TXT files and imported into ETABS for dynamic analysis.

### 3.5. Dynamic Analysis and Result Comparison

A combined tsunami load case named **TS\_FINAL** was created in ETABS. Linear Direct Integration Time-History Analysis was performed using the Hilber-Hughes-Taylor method with 5% damping, 0.05 sec time step and 300 sec total duration. After analysis, the results of all four models were compared in terms of overturning moment, roof joint displacement and storey drift. This comparison helped identify the influence of plan irregularity, vertical irregularity and exposed tsunami interaction area on the dynamic behaviour of RC buildings.

## 9 Results and Discussion

The analysis results were extracted from the TS\_FINAL linear direct integration time-history load case. The response histories showed that tsunami demand increased during initial inundation, remained high during peak inundation and reduced during recession. This confirms that the structural response followed the intended time-varying tsunami load functions. All four models were reported as safe in the ETABS design verification under the adopted load combination; therefore, the following comparisons represent differences in relative performance rather than member failure.

**Table 4.1. Structural safety verification summary**

| Building model              | ETABS design status |
|-----------------------------|---------------------|
| Regular Building            | Safe                |
| Plan-Irregular A Building   | Safe                |
| Plan-Irregular B Building   | Safe                |
| Vertical-Irregular Building | Safe                |

**Table 4.2 Peak overturning moment for different building models**

| Building Model              | Peak OTM (kN-m) |
|-----------------------------|-----------------|
| Regular Building            | 50154           |
| Plan-Irregular A Building   | 26503           |
| Plan-Irregular B Building   | 39385           |
| Vertical-Irregular Building | 50519           |

The peak overturning moment results require careful interpretation because the numerical table shows that the lowest OTM was obtained for the Plan-Irregular A Building (26,503 kN-m), not for Plan-Irregular B. The highest OTM was obtained for the Vertical-Irregular Building (50,519 kN-m), which was only about 0.73% higher than the Regular Building (50,154 kN-m). Plan-Irregular B recorded 39,385 kN-m, which is about 21.47% lower than the Regular Building, while Plan-Irregular A recorded about 47.16% lower OTM than the Regular Building. Thus, in terms of peak overturning demand alone, Plan-Irregular A has the minimum value and the Vertical-Irregular Building has the maximum value.

However, overturning moment alone cannot be used as the only performance index. A lower OTM may result from reduced exposed area or a different force path, but it does not necessarily mean better lateral stiffness or deformation control. As shown in the displacement and drift results, Plan-Irregular A developed the highest deformation response. Therefore, the scientifically correct interpretation is that Plan-Irregular A had the lowest overturning demand but the least favourable deformation performance, while Plan-Irregular B provided a better balance between reduced OTM and controlled displacement/drift.

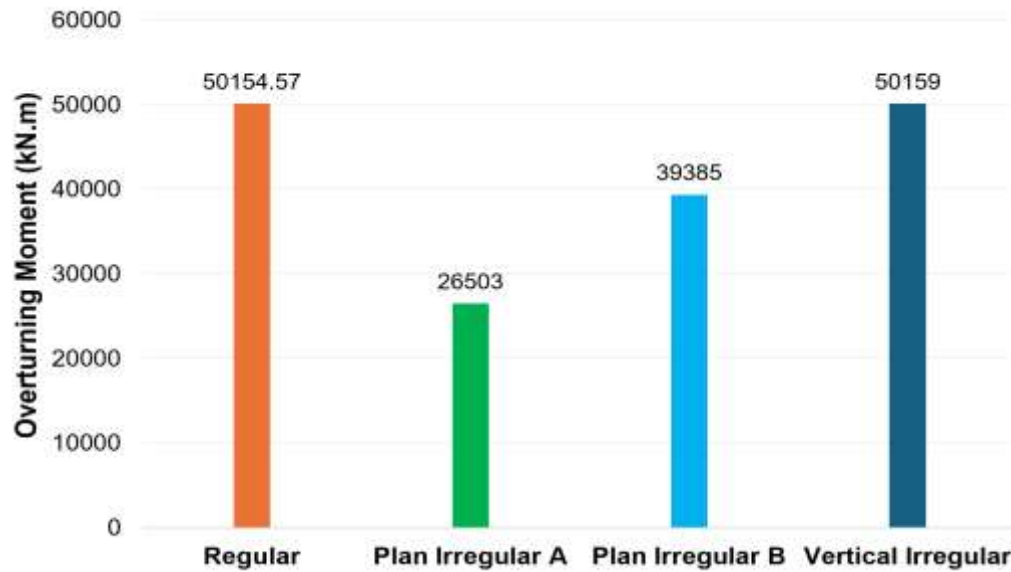


Figure 4.1 Comparison of peak overturning moment obtained from TS\_FINAL time-history analysis.

Table 4.3. Peak roof joint displacement for different building models

| Building Model              | Peak Roof Displacement (mm) |
|-----------------------------|-----------------------------|
| Regular Building            | 9.299                       |
| Plan-Irregular A Building   | 10.848                      |
| Plan-Irregular B Building   | 7.463                       |
| Vertical-Irregular Building | 9.275                       |

The roof joint displacement results indicate that Plan-Irregular A experienced the highest peak roof displacement of 10.848 mm. This value is about 16.66% higher than the Regular Building and reflects higher lateral flexibility caused by asymmetric stiffness distribution and less efficient force transfer. The larger roof displacement suggests that this configuration is more susceptible to lateral deformation during transient tsunami loading.

Plan-Irregular B showed the lowest roof displacement of 7.463 mm, approximately 19.74% lower than the Regular Building. This response may be attributed to improved force redistribution and reduced exposed tsunami interaction area. The Vertical-Irregular Building recorded 9.275 mm, nearly equal to the Regular Building value of 9.299 mm, which shows that the considered vertical irregularity had limited influence on roof-level displacement compared with plan irregularity.

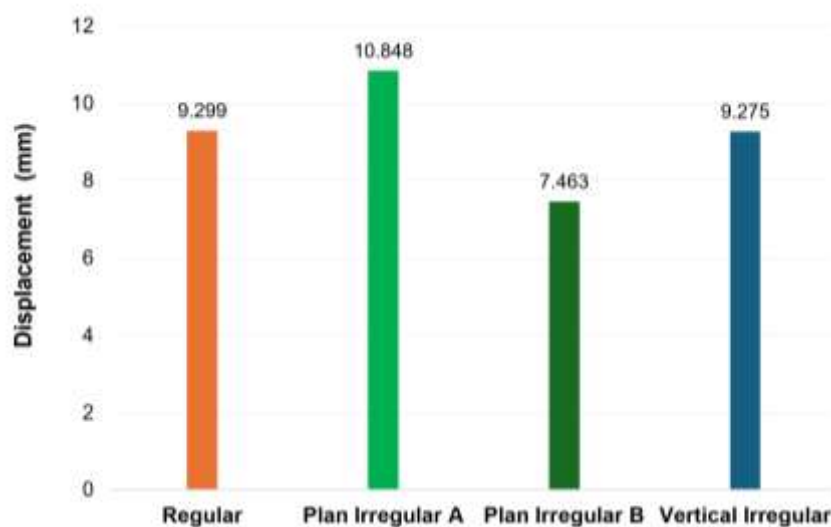


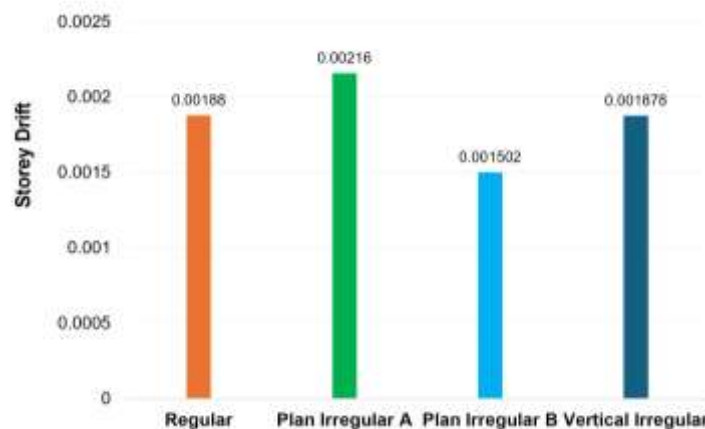
Figure 4.2. Comparison of maximum roof displacement for the four building models.

**Table 4.4. Maximum storey drift for different building models**

| Building Model              | Maximum Storey Drift |
|-----------------------------|----------------------|
| Regular Building            | 0.00188              |
| Plan-Irregular A Building   | 0.00216              |
| Plan-Irregular B Building   | 0.001502             |
| Vertical-Irregular Building | 0.001878             |

Storey drift directly represents relative lateral deformation between adjacent floors. Plan-Irregular A had the maximum storey drift of 0.00216, which is about 14.89% higher than the Regular Building. This confirms that its asymmetric and flexible plan arrangement caused greater inter-storey deformation demand. Such behaviour is critical because excessive drift may lead to cracking, non-structural damage and concentration of internal forces at vulnerable storey levels.

Plan-Irregular B recorded the lowest drift of 0.001502, approximately 20.11% lower than the Regular Building. This indicates better lateral stiffness distribution and superior deformation control. The Regular Building and Vertical-Irregular Building had almost identical drift values of 0.00188 and 0.001878, respectively. Hence, in the considered models, plan configuration had a stronger influence on storey drift than the adopted vertical irregularity.


**Figure 4.3. Comparison of maximum storey drift under tsunami loading.**

## 5. Comparative Performance Assessment

The comparative performance of the four models shows that structural configuration significantly affects tsunami-induced response. If only overturning moment is considered, Plan-Irregular A has the lowest numerical OTM and Vertical-Irregular has the highest OTM. However, deformation-based response gives a different and more useful performance picture. Plan-Irregular A shows the highest roof displacement and the highest storey drift, indicating that it is the most flexible and deformation-sensitive configuration. This makes it less favourable for tsunami resistance despite its low overturning demand.

Plan-Irregular B provides the best deformation performance because it has the lowest roof displacement and lowest storey drift. Its overturning moment is also lower than that of the Regular and Vertical-Irregular buildings, although it is higher than Plan-Irregular A. This combination indicates efficient force redistribution, reduced tsunami interaction area and favourable stiffness characteristics. Therefore, Plan-Irregular B can be considered the most suitable configuration among the analysed cases when overall stability and deformation control are considered together.

The Regular Building shows stable and intermediate response due to its symmetric geometry and uniform stiffness distribution. The Vertical-Irregular Building behaves very close to the Regular Building in displacement and drift, but it gives the highest overturning moment. This suggests that the specific vertical irregularity considered in the report mainly influenced global overturning demand, while plan geometry and exposed interaction area governed lateral deformation response more strongly.

## 6. Major Findings

1. Tsunami-induced response is significantly affected by structural configuration, exposed interaction area and stiffness distribution.
2. The peak overturning moment table shows that Plan-Irregular A has the lowest OTM value of 26,503 kN-m, while the Vertical-Irregular Building has the highest value of 50,519 kN-m.
3. Plan-Irregular A exhibits the highest roof displacement of 10.848 mm and the highest storey drift of 0.00216, showing greater lateral flexibility and deformation concentration.
4. Plan-Irregular B provides the best deformation control, with the lowest roof displacement of 7.463 mm and lowest maximum storey drift of 0.001502.
5. The Regular and Vertical-Irregular Buildings show nearly similar displacement and drift response, indicating that the considered vertical irregularity had limited effect on deformation compared with plan irregularity.
6. Linear time-history tsunami loading gives a more realistic representation of tsunami response than equivalent static loading because it captures inundation rise, peak loading and recession.
7. All analysed models were found safe in ETABS design verification under the considered gravity and tsunami loading conditions.
8. Overall tsunami performance should be judged using multiple response parameters; overturning moment alone is not sufficient for identifying the best structural configuration.

## 7. Conclusion

This study presented a journal-style comparative dynamic analysis of tsunami-induced loads on regular and irregular RC buildings in a coastal region. Four G+6 RC building configurations were analysed in ETABS using a combined tsunami load case consisting of hydrostatic pressure, hydrodynamic drag force, impulsive bore impact, debris impact and uplift pressure. The tsunami loading was represented using normalized time-history functions developed in Excel and imported into ETABS, and the final TS\_FINAL load case was analysed using linear direct integration with the HHT method, 5% damping, 300 s duration and 0.05 s time step.

The results demonstrate that tsunami response is governed by structural geometry, stiffness distribution, exposed tsunami interaction area and transient inundation behaviour. Based on the actual result tables, Plan-Irregular A developed the lowest peak overturning moment but also the highest roof displacement and storey drift. Hence, it cannot be classified as the best configuration when deformation safety is considered. Plan-Irregular B showed the lowest roof displacement and drift, along with a lower OTM than the Regular and Vertical-Irregular Buildings, making it the most favourable overall configuration in the present comparative study.

The Regular Building showed satisfactory and stable behaviour due to uniform stiffness distribution. The Vertical-Irregular Building showed displacement and drift similar to the Regular Building but developed the highest overturning moment. The study confirms that realistic dynamic tsunami analysis is necessary for coastal RC structures and that plan configuration can strongly influence tsunami force interaction and deformation response.

## 8. Engineering Implications

The findings are useful for structural engineers, coastal planners and disaster management authorities involved in the planning and assessment of buildings in tsunami-prone areas. For structural engineers, the study demonstrates the importance of considering hydrostatic, hydrodynamic, impulsive, debris and uplift components together in a time-history framework. For coastal planners, the results show that building geometry and exposed frontal area can influence tsunami demand and should be considered during layout planning. For disaster management authorities, the study supports the need for vulnerability assessment of existing coastal RC buildings, especially buildings with unfavourable plan irregularity and high deformation tendency.

## 9. Future Scope

Future work may include nonlinear time-history analysis to capture cracking, yielding, strength degradation and collapse mechanisms. Fluid-structure interaction modelling using computational fluid dynamics may be used to obtain more

detailed pressure distributions around irregular geometries. Soil-structure interaction, scour effects, foundation erosion and foundation uplift should be included to evaluate complete structural stability during tsunami inundation. Future studies may also consider multi-directional tsunami loading, different inundation depths and velocities, debris accumulation, repeated debris impacts and validation using experimental wave-flume data or field observations.

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