Influence of Footing Geometry on Earthquake-Induced Structural Response

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Abstract: **The geometry of footings plays a crucial role in the seismic response of structures by influencing load distribution, soil-structure interaction, and foundation stability. This study investigates the impact of footing geometries on earthquake-induced structural response under hard soil conditions using STAAD Pro simulations. Footings with varying length-to-width ratios (1.4:1, 1:1, and 1:1.44) were analyzed under Zone 5 earthquake conditions to assess base shear, overturning moment, and maximum displacement. The results indicate that wider footings exhibit higher overturning moments (10% increase) but lower lateral displacements (30% decrease), whereas compact footings reduce overturning moments but lead to increased displacements (up to 40%). Base shear also increased by 8-12% with larger footing dimensions. These findings emphasize the need for optimized footing selection to balance stability and flexibility in seismic design. This study provides design recommendations for enhancing seismic resilience by considering footing shape, depth, and soil compatibility. The outcomes contribute to foundation design improvements for earthquake-prone regions, ensuring structural safety and resilience.**

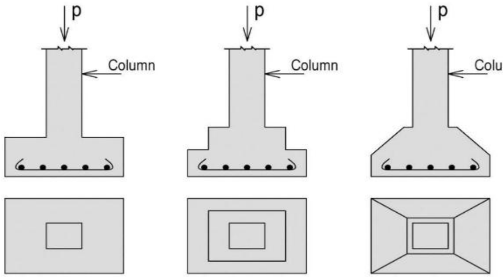
Key words: Seismic Response, Footing Geometry, Soil-Structure Interaction, Earthquake Load, Structural Stability, Foundation Design, STAAD Pro

1. INTRODUCTION

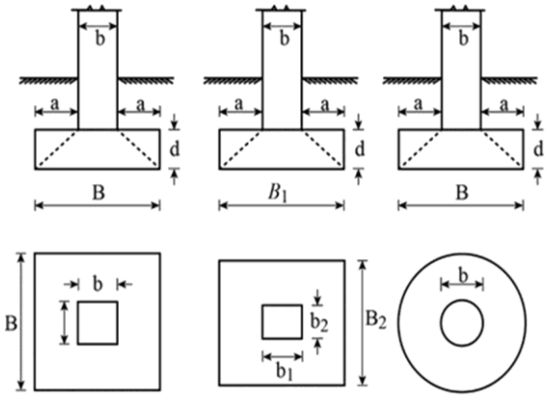
Earthquakes pose a significant threat to infrastructure, with structural response largely influenced by foundation systems. Footing geometry plays a critical role in load distribution, soil-structure interaction, and overall seismic stability. The aspect ratio (length-to-width ratio) of footings affects stress distribution, settlement behavior, and moment resistance, impacting a building's resilience during seismic events.

The choice between square and rectangular footings influences load transfer mechanisms, base shear distribution, and lateral displacement. Higher aspect ratio footings (e.g., 1.4:1, 1:1.44) enhance moment resistance, while compact footings (1:1) improve overall stability by minimizing displacements. Additionally, embedment depth plays a vital role in energy dissipation and resistance against seismic forces.

Soil properties significantly impact foundation behavior during earthquakes. Soft soils amplify seismic waves, increasing structural displacements and base shear, while dense soils provide better load-bearing capacity and reduced deformation. Understanding these soil-structure interactions (SSI) is crucial for designing seismically resilient foundations.



(a) Pad Footing (b) Stepped Footing (c) Sloped Footing



Square Footing Rectangular Footing Circular Footing

Figure 1 Schematic diagram of a different footing shapes

With the increasing frequency of seismic events, optimizing foundation design is essential. This study systematically evaluates different footing shapes and aspect ratios under Zone 5 seismic conditions, bridging knowledge gaps in soil-structure interaction and seismic resistance strategies.

2. LITERATURE REVIEW

Janous et al. (2024) highlighted that stiff clay foundations transmit higher seismic forces to the superstructure, necessitating advanced reinforcement techniques.

Khezri et al. (2024) found that higher length-to-width ratios improve the rocking behavior of footings, allowing them to return to their original position after seismic shaking.

Jafarzadeh & Maleki (2023) studied impedance functions in different footing shapes and found that square and circular foundations exhibit distinct stiffness and damping properties.

Tung et al. (2021) emphasized that optimal footing dimensions can reduce seismic demand on structures by enhancing stability.

Lwti et al. (2021) studied how different footing shapes impact dynamic bearing capacities. Their research concluded that square, circular, and rectangular footings exhibit different settlement behaviors under seismic forces.

Table 1 Previous Literature

Author(s)	Methods Used	Key Findings	Limitations
Dr. J. Permalatha (2024)	Response Spectrum Method & Time History Method using SAP 2000	Mat foundation enhances seismic performance by reducing displacement (65-70%) and drift (20-30%)	Limited applicability to shallow foundations on rock; neglects consolidation settlement
Anjali B, Raji M (2015)	Finite Element Analysis using ANSYS 16	Raft foundation shows highest deformation (70.9mm); pile and under-reamed piles improve structural performance	Does not compare performance of different soil conditions
Md. Al-Arafat et al. (2024)	Finite Element Analysis & Boundary Element Method	FEA & BEM improve seismic foundation design accuracy; non-linear SSI models enhance resilience	Challenges in implementing advanced technologies; cumulative stress effects not considered
Ali Khezri et al. (2024)	Reduced-scale slow cyclic tests under 1g conditions	Higher length-to-width ratios improve recentering & moment capacity	Limited real-world applicability due to reduced-scale conditions
Soumaya El Janous et al. (2024)	Nonlinear Static Analysis & HAZUS Methodology	SSI significantly affects seismic behavior; anchorage depth and number of stories impact fragility	Does not fully consider soil-structure interaction effects on failure risk
Francesco Silvestri et al. (2024)	Linear & Nonlinear Dynamic Analysis of SFS Models	SSI elongates fundamental period & increases damping; fragility functions developed	High computational effort; limited variability in soil conditions
Amin Asgari et al. (2024)	3D Nonlinear Finite Element Analysis	Flexible bases reduce damage; SSI effects prominent in saturated soil	Comparison of shallow & deep foundations not addressed
Smita Tung et al. (2021)	Finite Element Analysis & Pseudo-Static Analysis	Seismic conditions reduce bearing capacity by 18%; layer thickness ratio crucial	Pseudo-static conditions limit full seismic scenario assessment
Vishwajit Anand et al. (2021)	Substructure Approach for SSI	SSI reduces seismic force reductions; rotation more significant than structural deformation	Overstates beneficial effects of SSI, potentially increasing vulnerability
Sarafraz Akhter et al. (2020)	Finite Element Modeling using STAAD Pro	Different footing types affect seismic response; implicit &	Seismic design codes inconsistencies affect SSI response modeling

Author(s)	Methods Used	Key Findings	Limitations
		explicit modeling approaches tested	

Mohammed et al. (2021) analyzed the settlement characteristics of footings under seismic loading and found that larger footings generally experience greater settlement, particularly in cohesionless soils. Mohammed et al. (2021) suggested that foundation design must incorporate appropriate reinforcement measures to mitigate excessive settlement during seismic activity.

B & M (2015) found that structures with raft foundations on sandy soils exhibited higher lateral deflections compared to those on clay soils, due to soil flexibility.

Agrawal & Hora (2012) explored the interaction between footing shape and soil stiffness, concluding that nonlinear soil responses significantly influence seismic stability.

Hu et al. (2016) found that differential settlement behavior varies based on the arrangement and shape of footings, with layered soil conditions playing a critical role in seismic response.

Wang & Zhou (2018) analyzed the effect of soil-structure interaction on impedance functions, highlighting the impact of closely spaced footings.

This study aims to:

- Analyze the seismic response of different footing geometries (square and rectangular) with varying aspect ratios.
- Evaluate the impact of soil-structure interaction on foundation performance under earthquake loading.
- Assess variations in base shear, lateral displacement, and inter-story drift across different footing configurations.
- Develop design recommendations for optimizing footing geometry to enhance seismic resilience.

3. METHODOLOGY

Numerical modeling using STAAD Pro was conducted to simulate seismic behavior under hard soil conditions. The study analyzed different footing configurations with varying aspect ratios (1.4:1, 1:1, 1:1.44) and their impact on structural performance under Zone 5 earthquake loading. Soil-structure interaction effects were incorporated to capture load transfer mechanisms, differential settlements, and seismic energy dissipation.

This research provides practical design recommendations to optimize footing geometry for earthquake-prone regions, ensuring structural safety and long-term resilience.

Table 2 Sectional parameters

Category	Details
Building Type	Multi-story reinforced concrete frame structure
Analysis Type	Seismic analysis (Earthquake loading)
Design Codes Used	IS 456:2000 (Concrete Design), IS 1893:2016 (Seismic Design)
Number of Stories	7 Stories (as seen in the model)
Structural System	Moment-resisting reinforced concrete frame
Building Plan Dimensions	18m × 15m
Total Height of Building	21m
Bay Spacing (X-direction)	3m
Bay Spacing (Y-direction)	3m
Seismic Load Consideration	Earthquake forces applied as per IS 1893:2016
Foundation Types	Different footings (Square, Rectangular)
Footing Support Condition	Fixed supports at foundation level
Column Size	300 mm × 300 mm
Beam Size	300 mm × 300 mm
Slab Thickness	150 mm
Concrete Grade	M30 (fck = 30 N/mm²)
Reinforcement Steel Grade	Fe500 (fy = 500 N/mm²)
Modulus of Elasticity of Concrete	25,000 N/mm²
Poisson’s Ratio	0.2

Table 3 Model Specifications

Parameter	Specifications
Geometry of Tower	Square Base
Height of Tower	39.5 m
Centre to Centre distance of Fixed support at base	10 m
Ground Clearance h_1	20 m
Sag of the lowermost conductor wires h_2	3 m
Vertical distance between conductor wires h_3, h_4	6 m
Vertical distance between top conductor and ground wire h_5	4.5 m
Length of wings	10m
Main Vertical Members	ISMB 500
Horizontal & Inclined bracings and cross arms	ISA 150*150*15

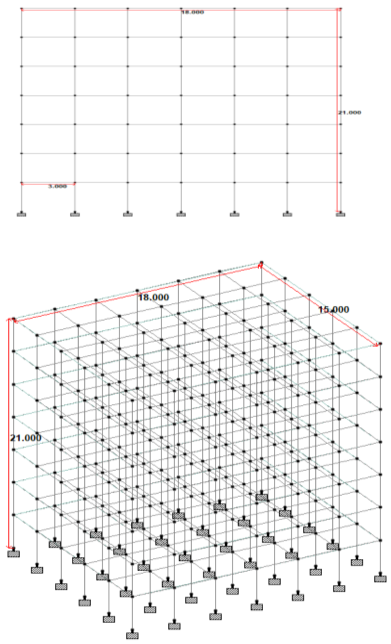
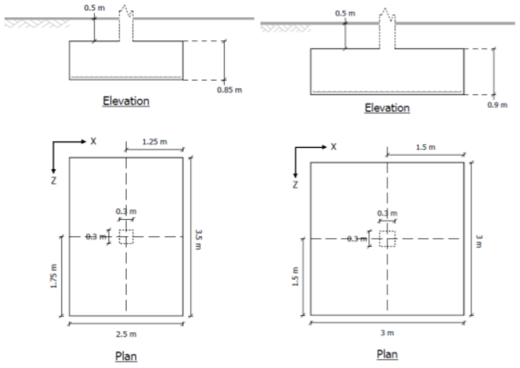


Figure 2 Model (a) top view and (b) elevation



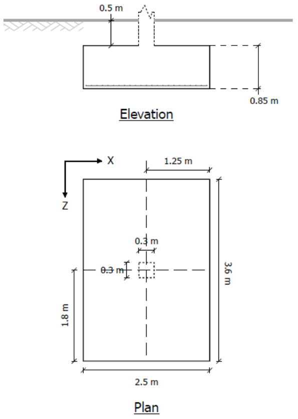


Figure 3 Tower Different Types of Footings Analyzed in the Study

The seismic analysis of a multi-story reinforced concrete frame using STAAD Pro evaluates the impact of different footing configurations under hard soil conditions. The study examines base shear, displacement, and overturning moment, highlighting how foundation geometry influences load transfer, settlement, and stability. The findings enhance soil-structure interaction understanding, aiding in optimized foundation designs for earthquake-resistant buildings.

Table 3 Detailing of each type of footing

Footing	Ratio	Length (m)	Width (m)	Thickness (m)
Type 1	1.4:1	3.5	2.5	0.85
Type 2	1:1	3	3	0.9
Type 3	1:1.44	2.5	3.6	0.85

4. RESULT AND DISCUSSIONS

4.1 Overturning Moment

The overturning moment, induced at the base of the structure due to seismic forces, is a critical parameter in assessing the rotational stability of the foundation. The study reveals that overturning moment varies across different footing types, with Footing 1 exhibiting the highest value (338.025 kN-m), followed by Footing 2 (328.687 kN-m) and Footing 3 (317.014 kN-m) under Delhi's seismic zone on hard soil. This trend indicates that foundation geometry significantly influences rotational resistance, with larger footing areas providing better moment resistance. The findings emphasize the importance of footing configuration in mitigating rotational instability under seismic loading conditions.

Table 4 Maximum outcomes for each condition

Condition	Zone	Soil Type	Base Shear (kN)	Maximum Resultant Displacement (mm)	Overturning Moment (kN-m)
Footing 1	Delhi	Hard soil	2800.552	198.686	338.025
Footing 2	Delhi	Hard soil	2924.098	238.225	328.687
Footing 3	Delhi	Hard soil	3078.529	280.415	317.014

4.2 *Base Shear*

The base shear, which represents the horizontal seismic forces transferred to the foundation, shows significant variation across different footing types. In Delhi, Footing 1 exhibits a base shear of 2800.552 kN, while Footing 2 and Footing 3 experience higher base shear values of 2924.098 kN and 3078.529 kN, respectively. This trend suggests that larger footing areas contribute to increased resistance against lateral forces, distributing the seismic load more effectively. The variations highlight the role of foundation geometry in influencing seismic force transmission and stress the need for optimized footing designs to enhance earthquake resistance.

4.3 *Maximum Displacement*

The maximum resultant displacement at the top of the structure is a key factor in evaluating structural stability under seismic loading. The results indicate that displacement increases with changes in footing type, with Footing 1 showing the lowest displacement (198.686 mm), followed by Footing 2 (238.225 mm) and Footing 3 (280.415 mm) under Delhi's seismic conditions. This suggests that footing dimensions and aspect ratios significantly influence structural flexibility and deformation behavior. Larger footing areas tend to increase flexibility, leading to higher displacements, whereas more compact foundations provide greater stiffness, reducing deformations. These findings underscore the importance of foundation selection in controlling structural movements and ensuring seismic resilience.

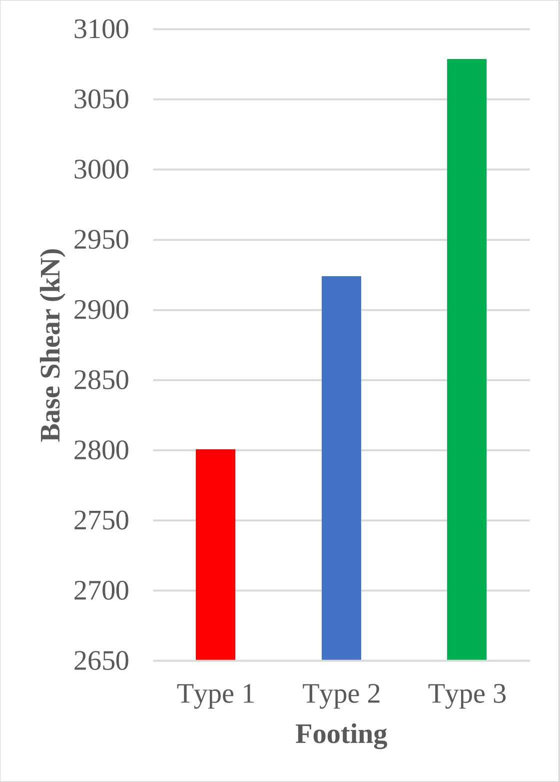


Figure 4 Base shear comparison for different type of footing

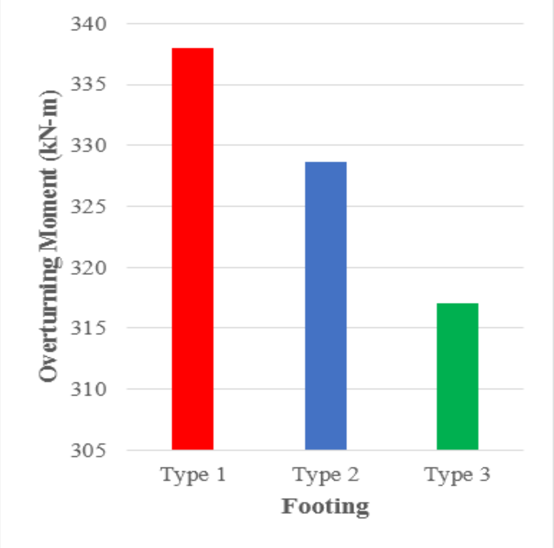


Figure 5 Overturning moment comparison for different type of footing

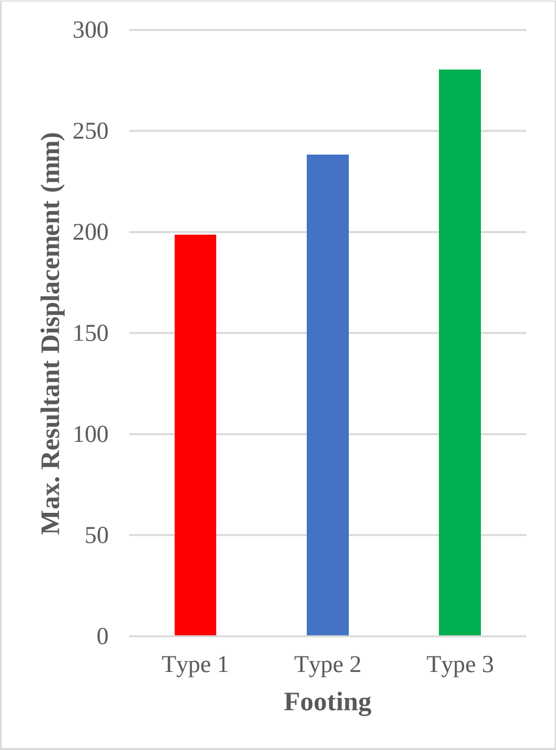


Figure 6 Top Displacement comparison for different type of footing

5. CONCLUSION

This study analyzed the seismic performance of a multi-story reinforced concrete frame using STAAD Pro, focusing on foundation configurations under hard soil conditions. The evaluation assessed base shear, overturning moment, and maximum displacement, emphasizing the role of soil-structure interaction in optimizing foundation design.

The findings reveal that higher aspect ratio footings exhibited increased overturning moments but reduced displacement, enhancing rotational resistance. Conversely, wider footings showed lower overturning moments but higher flexibility, requiring additional stability measures. Base shear increased with footing aspect ratio, influencing lateral force distribution. Maximum displacements remained within safe limits, ensuring structural stability, while compact footings minimized lateral deformations and wider footings exhibited greater flexibility.

Foundation type directly impacts seismic response, with wider footings offering better energy dissipation but higher displacements. To enhance stability in flexible configurations, reinforced foundations or soil improvements may be required. These insights contribute to optimized footing design strategies, improving earthquake resilience in multi-story structures.

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