

Structural Analysis of Reinforced Concrete Foundations Under Axial, Lateral, and Eccentric Loading for Bending and Shear Responses

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Abstract

Reinforced concrete foundations are subjected to axial, lateral, and eccentric loads that influence their bending and shear behavior and overall structural safety. This study presents a structural analysis of an isolated reinforced concrete foundation supporting a three-storey building under these three loading conditions. The methodology defines foundation load, bearing pressure, overturning moment, eccentric moment, flexural stress, shear stress, and utilization ratios, and applies them consistently to each loading case. Bending moment and shear force distributions along the normalized footing position are evaluated, and a normalized response index is used for comparison. Results show that eccentric loading produces the highest bending moment, flexural stress, and shear force, with a shear utilization ratio of 0.89. Axial and lateral loading reach 50.9 and 77.2 percent of the eccentric bending response, respectively. Eccentric loading is therefore the governing condition for foundation design. Controlling eccentricity during design and construction is essential to maintain safety margins.

Keywords— Reinforced concrete, Foundation, Axial load, Lateral load, Eccentric load, Bending, Shear.

1. Introduction

Reinforced concrete foundations are used to distribute the forces of a structure to the underlying soil and play a key role in the safety and serviceability of a structure [1]. In practice, foundations will not only experience an axial column load, but also lateral and eccentric loads, these which induce extra bending moments and shear demands. The effects change along the footing and may have a significant impact on the internal force distribution of the footing section [2]. Lateral forces create overturning moments and eccentric loads change the line of action from the centroid of the footings and create non-uniform soil pressures. Therefore, the bending and shear responses to such loading can vary significantly from that under simple axial loading. Unconservative designs could result if these effects are not considered, especially when designing for footings supporting heavy loaded columns in multi-story structures where load offsets and horizontal actions are unavoidable[3].

Thus, it is important to understand the effect of these loading conditions on the response of a structure to be able to design a reliable structure [4]. This study considers a three-storey reinforced concrete building with its isolated footings under the action of axial, lateral and eccentric loading, and compares its bending and shear response to determine which is the controlling condition [5]. Flexural stress, shear stress and utilization ratios are compared at critical points along the footing length. Each loading case is also ranked according to the normalized response index [6]. This evaluation can be used to verify that the flexural and shear capacities are still adequate in practice for each loading case determined [7]. The results offer a sound reference to identify the critical loading situation, and to enhance the safety and dependability of the design of reinforced concrete foundation.

1.1 Problem Statement

In the design of foundations, the axial load is usually the only one considered, and the lateral and eccentric effects are treated approximately [8]. This method might underestimate bending and shear demand, especially at the interface of the column and the footing [9]. It is necessary to compare all three loading situations on the same base and find the critical situation in order to make the structural safe [10].

1.2 Research Motivation

In real buildings, horizontal forces and load offsets can be introduced by wind, construction tolerances and non-uniform loading. These effects can cause moments to increase in the footing, shear to increase in the footing and may lead to a reduced safety margin. This encouraged to compare systematically the axial, lateral and eccentric loading on the same reinforced concrete foundation.

1.3 Research Significance

The results can guide designers to identify the loading condition where the foundation is operated and provide appropriate checks in practice. The results of the study indicate the correlation between bending moment, flexural stress, shear force and utilization ratio, which is helpful to the design of safe and economical foundation and gives a clear reference for eccentric loading effect evaluation.

1.4 Key Contributions

- Proposed a common method for assessing the reinforced concrete foundation response under axial loading, lateral loading and eccentric loading.
- Derived the analytical relationships for foundation load, bearing pressure, overturning and eccentric moments, flexural stress and shear stress.
- Calculated bending moment and shear force sections of the footing for the normalized footing position for each loading condition.
- Introduced normalized response (NR) and shear utilization ratio (SUR) to characterize the condition of eccentric loading.

1.5 Organization of the Paper

The rest of this paper is organized as follows. The related work is reviewed in Section II, the proposed methodology in Section III, the obtained results are presented and discussed in Section IV with a comparative assessment, and the conclusions of the study along with its practical design implications and suggestions for future research are presented in Section V.

2. Related Works

El-Naqeeb et al. [11] studied the lateral response of GFRP reinforced concrete columns using closed-type winding ties. The effects of shear-span ratio, axial load, concrete strength, tie size, spacing, and configuration were investigated using a validated numerical model and parametric study. The results showed an improvement in confinement, lateral performance, and deformation capacity, particularly when using high-strength concrete. At high levels of axial loading, tie size and tie spacing became more important. Future work should look at optimizing configurations further and experimentally validating the findings.

Cengiz et al. [12] examined reinforced concrete columns exposed to combined axial load, bending and torsion through cyclic testing of ten column specimens. The axial load ratio, the torsional rotation, the lateral drift, and the stirrup spacing were varied to evaluate the structural response. The results indicated that torsion reduced the energy dissipation, the ductility and the plastic rotation, but increased the plastic hinge length. The results demonstrate coupled-action effects, whereas the research should improve interaction models for seismic design.

Shen et al. [13] studied the reinforced concrete columns under blast loading with different eccentric positions of charge. Numerical simulations with the RHT concrete model, overpressure datasets and SDOF validation supported half-scale field blast tests. Effect of column dimensions, reinforcement, scaled distance, explosion location and axial compression was included in parametric analyzes. The results showed that closer charges favored shear failure. Additional studies are needed to broaden the eccentric blast conditions and improve the predictive equations.

Duan et al. [14] studied flexure-shear response of reinforced concrete bridge piers through seven cyclic column tests and system-level OpenSees simulations. The variables studied were shear-span ratio, transverse reinforcement and longitudinal reinforcement. The fiber approach and AFSI-MBTEM approach were compared. It was found that shorter shear spans increased resistance but aggravated cracking and postpeak deterioration. Shear-sensitive modeling improved the prediction of response. Further research is needed to improve system level models for reliable structural assessment of shear-critical bridge structures.

Ors et al. [15] investigated punching shear in reinforced concrete footings by three-dimensional nonlinear PLAXIS 3D modeling. The verification was carried out with nine square footing tests under vertical loading. A parametric study was conducted to evaluate the effects of concrete strength, column aspect ratio, punching reinforcement, soil stiffness and subgrade reaction. The results indicated significant effects on punching capacity and settlement. The developed equations improved the code predictions. The validation can be extended to different loading conditions and wider soil–foundation configurations in the future work.

3. Proposed Methodology

The methodology that is proposed in this paper examines the structural response of reinforced concrete foundations when subjected to axial, lateral and eccentric loading conditions. The analysis takes into account foundation geometry, concrete properties, reinforcement properties, applied loading, bending response and shear response. This leads to the determination of the critical loading condition in the foundation's performance and safety by comparing the resulting structural parameters.



Fig. 1. Research Methodology Flowchart for Structural Analysis of Reinforced Concrete Foundations

Fig.1 shows the sequence of the study, starting with building and foundation modelling, followed by loading analysis under axial, lateral, and eccentric loading. The resulting bending and shear responses are then evaluated and compared to determine the overall foundation performance.

3.1 Building and Foundation Modelling

A representative three-storey reinforced concrete building model is chosen and the gravity and lateral load transfer path between the superstructure and the foundation is set. The foundation pattern is determined based on the layout of the building, the positions of columns, and the type and level of support for each column. The size (the length, width and thickness) of the foundation depends on the loads on the column and the structural and soil conditions that it must meet. The concrete grade, reinforcement grade, reinforcement diameter, reinforcement spacing and concrete cover are determined based on the standard structure design. The geometry of the foundation is represented along with the connection between the columns and the footings to ensure that the loads are transferred from the superstructure to the foundation properly, both axially and laterally. The foundation configuration selected is used as a basis for the bending and shear response analysis and the material and reinforcement properties remain the same throughout the analyses of the structural response of the foundation under various axial, lateral and eccentric load conditions.

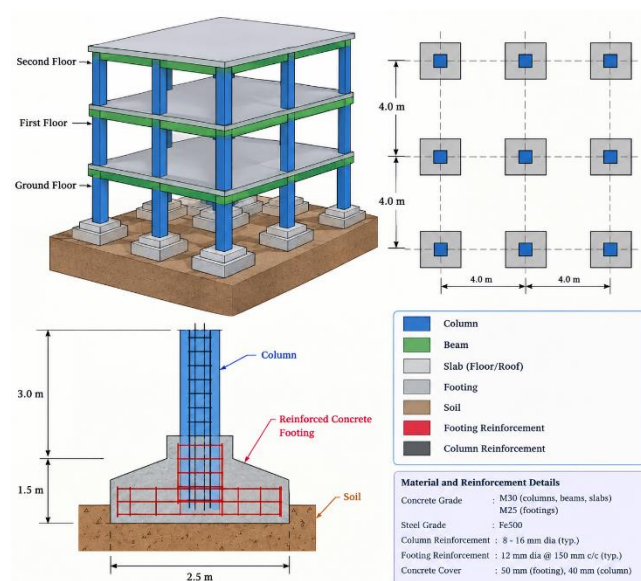


Fig. 2. Three-storey reinforced concrete building and foundation configuration with material and reinforcement details

Fig. 2 shows the representative three-storey reinforced concrete building (ground, first and second floor) supported on isolated footing. The plan view is a 3×3 grid with the distance between columns and rows of 4.0 m. It is a sectional detail of a 3.0 m high column supported on soil with a 2.5 m wide by 1.5 m deep reinforced concrete footing. The details of the material used are M30 for columns and beams, M25 for footing and Fe500 steel. Column reinforcement is 8-16 mm diameter and footing is 12 mm bar at 150 mm c/c. Concrete cover is 50 mm for footing, and 40 mm for column.

3.2 Loading Analysis

The loading analysis consists of the assessment of the reinforced concrete foundation's response to axial, lateral and eccentric loading. These loading cases are used individually to assess the impact on the foundation stability, load distribution, bending moments, shear forces, and overall structural performance.

3.2.1 Axial Loading

Axial loading is the vertical force that is carried down in the building column to the foundation by approximately concentric loading. The soil reaction is calculated over the contact area of the foundation and used to assess the establishment of structural demand. The average bearing pressure which is generated by the axial loading is given by eqn. (1).

$$q_a = \frac{P}{A_f} \quad (1)$$

Here q_a is the average soil bearing pressure due to the axial loading; P is the applied axial load; and A_f is the effective foundation area.

3.2.2 Lateral Loading

Lateral loading is a horizontal load that is applied to the foundation via the building column. This loading condition will cause extra shear and overturning in the foundation and a non-uniform structural response. The overturning moment created by the lateral force is given as eqn. (2).

$$M_L = Hh \quad (2)$$

Where, M_L is the product of the lateral load H and its effective height h from the foundation level.

3.2.3 Eccentric Loading

An eccentric loading is applied when the vertical load is placed at a certain distance from the centroidal axis of the foundation. The eccentricity creates in addition an extra moment and changes the soil pressure distribution under the foundation. Is defined in eqn. (3).

$$M_e = Pe \quad (3)$$

Where, M_e eccentric moment, P applied axial load, and e eccentricity between the point of load application and the centroid of the foundation.

3.3 Bending Response Analysis

The bending response of the foundation is determined through calculating the bending moment created from the applied loading conditions and the flexural stress of the section of the foundation made of reinforced concrete. Axial, lateral and eccentric loads are taken separately to calculate the bending demand. The flexural stress due to the computed bending moment is obtained by means of section properties. The bending stress relation is given in eqn. (4).

$$\sigma_f = \frac{M}{Z} \quad (4)$$

Here, σ_f denotes the flexural stress, M the bending moment imposed on the foundation section and Z the section modulus of the foundation cross-section. The bending demand is also compared with the flexural capacity of the reinforced concrete section to allow for foundation structural limit check. The flexural utilization ratio is given in eqn. (5).

$$R_f = \frac{M_{Ed}}{M_{Rd}} \quad (5)$$

Where, R_f is the flexural utilization ratio, M_{Ed} is the design flexural moment from the imposed load and M_{Rd} is the design flexural resistance of the reinforced concrete foundation.

3.4 Shear Response Analysis

The shear response is studied through the calculation of shear force that is generated in the foundation due to the axial load, lateral load and eccentric load applied on it. Special attention is paid to critical zones in the vicinity of the column–foundation interface where forces are concentrated can generate high shear demand. The shear stress is calculated from the shear force and effective resisting area which are given as nominal shear stress. The shear stress is given in eqn. (6).

$$\tau_v = \frac{V}{b_w d} \quad (6)$$

Where, τ_v is the applied shear force, V the effective width of the foundation section, b_w ; the effective depth of the reinforced concrete section, d . The computed shear stress is checked against the related design shear to determine if the foundation is

sufficient to resist shear failure. This is then repeated for each loading condition, allowing for an easy comparison of the impact of axial, lateral and eccentric load on the shear demand.

3.5 Comparative Assessment

Structural responses due to axial loading, lateral loading, and eccentric loading are compared based on the bending moment, flexural stress, shear force, and shear stress as the main parameters of responses. The response for each loading condition is then “normalized” by dividing by the largest observed demand on the structure, so as to be able to identify which loading condition corresponds to the critical loading condition. The severity of each loading case is compared using a response index, defined by eqn. (7).

$$R_i = \frac{X_i}{X_{max}} \times 100 \quad (7)$$

Here, R_i is the response index normalized to 1 for loading condition i , and X_i is the structural response for loading condition i and X_{max} is the maximum response of loading conditions investigated.

4. Result and discussion

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4.1 Axial Loading Response

Axial loading refers to the vertical load applied to the column and then to the foundation and finally to the supporting soil. It was assessed the response of the structure in terms of bending moment and shear force in the foundation. The bending response is due to the bending load caused by the applied axial load and soil reaction, and the shear response is due to the bending load caused by the internal shear demand generated in the footing.

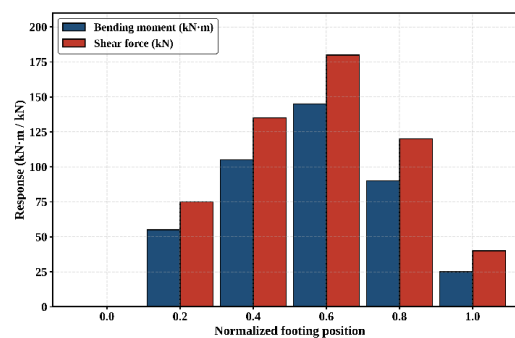


Fig. 3. Bending and shear response of the foundation under axial loading

Fig. 3 shows bending moment and shear force distribution of the foundation under the axial loading applied in the normalized ft position. The two responses start at zero at 0.0, rise steadily to their maximum values of 145 kN·m and 180 kN at 0.6, and then fall off sharply at 1.0, to 25 kN·m and 40 kN, respectively, showing a strong central response.

4.2 Lateral Loading Response

The lateral loading case was analyzed by applying a loading force horizontally on the building–foundation system. The overturning action and transfer of load to the horizontal produces extra bending and shear in the foundation as a result of the lateral force. To isolate the effects of lateral loading on the structural response, the same foundation and material configuration was retained.

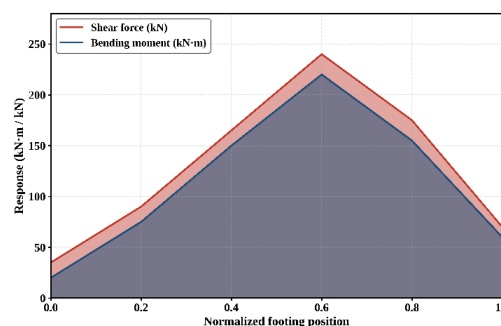


Fig. 4. Bending and shear response of the foundation under lateral loading

Fig. 4 shows the bending and shear response of the foundation when it is subject to lateral loading. Unlike axial loading, both responses start at a non-zero value of 20 kN·m and 35 kN at 0.0, peak at 220 kN·m and 240 kN at 0.6, and then decrease to 60 kN·m and 70 kN at 1.0 indicating higher structural demand than axial loading.

4.3 Eccentric Loading Response

The eccentric loading condition was analyzed by placing the axial load a certain distance from the foundation's centroidal axis. This eccentricity creates an extra moment, thus altering the distribution of demand for the structure within the footing. The two responses of bending and shear were considered to assess the impact of eccentric loading effect on the behaviour of foundation.

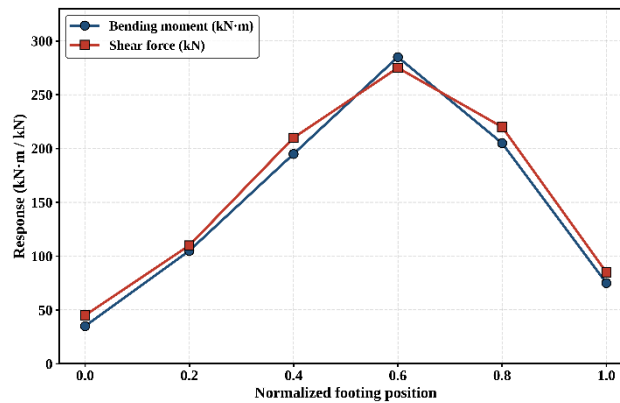


Fig. 5. Bending and shear response of the foundation under eccentric loading

Fig. 5 shows the bending and shear response of the foundation with eccentric loading. The values for both responses start at 35 kN·m and 45 kN at 0.0, rise sharply to maximum values of 285 kN·m and 275 kN at 0.6, and decrease to 75 kN·m and 85 kN at 1.0, which is the most severe loading condition of the three examined.

4.4 Bending Response Analysis

The bending response of the foundation was analysed in both the axial, lateral and eccentric loading conditions in terms of the maximum bending moment and flexural stress. The comparison was carried out under the same foundation and material conditions, avoiding the effect of loading type from other factors. The flexural performance was assumed to be for the most severe loading condition, which gave the highest bending demand.

Table 1 Comparative bending response under different loading conditions

Loading condition	Maximum bending moment (kN·m)	Maximum flexural stress (MPa)
Axial	145	2.90
Lateral	220	4.40
Eccentric	285	5.70

Table 1 shows the maximum bending moment, flexural stress and critical location per loading condition. The maximum values of axial loading, lateral loading and eccentric loading are 145 kN·m, 2.90 MPa, 220 kN·m and 4.40 MPa, and 285 kN·m and 5.70 MPa, respectively, near column, at column–footing interface and on the eccentric load side, respectively.

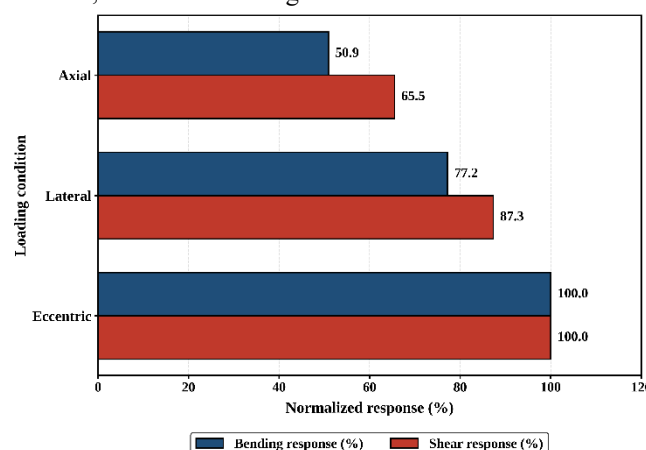


Fig. 6. Comparison of maximum bending response under axial, lateral, and eccentric loading

Fig. 6 shows the normalized bending and shear response for axial, lateral and eccentric loading compared to the maximum eccentric response. It is found that eccentric loading is the most severe loading condition for both bending and shear responses with 100% bending and 100% shear, whereas the lateral loading and bending response attain 77.2% and 87.3% respectively for the same scenario, and the axial loading and shear response attain 50.9% and 65.5% respectively under the same loading condition.

4.5 Shear Response Analysis

To determine the shear response, the shear force and shear stress generated in the foundation under the axial, lateral and eccentric loading were calculated. To make a consistent comparison of the shear demand, the same critical sections were selected for each loading condition. Shear responses calculated were compared with the shear capacity of the foundation to check the structural sufficiency of the foundation.

Table 2 Comparative shear response under different loading conditions

Loading condition	Maximum shear force (kN)	Maximum shear stress (MPa)	Shear capacity (kN)	Utilization ratio
Axial	180	0.42	310	0.58
Lateral	240	0.56	310	0.77
Eccentric	275	0.64	310	0.89

Table 2 summarized the results for maximum shear force, shear stress, shear capacity and shear utilization ratio under different loading condition. Axial loading produces 180 kN, 0.42 MPa, and a ratio of 0.58, lateral loading 240 kN, 0.56 MPa, and 0.77; eccentric loading reaches 275 kN, 0.64 MPa, and 0.89 against the 310 kN capacity.

4.6 Comparative Analysis of Loading Conditions

The overall comparison was carried out by comparing the bending and shear response of the different methods of loading (axial, lateral and eccentric). In the case of comparing the structural parameters in different loads the same parameters were used for all three load cases (bending moment, flexural stress, shear force, shear stress). This gives an equal foundation to take the most important loading situation for reinforced concrete foundation.

Table 3 Overall Comparative Assessment of Foundation Responses Under Different Loading Conditions

Loading condition	Maximum bending moment (kN·m)	Bending response (%)	Maximum shear force (kN)	Shear response (%)
Axial	145	50.9	180	65.5
Lateral	220	77.2	240	87.3
Eccentric	285	100.0	275	100.0

Table 3 shows the numerical maximum bending and shear response by loading conditions. Axial loading gives 145 kN·m (50.9%) and 180 kN (65.5%), lateral loading 220 kN·m (77.2%) and 240 kN (87.3%), and eccentric loading 285 kN·m and 275 kN (100%).

4.7 Discussion

The findings reveal that the loading condition greatly influences the bending and shear behavior of the reinforced concrete footing, where the axial load produces the normal bending and shear values, which include the maximum bending moment and shear force values of 145 kN·m and 180 kN, respectively, at the normalized position of 0.6, as well as the flexural stress of 2.90 MPa and shear utilization ratio of 0.58. The lateral loading increases the structural loads such that the maximum bending moment, shear force, and flexural stress produced at the column-footing interface are 220 kN·m, 240 kN, and 4.40 MPa, respectively, with the shear utilization ratio being 0.77. The highest critical response takes place at eccentric loading with maximum bending moment of 285 kN·m, shear force of 275 kN, and flexural stress of 5.70 MPa on the eccentric loading side. The effect of additional moment from eccentric vertical load changes the pressure of the soil and increases the demand of structure, which results in a shear utilization of 0.89 compared to a shear capacity of 310 kN. From the comparison of responses, axial and lateral loading generate only 50.9% and 77.2% of bending response and 65.5% and 87.3% of shear response, respectively, of eccentric loading. This proves eccentric loading to be the controlling loading case. Even though all the utilization ratios are less than 1.0, the lesser safety factor for eccentric loading suggests that eccentricity needs to be kept within control in foundation loading.

5. Conclusion and future works

This study evaluated the bending and shear responses of an isolated reinforced concrete footing supporting a three-storey building under axial, lateral, and eccentric loading, using identical geometry and materials (M25 concrete, Fe500 steel, 2.5 m ×

1.5 m footing). Demand increased consistently from axial to lateral to eccentric loading. Maximum bending moments were 145, 220, and 285 kN·m, flexural stresses were 2.90, 4.40, and 5.70 MPa, and shear forces were 180, 240, and 275 kN, respectively. The peak response in every case occurred at a normalized footing position of 0.6, with critical locations near the column, at the column–footing interface, and on the eccentric load side. Relative to eccentric loading, the axial and lateral cases reached only 50.9% and 77.2% of the bending response and 65.5% and 87.3% of the shear response. Eccentric loading is therefore the governing condition, with a shear utilization ratio of 0.89 against a 310 kN capacity, leaving a margin of only about 11%. Although all utilization ratios remain below 1.0 and the footing is adequate, designing for axial load alone would underestimate bending demand by roughly half. Designers should explicitly check lateral and eccentric effects and control eccentricity through accurate column positioning, construction tolerances, and, where necessary, strap or enlarged footings. Future work should validate these analytical results experimentally and through nonlinear finite element models including soil–structure interaction. It should also extend the study to combined, cyclic, and seismic loading, other footing types, and parametric variations in dimensions, reinforcement, and soil, supported by long-term monitoring of instrumented buildings.

Future research can extend the analysis to experimental validation using scaled reinforced concrete foundation specimens under controlled laboratory loading, allowing direct comparison with the analytical results. Nonlinear finite element modelling, including soil–structure interaction and different soil stiffness conditions, may further improve the prediction of foundation behavior. Additional studies can consider combined and cyclic loading, seismic effects, and different footing types such as combined and raft foundations. Parametric investigation of footing dimensions, reinforcement ratio, soil type, and concrete grade may also support optimized and more economical foundation design. Long-term monitoring of instrumented buildings can further confirm the numerical trends and support the development of practical design guidelines for eccentric loading. Surrogate models trained on such results could enable rapid design screening.

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