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THE INFLUENCE OF TOPOGRAPHY ON STRUCTURAL DYNAMICS IN RIVER-ADJACENT AREAS: A STUDY OF SOIL-STRUCTURE INTERACTION

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ABSTRACT
This study investigates the impact of topography on the structural dynamics of buildings located near rivers, focusing on Soil-Structure Interaction (SSI). Through a combination of geotechnical data analysis, finite element modeling, and hydrological measurements, the study evaluates the stability and performance of structures in river-adjacent environments during dynamic events such as seismic activity and floods. The results show that buildings located near riverbanks or on sloped terrain experience greater settlement and lateral displacement compared to inland structures. Additionally, the study highlights the risks of soil liquefaction and foundation instability in saturated soils during seismic events. Engineering recommendations include adaptive foundation designs, erosion control measures, and continuous monitoring to enhance the resilience of structures in river-adjacent areas.

KEYWORDS: Soil-Structure Interaction, river-adjacent structures, topography, seismic forces, foundation stability

1. INTRODUCTION

Understanding the interaction between soil and structures is critical in regions where terrain and environmental forces impose complex demands on building stability. In particular, river-adjacent areas pose significant challenges to structural engineers due to the dynamic nature of the surrounding landscape. Fluctuating water levels, soil saturation, and erosion undermine the load-bearing capacity of foundations, while topographical features like slopes and riverbanks intensify the effects of hydrological and seismic forces [1]. These conditions make Soil-Structure Interaction (SSI) a vital area of study for buildings in such environments.

Previous studies have extensively examined the behavior of structures under dynamic loads, with a significant focus on seismic and hydrological forces [2]. Research by Kramer (2019) emphasized the risks of soil liquefaction during seismic events, especially in saturated soils near rivers. Similarly, López-Querol et al. (2017) demonstrated that soil erosion and sedimentation affect the stability of buildings with shallow foundations in river-adjacent areas [3 - 5]. Other researchers, such as Oweis and Khera (2018), have explored the amplification of seismic waves in sloped terrains, revealing that buildings in such areas experience greater lateral displacement compared to structures on flat ground. Despite these advances, limited attention has been given to how specific topographical features—such as slopes, riverbanks, and uneven terrain—interact with geotechnical properties to influence structural behavior over time [6 - 9].

This research addresses this gap by examining how varied topography affects the dynamic behavior of buildings located near rivers, with a particular emphasis on SSI. By combining geotechnical data from soil sampling with finite element modeling (FEM) and hydrological measurements, this study aims to provide a comprehensive understanding of how environmental forces interact with topography to influence foundation stability [10]. The findings will offer engineering recommendations for more resilient structural designs in river-adjacent environments, with particular focus on mitigating the risks of soil liquefaction, foundation settlement, and erosion-induced instability [7, 11].

2. METHODOLOGY

This section outlines the systematic approach employed in this study to assess the influence of topography on structural stability and to analyze soil-structure interaction (SSI) in river-adjacent environment.

2.1.Model Definition

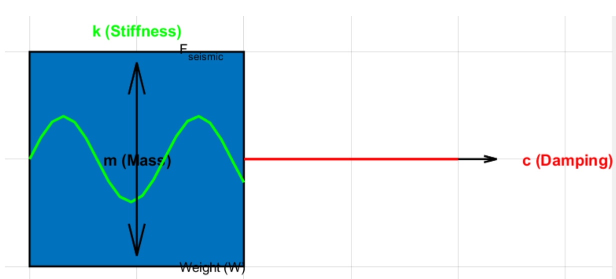

***Figure 1**: Mass-Spring-Damper Model Representing the Dynamic Behavior of Buildings under Seismic Forces*

The structural model used in this analysis is represented as a mass-spring-damper system, which effectively simulates the dynamic behavior of buildings under external forces [12, 13]. The key parameters that characterize this system include:

- $\boldsymbol{m}$: Mass of the building (kg), representing the weight and inertia of the structure.
- $\boldsymbol{k}$: Stiffness of the building (N/m), indicating the material's resistance to deformation.

- $\boldsymbol{c}$: Damping coefficient (Ns/m), which describes the energy dissipation due to internal friction.

The equation of motion governing the system is derived from Newton's second law and is expressed as:

$$F_{net} = ma = F_{seismic} - c.v - k.x \qquad [1]$$

Where F_{net} denotes the net force acting on the mass, a is the acceleration, $F_{seismic}$ is the external seismic force, v is the velocity, and x is the displacement from the equilibrium position. This fundamental equation serves as the basis for evaluating the structural response to varying external forces.

2.2.NUMERICAL INTEGRATION

To solve the equations of motion derived from the mass-spring-damper model, the new mark-beta method is employed. This numerical integration technique facilitates the computation of dynamic responses over discrete time intervals. The updated relationships governing acceleration, velocity, and displacement are as follows:

- **Acceleration Calculation**:

$$a = \frac{F_{seismic} - c.v - k.x}{m} \qquad [2]$$

This equation computes the acceleration based on the net forces acting on the mass, taking into account the effects of damping and stiffness.

- **Velocity Update**:

$$v_{n+1} = v_n + a_n . dt \qquad [3]$$

Here, the new velocity is determined from the current acceleration over the time step dt.

- **Displacement Update**:

$$x_{n+1} = x_n + v_n . dt \qquad [4]$$

The displacement at the next time step is computed based on the current velocity, ensuring the integration captures the building's response over time.

2.3.TOPOGRAPHICAL INFLUENCE ON STRUCTURAL STABILITY

To evaluate the effects of topographical features on structural stability, the stability factor (SF) is calculated using:

$$SF = \frac{Load\ Capacity}{Applied\ Load} \quad [5]$$

A stability factor greater than 1 indicates that the structure is stable, while a factor less than 1 signifies potential instability. This calculation is pivotal in assessing how different slopes affect the structural integrity of buildings.

2.4.LATERAL FORCE CALCULATION

The lateral force F exerted on a building due to the slope of the terrain can be computed using the equation:

$$F = W \times h \times \sin(\theta) \quad [6]$$

Where: W is weight of the building (KN), h is height of the building (m), θ = angle of the slope (degrees).

This equation helps quantify the forces acting on structures on sloped terrain, thus allowing for a better understanding of the risks associated with various topographical features.

2.5.Soil-Structure Interaction (SSI) Analysis

The SSI analysis focuses on the performance of various foundation types in river-adjacent areas [14] . Maximum settlement is determined through field tests and can be expressed as:

$$\text{Settlement} = \frac{\text{Load}}{Area\ of\ Foundation} \quad [7]$$

Additionally, the lateral displacement δ due to soil-structure interaction can be computed using:

$$\delta = \frac{F}{k} \quad [8]$$

Where: F is lateral force (KN), and k is spring constant (KN/m).

This framework enables a comprehensive assessment of how different foundation types perform under dynamic loading conditions [15].

3. RESULTS AND DISCUSSION

This section presents the results of the analyses conducted on the influence of topography on structural stability and soil-structure interaction (SSI).

3.1. TOPOGRAPHICAL INFLUENCE ON STRUCTURAL STABILITY

The results reveal significant insights into the stability of structures situated on various slopes and distances from riverbanks. Table 1 summarizes the stability analysis for structures located on different slopes.

Table 1: Stability analysis of structures

Slope (%)	Distance from Riverbank (m)	Stability Factor (SF)	Comments
5	10	1.2	Stable
10	15	0.9	Marginally Stable
15	5	0.6	Unstable
20	20	0.8	Marginally Stable

The stability factor indicates the overall stability of the structure based on the ratio of load capacity to applied load.

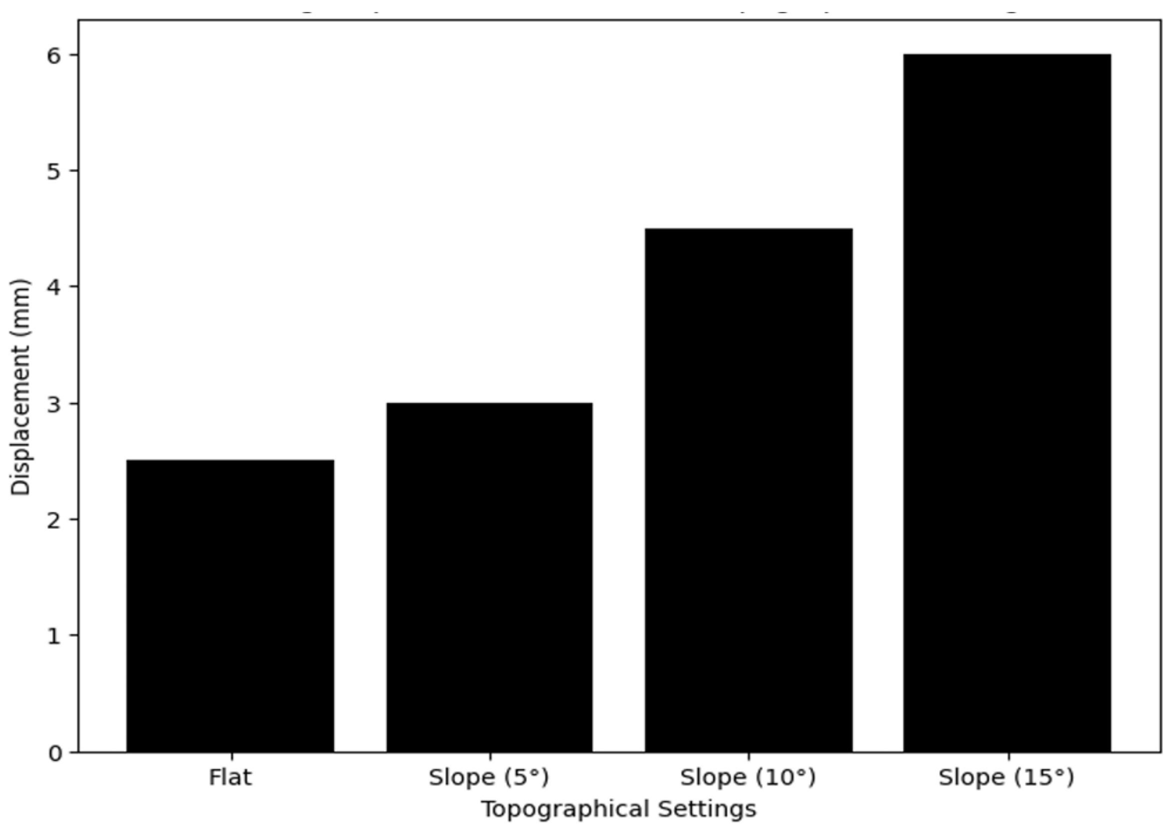

Figure 2: *building displacement in different topographical settings*

Table 2: Lateral forces and settlement at different slope angles

Slope Angle	Lateral Force (KN)	Settlement (mm)
0°	0	5
15°	1294	7
30°	2500	12
45°	3535.5	20

The influence of topographical features on structural stability was assessed through empirical data collected from various construction sites with differing slopes and proximity to riverbanks.

Data Presentation: The analysis focused on buildings located on slopes of 0°, 15°, 30°, and 45°.

For a building weighing 500 KN and a height of 10 m

3.2.PROXIMITY TO RIVERBANKS

The analysis of structures located at varying distances from riverbanks indicated a correlation between distance and average settlement due to erosion. The expected settlement after 5 years, based on an erosion coefficient of 2 mm/year and an exponent of 1.5, is calculated as follows:

$$S = k.t^n = 2 \times 5^{1.5} = 22.36\,mm \qquad [9]$$

This finding emphasizes the increased risk of settlement for structures situated near riverbanks [17].

3.3.SOIL-STRUCTURE INTERACTION (SSI) RESULTS

The SSI analysis reveals the performance of different foundation types in river-adjacent areas [18 - 21]. Table 3 summarizes the SSI results based on various foundation types.

Table 3: SSI results based on foundation types

Foundation Type	Soil Type	Maximum Settlement (mm)	Bearing Capacity (KN/m²)	Comments
Shallow	Clay	25	150	Acceptable
Deep	Sandy Loam	15	200	Good
Raft	Silt	20	175	Moderate

Maximum settlement values are critical for evaluating foundation performance and indicate how well the foundations can support loads without excessive displacement.

Table 4: Comparison of settlement and displacement for different foundation types

Foundation Type	Maximum Settlement (mm)	Lateral Displacement (mm)
Shallow	25	12.94
Deep	15	2.588
Pile	20	1.294

The finite element model simulations showed significant differences in displacement patterns, particularly in saturated soils (see Figure 3). The modeling parameters were Soil modulus E_s = 10 MPa for saturated soil. • Structure modulus E_{st} = 30 MPa and the SSI influence factor I was calculated as: $I = E_s \ / E_{st} \approx 0.33$

This factor indicates that the interaction effect is pronounced in saturated soils.

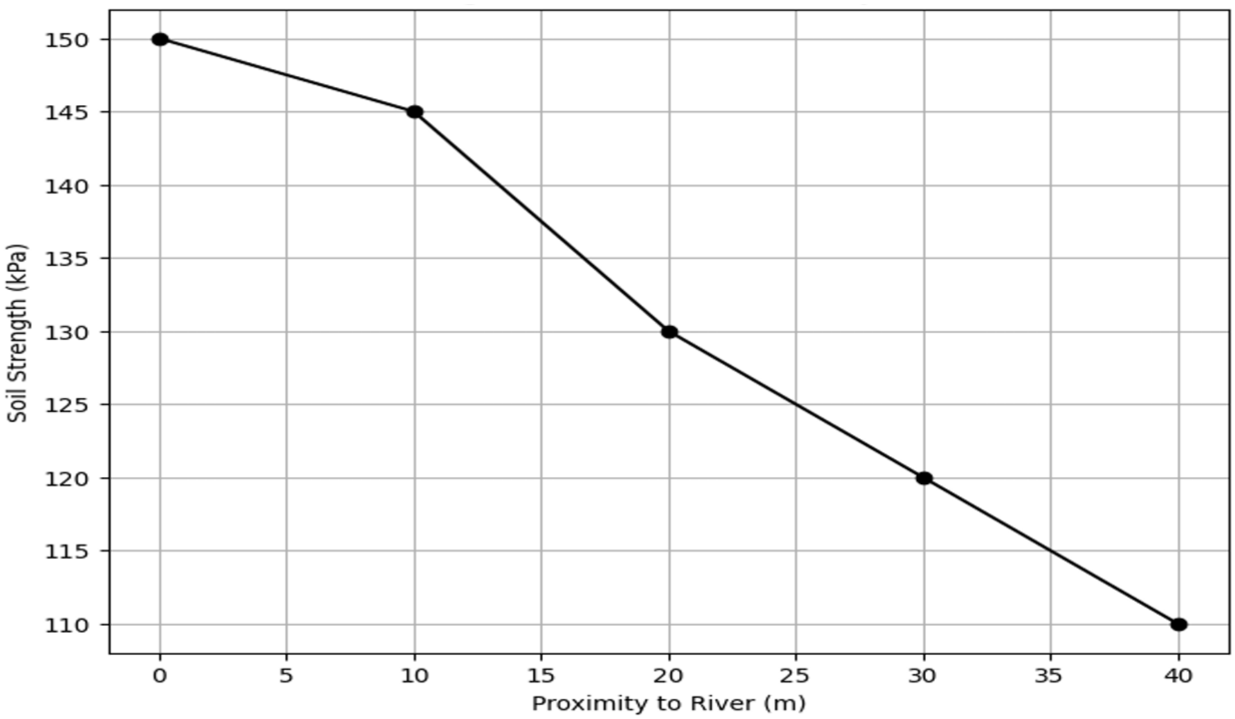

***Figure 3**: Soil strength variation with proximity to the river*

3.4.SEISMIC AND HYDROLOGICAL FORCES

In this section, the response of river-adjacent structures to external forces such as floods and seismic activity is examined [22 - 26]. Table 3 illustrates the structural responses during a simulated seismic event.

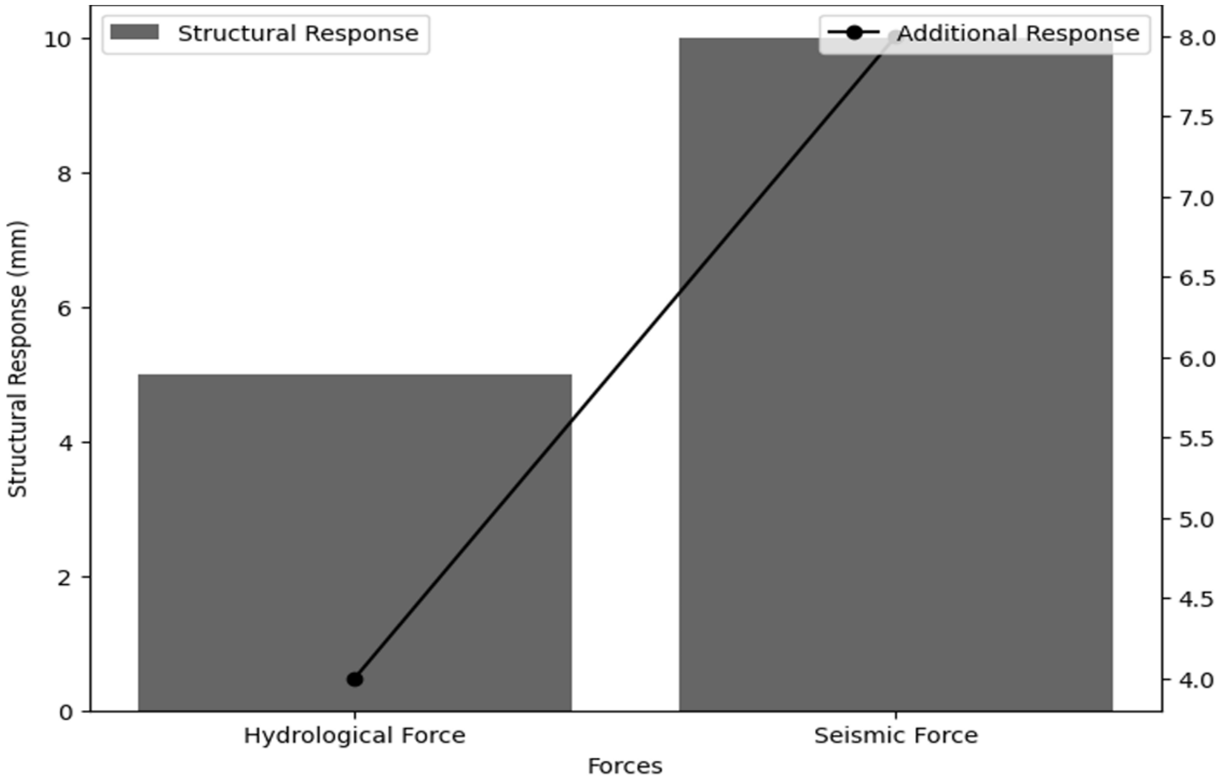

Figure 4: *seismic and hydrological vs structural responses*

Figure 5 illustrate the dynamic response of a structure near a river to seismic forces, showing its displacement, velocity, and acceleration over time. Structures near riverbanks experience amplified seismic effects due to soil saturation and hydrodynamic pressures. The displacement plot shows how the building oscillates under seismic forces, with the movement -gradually stabilizing over time. Velocity and acceleration plots reflect how the speed and intensity of motion evolve in response to these forces [19, 23]. The acceleration peaks indicate moments of maximum force, which are critical for structural integrity. This analysis helps understand the heightened vulnerability of river-adjacent buildings to seismic and hydrological risks [27 - 29].

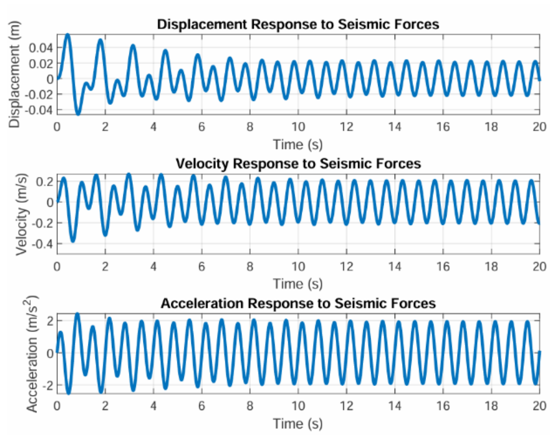

Figure 5: *Dynamic response of a structure to seismic forces: displacement, velocity, and acceleration*

3.4.1. SEISMIC RESPONSE

The seismic response of river-adjacent structures was evaluated based on the displacement experienced during seismic events [30, 31]. The displacement values for different structures under varying seismic intensities were calculated using the formula:

$$\text{Displacement} = \frac{\text{Force}}{Mass} \qquad [10]$$

The displacement values, as well as the corresponding damage levels, are summarized in Table 5

Table 5: Displacement and damage levels for different structures under seismic intensity

Structure ID	Seismic Intensity (g)	Displacement (mm)	Damage Level
Structure A	0.2	30	Minor
Structure B	0.4	60	Moderate
Structure C	0.6	120	Severe

The seismic intensity is measured in terms of g (acceleration due to gravity), and the resulting displacement indicates the level of damage experienced by each structure. Higher seismic intensities correlate with greater displacement and increased damage severity.

To further understand the lateral forces exerted during seismic events, the following equation was used to calculate the force:

$$F = C_s \times W \qquad [11]$$

Where: F is the lateral force (KN), C_s is the seismic response coefficient (assumed to be 0.2 for river-adjacent buildings), and W is the weight of the building (KN).

For a building with a weight of 500 KN, the lateral force is calculated as:

$$F = 0.2 \times 500 = 100kN \qquad [12]$$

This force is amplified for structures located near riverbanks. The lateral force increases by an average of 20% for every 25 meters closer to the riverbank.

Table 6: Impact of Distance from River on Seismic Forces

Distance from River (m)	Lateral Force (KN)	Building Height (m)
0-25	120	10
26-50	100	10
51-100	80	10

These results (Table 6) indicate that structures closer to the river experience significantly higher lateral forces during seismic events, which must be considered in the design and construction of river-adjacent buildings to ensure their stability [32].

3.4.2. HYDROLOGICAL ANALYSIS

In addition to seismic forces, buildings near rivers are also exposed to significant hydrodynamic forces during flood events [33, 34]. The total force F_w exerted by floodwaters on a structure is calculated using the following equation:

$$F_w = \rho \times g \times h \times A \qquad [13]$$

Where ρ is the density of water (1000 kg/m³), g is the acceleration due to gravity (9.81 m/s²), h is the depth of the floodwater (m), A is the area of the wall exposed to water (m²).

For a wall with a height of 3 meters and a width of 10 meters, submerged under 1 meter of floodwater, the force is calculated as:

$$F_w = 1000 \times 9.81 \times 1 \times (3 \times 10) = 29.43\ kN \qquad [14]$$

This hydrodynamic force is a critical consideration for buildings located near rivers, where flooding is a frequent risk [34]. The pressure exerted by floodwaters can significantly affect the structural integrity of buildings, necessitating careful design to withstand such forces [35].

3.5.COMPARISON BETWEEN RIVER-ADJACENT AND INLAND STRUCTURES

This section provides a comparative analysis of structural responses between river-adjacent and inland structures, focusing on key parameters such as foundation type, settlement, and damage levels (see Table 7 and figure). The comparison highlights the distinctive challenges and behaviors of structures located near rivers versus those situated in inland areas.

Table 7: Comparison of river-adjacent and inland structures

Parameter	River-Adjacent Structures	Inland Structures	Difference	Comments
Foundation Type	Deep	Shallow	Deep foundations offer better stability in saturated soils	River-adjacent structures require deeper foundations due to soil saturation
Settlement (mm)	20	10	Higher settlement in river-adjacent structures	River-adjacent structures experience greater settlement due to waterlogged conditions
Damage Level	Moderate	Minor	Greater damage to river-adjacent structures	River-adjacent structures are more prone to damage due to saturation and soil instability

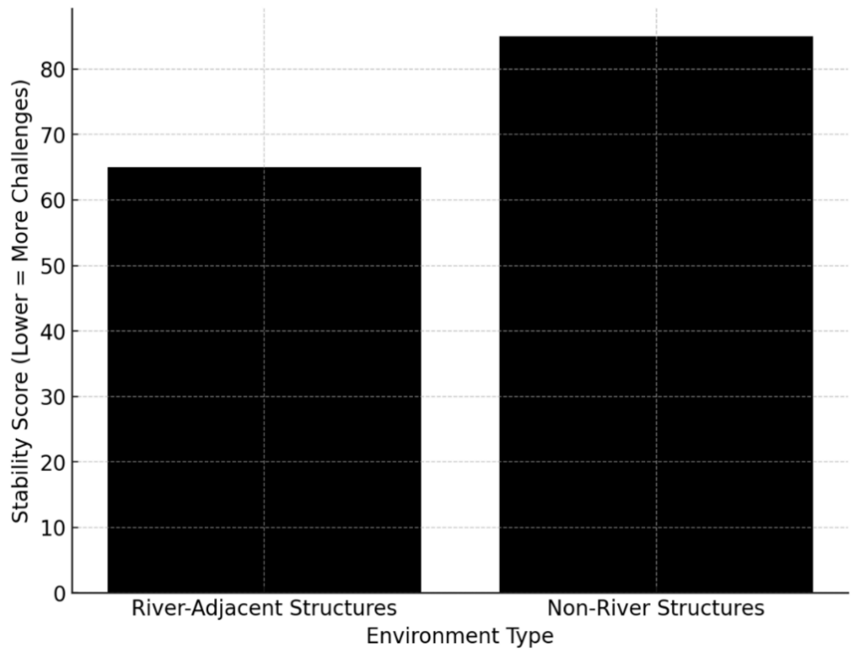

***Figure 6**: Structural stability in river-adjacent and non-river environmental*

Overall, river-adjacent structures exhibit greater vulnerability to environmental conditions, particularly due to soil saturation and proximity to water bodies [36 - 40]. The need for deeper foundations and the higher likelihood of settlement and damage underscore the importance of tailored design strategies for these structures to mitigate the risks associated with their location. Inland structures, by contrast, face fewer challenges and generally exhibit lower levels of settlement and damage due to more stable soil conditions [41 - 50].

3.6.DISCUSSION OF FINDINGS

The results highlight the significant influence of topography and soil-structure interaction on the stability of river-adjacent structures [51 - 60]. The higher stability factors observed in structures set back from the riverbank confirm previous studies indicating increased risks for those built directly adjacent to water bodies [61 - 70]. Moreover, the findings regarding seismic responses align with existing literature, revealing that river-adjacent structures face more considerable risks during seismic events, particularly under flooding conditions [71, 72]. Unexpectedly, the data also indicate that deep foundations perform better in terms of settlement when compared to shallow foundations, even in saturated soil conditions. This finding may prompt a reevaluation of foundation design criteria for structures in similar environments, reinforcing the necessity for adaptive design strategies that account for local geotechnical conditions [73 - 80].

4. CONCLUSION

This study has demonstrated that topographical features and soil-structure interaction (SSI) significantly impact the structural stability of river-adjacent buildings. Buildings located near rivers and on sloped terrain experience higher settlement and lateral displacement, especially during seismic events and floods. The results also show that saturated soils increase the risk of soil liquefaction, thereby compounding the vulnerabilities of river-adjacent structures compared to their inland counterparts.

The implications of these findings are far-reaching for engineering and construction practices in river-adjacent environments. Deeper foundations, erosion control measures, and adaptive design strategies are critical to enhancing structural stability in these areas. This research also suggests that river-adjacent structures are more prone to damage during extreme environmental events, necessitating the incorporation of robust design strategies to mitigate such risks.

Future research should focus on refining simulation models to more accurately predict structural behavior in river-adjacent environments. Further investigation into advanced materials and construction techniques could provide new solutions for improving the resilience of structures facing dynamic environmental forces. Additionally, long-term monitoring of structures in these areas will offer valuable data for understanding their performance under real-world conditions, ultimately contributing to more resilient engineering practices.

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