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A Comparative Analysis of Isolated and Tapered Footing with Insertions for Eccentric Load

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ABSTRACT

Conventional footings for boundary line columns often suffer from tilt and uneven pressure distribution due to eccentric loading, reducing their performance. While combined and strap footings are commonly used to address eccentric loads, they rely on adjacent footings, limiting their effectiveness in independent foundation systems. This study develops and evaluates two innovative designs—Isolated Footing with Insertion (IFI) and Tapered Footing with Insertion (TFI)—to mitigate these challenges. Using finite element analysis in ANSYS, the performance of these designs was assessed under varying eccentric loading conditions, with insertion depth ratios (H/B) ranging from 0 to 1.0 and eccentricity ratios (x/B) from 0.1 to 0.5. Results indicate that both designs significantly outperform conventional footings, with the IFI design reducing settlement and tilt by up to 5 times at $H/B = 1.0$. The TFI design demonstrated further improvements, delivering 1.18 to 1.39 times better performance than IFI across all insertion depths while reducing material usage by 15–20%. Optimal performance for TFI was observed at $H/B = 0.4$, striking a balance between structural efficiency and material economy. These findings highlight TFI as an efficient and economical solution for managing eccentric loads, particularly for boundary columns and space-constrained sites.

1 Introduction

The study of footings under eccentric loading is critical for ensuring the stability and safety of various structural systems. Eccentric loading occurs when the resultant force on the footing does not act through its centroid, causing bending moments that impact the footing's performance. Experimental and numerical investigations have extensively examined isolated footings under eccentric loading to understand their bearing capacity, settlement behavior, and failure mechanisms. Georgiadis and Butterfield [1] conducted pioneering research on the displacements of footings on sand under eccentric and

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inclined loads, providing valuable insights into footing-soil interactions. Singh et al. [2] and Prasad and Singh [3] further explored the effects of soil confinement on the bearing capacity of square and rectangular footings under eccentric-inclined loads, highlighting the improvements achieved through confined soil conditions. Recent studies by Kirtimayee and Samadhiya [4] demonstrated the performance of loosely skirted square footings resting on reinforced sand under vertical concentric and eccentric loading, emphasizing the influence of reinforcement on stability. Similarly, Campione [5] investigated the load-carrying capacity of square footings under concentric and eccentric loading, providing simplified analytical models for practical design applications. Additionally, Rawat et al. [6] analyzed isolated rectangular footings under biaxial bending, presenting critical appraisals and simplified analysis methodologies for dealing with eccentric loads. Moreno-Landeros et al. [7] explored optimal areas for rectangular isolated footings with eccentric columns, focusing on partial ground compression behavior. Al-Ansari and Afzal [8] provided structural analysis and design methodologies for irregularly shaped footings subjected to eccentric loading, contributing to the practical understanding of footing performance.

Combined footings, including strap footings, have been studied extensively under eccentric loading to optimize their performance. Strap footings are used to connect two or more columns with a rigid beam to distribute loads more evenly. Elsamny et al. [9] investigated the effects of eccentric loading on footings connected with tie beams, emphasizing the role of tie beam dimensions in enhancing stability under various load conditions. Nashaat [10] also examined the influence of tie beam configurations on isolated footings subjected to eccentric loads, highlighting structural response variations. Luévanos-Rojas et al. [11] presented mathematical models to optimize the cost and performance of strap combined footings, focusing on balancing economic efficiency and structural stability. Similarly, Garg and Hora [12] analyzed the space frame-strap footing-soil system under seismic loading, revealing significant interactions between structural components and soil. Aishwarya and Balaji [13] conducted an analysis and design of eccentrically loaded corner combined footings for rectangular columns, providing practical recommendations based on experimental and numerical results. Further, Luévanos-Rojas et al. [14] and Moreno Hernández et al. [15] proposed advanced mathematical models for corner strap combined footings, enhancing the understanding of footing behavior under complex loading conditions. Graciano et al. [16] expanded on the modeling of strap footings, contributing to the optimization of structural performance and cost-efficiency in engineering applications. Chandrawanshi and Garg [17] investigated how adjacent buildings influence footing forces, showing that nearby structures can affect load distribution and settlement. Chandrawanshi and Garg [18] studied the impact of multi-building arrangements on footing settlement and found that different configurations can significantly alter footing behavior.

Recent advancements in footing shapes have led to the development of innovative solutions, such as T-shaped and angle-shaped footings, to address the challenges posed by eccentric loading. Joshi and Mahiyar [19, 20] explored the moment-tilt characteristics and behavior of angle-shaped footings under eccentric inclined loading, offering insights into their performance and stability. Mahiyar and Patel [21] analyzed the behavior of angle-shaped footings under eccentric vertical loads, presenting design methodologies for practical applications. Agrawal and Mahiyar [22] conducted finite element analysis of T-shaped footings using ANSYS, demonstrating the impact of varying projection locations on structural behavior. Experimental and numerical studies by Kaya and Ornek [23] provided a comprehensive understanding of T-shaped footings, emphasizing their load distribution and settlement patterns. Kounlavong et al. [24] developed optimized CatBoost-based soft-computing models to predict the ultimate bearing capacity of T-shaped footings subjected to eccentric loads, combining machine learning with experimental data to enhance prediction accuracy. Luevanos-Soto et al. [25] introduced a minimum-cost design framework for circular isolated footings with eccentric columns, addressing partial ground compression issues. Elsamny et al. [26] examined the effect of tie beam dimension for eccentric loading, providing practical guidelines for engineering applications. Prateek and Garg [27] conducted parametric studies on hyperbolic paraboloidal shell footings, showing how different geometric configurations can improve structural response under eccentric loads. These advanced footing solutions provide practical alternatives for handling eccentric loads efficiently, ensuring improved stability and performance in diverse soil conditions.

Columns located near the boundary line of a structure often experience higher load eccentricity, leading to excessive tilt and settlement of the footing. This study focuses on improving the performance of such footings by reducing eccentricity and enhancing load transfer to the underlying soil. Two modified footing configurations are proposed: the Footing with Insertion (IFI) (Fig. 2) and the Tapered Footing with Insertion (TFI) (Fig. 3). These designs help shift the center of gravity closer to the applied load, thereby reducing tilt and settlement. While combined and strap footings are commonly used to manage eccentric loads, they rely on neighboring footings or columns, which may not be suitable in all situations, especially near property lines. To address this limitation, the study explores isolated footings with inserted geometries that function independently. The depth and thickness of the inserted portion are varied to optimize the footing shape and improve its

interaction with the soil. By refining these parameters, the IFI and TFI models offer an effective solution for reducing eccentricity and improving footing (Fig. 1) stability under boundary loading conditions.

Although a few studies have examined footings under eccentric loading by varying load positions, none have directly linked this condition to boundary line columns, where eccentricity naturally occurs due to space constraints. This study introduces a new approach by using tapered footing with insertion (TFI) to reduce the effects of eccentric loading in such boundary conditions.

1.1 Isolated Footing with Insertion (IFI)

The isolated footing with insertion (IFI) incorporates a vertical insertion of constant thickness (Fig. 2) into the base of a traditional footing, making it particularly suitable for eccentric loading. By increasing the depth of the insertion, the center of gravity (CG) of the footing shifts closer to the applied load, thereby reducing the eccentricity. This reduction in eccentricity helps minimize the moment generated by the load.

1.2 Tapered Footing with Insertion (TFI)

The tapered footing with insertion (TFI) is an advanced variation of the footing with insertion, where both the footing and insertion feature a variable thickness (shown Fig. 3). The thickness is greater at the end where the load is applied, resulting in a shift of the center of gravity (CG) more significantly compared to a standard isolated footing with insertion.

2 Problem for Investigation

This study investigated the performance of footings subjected to eccentric loading, focusing on isolated footings with insertion (IFI) and tapered footings with insertion (TFI), and comparing them to traditional isolated footings. The main objective was to explore the impact of increasing the depth of insertion for both the IFI and TFI, with the aim of improving the performance of isolated footings under eccentric loads. Specifically, the study addressed the reduction of settlement and tilt. Through a Soil-Structure Interaction (SSI) analysis, the study evaluated the interaction between the footing and the underlying soil, providing insights into the stability and effectiveness of each footing type. By comparing these footing designs, the research aimed to determine whether IFI or TFI offered superior resistance to the negative effects of eccentric loading.

2.1 Material Properties

The mechanical properties, such as the modulus of elasticity (E) and poisson's ratio (ν), are essential for understanding the behavior of soils and foundations under loads. These properties are derived based on material type, density, and load conditions as observed in various studies. The behavior of soils under eccentric loading is critically influenced by their mechanical properties, particularly elasticity (E) and poisson's ratio (ν).

Table 1- Material properties of concrete and soil for SSI analysis

Parameters	Values
Elasticity of Concrete	$2.5 \times 10^7 \text{ kN/m}^2$
Poisson's Ratio of Concrete	0.17
Elasticity of Soil	25000 kN/m^2
Poisson's Ratio of Soil	0.3
Soil Domain Size	$20 \text{ m} \times 20 \text{ m} \times 10 \text{ m}$

In present study the soil domain is assumed to be homogenous, elastic and rocky strata is available at 10 m depth. Soil domain with various sizes is modeled and it is found that the soil domain of five times the footing width (5B) on each side to ensure that the pressure bulb generated by the applied loads is fully captured within the model boundaries. Beyond this distance, the influence of stress becomes minimal, and boundary effects do not significantly alter the footing behavior.

2.2 Geometric Configuration of footing

Figures 1 and 2 illustrate the geometry of an Isolated Footing with Insertion (IFI) and a Tapered Footing with Insertion (TFI), respectively, for finite element analysis. Points P and Q are marked on these footings for comparison of the results at these locations.

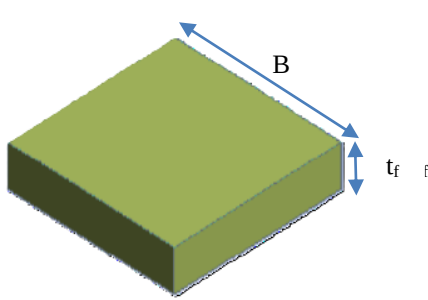


Fig. 1 – Conventional Isolated footing

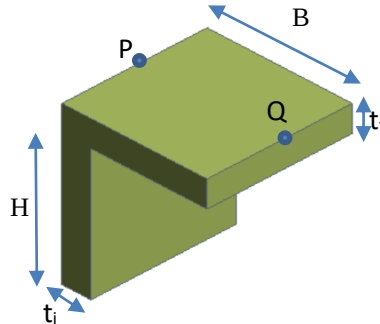


Fig. 2 – Isolated footing with insertion (IFI)

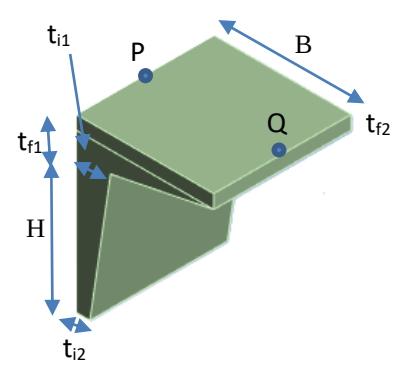


Fig. 3 – Tapered footing with insertion (TFI)

Here, H = Depth of Insertion, B = Width of footing, t_f = Thickness of footing for IFI, t_p = Thickness of insertion for IFI

t_{f1} = Thickness of footing for TFI, t_{p1} = Thickness of insertion for TFI t_{f2} = Thickness of footing for TFI

t_{p2} = Thickness of insertion for TFI, P & Q = Point at mid edge

Table 2- Size of various footing models for SSI Analysis

Footing Type	H (m)	Side of square footing (B) (in m)	Thickness of footing (m)		Thickness of insertion (m)	
Isolated footing (IF)	-	2	0.4		-	
	0.4	2	0.4		0.4	
	0.8	2	0.4		0.4	
Isolated footing with insertion (IFI)	1.2	2	0.4		0.4	
	1.6	2	0.4		0.4	
	2	2	0.4		0.4	
	0.4	2	t_{f1}	t_{f2}	t_{p1}	t_{p2}
Tapered footing with insertion (TFI)	0.8	2	0.4	0.2	0.4	0.2
	1.2	2	0.4	0.2	0.4	0.2
	1.6	2	0.4	0.2	0.4	0.2
	2	2	0.4	0.2	0.4	0.2
	0.4	2	0.4	0.2	0.4	0.2

Table No. 2 presents the dimensions of the footings used in this study, including isolated footings, footings with insertion, and tapered footings with insertion. The table specifically highlights the insertion depth (H) in the footings with insertion and tapered footings with insertion, along with their corresponding width (B). For footings with insertion, the depth varies in relation to the width, represented by the H/B ratio. Similarly, tapered footings with insertion show different insertion depths depending on their design and insertion depth ratio.

2.3 Loading on Geometry of footings

In this analysis, a 500 kN load acts on three different types of footings: isolated footing, isolated footing with insertion, and tapered footing with insertion. Figure 4 illustrates the isolated footing with insertion, with the same load applied to the isolated footing and tapered footing with insertion. The distance X from the left end varies for each footing type, taking values of 0.2m, 0.4m, 0.6m, 0.8m, and 1m. To evaluate the behavior of these footings under eccentric loading, the ratio x/B is considered, where B is the width of the footing. The values of x/B range from 0.1 to 0.5, representing different levels of eccentricity.

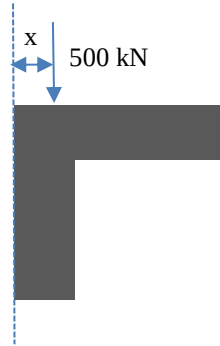


Fig. 4- Loading act on isolated footing with insertion

2.4 Centre of Gravity (CG) for IFI and TFI models

The center of gravity (CG) differs for each IFI and TFI model because each model has a unique insertion depth, as shown in Table 3. An increase in insertion depth in IFI and TFI models results in shifting the center of gravity towards the edge of the footing where the insertion is applied. In TFI models, this shift is more noticeable, as they are expected to be more stable under high eccentric loads, which occur due to the boundary line column. The position of cg shifts towards insertion by increasing depth of insertion

Table 3- Position of CG (in m) in IFI and TFI models for different insertion depths

$\begin{matrix} \text{H/B} \\ \text{Models} \end{matrix}$	0	0.2	0.4	0.6	0.8	1
IFI	1.00	0.87	0.77	0.70	0.64	0.60
TFI	-	0.77	0.68	0.62	0.57	0.53

In IFI and TFI models CG shifts towards the edge of footing where insertion is provided by increasing insertion. The center of gravity (CG) in Table 3 is measured from the left edge of the footing. It shows a reduction in CG value, from 1 meter to 0.6 meters for IFI models, and from 1 meter to 0.53 meters for TFI models, as the depth of insertion increases up to the width of the footing.

2.5 Eccentricity for IFI and TFI models

The performance of an isolated footing (IF) is generally stable under centric loads but becomes unstable, showing uneven tilt, when subjected to eccentric loads. Eccentricity, which is the difference in distance between the load position and the center of gravity (CG) from a reference axis (considered to be at the left edge of each model in this study), plays a key role in footing performance. When the CG and load position align, eccentricity becomes zero. To achieve this alignment and reduce eccentricity, the depth of insertion is adjusted. However, if the insertion depth becomes too large, it can make the structure uneconomical, so the goal is to minimize eccentricity while still maintaining the permissible tilt. By positioning the load closer to the center of gravity, eccentricity is reduced. Increasing the insertion depth in IFI and TFI models shifts the center of gravity towards the edge of the footing, where the insertion occurs, which helps to reduce the eccentricity between the applied load and the CG of the footing. This shift minimizes uneven settlement, tilt, and pressure distribution under the footing. The effect is more significant in TFI models due to the tapering action of the footing.

Table 4 presents the eccentricity values for various cases of footings with insertion and tapered footings with insertion, comparing them to those of isolated footings in both IFI (isolated footing with insertion) and TFI (tapered footing with insertion) models. The ratio of the depth of insertion to the width of the footing (H/B) is used to describe the footing geometries, where $H/B = 0$ represents an isolated footing and tapered footing with insertion starts at $H/B = 0.2$. This distinction is important because $H/B = 0$ refers to isolated footings that have no insertion or tapering.

Table 4- Comparative Analysis of Eccentricity (m) between IFI and TFI models for different load locations and insertion depths

Particulars	x/B	H/B					
		0 (IF)	0.2	0.4	0.6	0.8	1
IFI	0.1	0.80	0.67	0.57	0.50	0.44	0.40
	0.2	0.60	0.47	0.37	0.30	0.24	0.20
	0.3	0.40	0.27	0.17	0.10	0.04	0.00
	0.4	0.20	0.07	-0.03	-0.10	-0.16	-0.20
	0.5	0.00	-0.13	-0.23	-0.30	-0.36	-0.40
TFI	0.1	-	0.57	0.48	0.42	0.37	0.33
	0.2	-	0.37	0.28	0.22	0.17	0.13
	0.3	-	0.17	0.08	0.02	-0.03	-0.07
	0.4	-	-0.03	-0.12	-0.18	-0.23	-0.27
	0.5	-	-0.23	-0.32	-0.38	-0.43	-0.47
Ratio of IFI/IF	0.1	1.00	0.83	0.71	0.63	0.56	0.50
	0.2	1.00	0.78	0.62	0.50	0.41	0.33
	0.3	1.00	0.67	0.43	0.25	0.11	0.00
	0.4	1.00	0.33	-0.14	-0.50	-0.78	-1.00
	0.5	-	-	-	-	-	-
Ratio of TFI/IF	0.1	-	0.71	0.61	0.53	0.46	0.41
	0.2	-	0.61	0.47	0.37	0.29	0.22
	0.3	-	0.42	0.21	0.05	-0.07	-0.17
	0.4	-	-0.16	-0.58	-0.89	-1.14	-1.34
	0.5	-	-	-	-	-	-

For the cases where $x/B = 0.1, 0.2$, and 0.3 , the minimum eccentricity occurs when $H/B = 1$ in both IFI and TFI models, with TFI models showing slightly less eccentricity than IFI models. Interestingly, for $x/B = 0.3$ and $H/B = 1$, the eccentricity becomes zero, indicating a balanced load distribution in the IFI model. When considering $x/B = 0.4$, both IFI and TFI models show the minimum eccentricity, but at different insertion depths: for IFI, the minimum eccentricity occurs at a low insertion depth of $H/B = 0.4$, while for TFI, it is found at $H/B = 0.2$. Finally, for $x/B = 0.5$, no insertion is needed, and the eccentricity remains zero when $H/B = 0$.

2.6 Finite element Analysis

The finite element method (FEM) divides the soil and footing system into smaller elements to calculate displacements, stresses, and strains under applied loading conditions. SOLID186 (20-node hexahedral) elements are employed for regions with regular geometry, providing high accuracy in displacement and stress calculations. SOLID187 (10-node tetrahedral) elements are used for irregular geometries, ensuring precise modeling near complex boundaries, such as the soil-structure interface.

In this study, ANSYS 2023 is employed to simulate the behavior of footings subjected to eccentric loading using advanced finite element analysis (FEA). The model focuses on soil-structure interaction (SSI) and provides comprehensive insights into the performance of various footing configurations under different eccentricities and insertion depths, including SSI model of footings with insertion (Fig. 5) and tapered footings with insertion (Fig. 6). Adaptive meshing is applied to refine the mesh at critical regions, such as the soil-structure interface, load application zones, and insertion boundaries. A mesh sensitivity analysis is performed to verify that the results are independent of mesh size, and convergence is confirmed by comparing outcomes for different mesh densities, with particular attention given to settlement, tilt, and stress distributions.

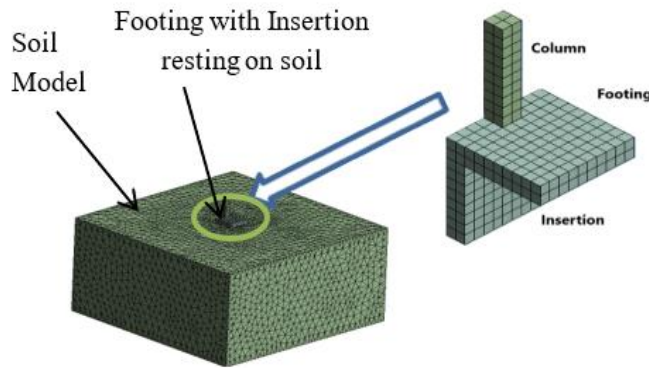


Fig. 5 - SSI Model of Isolated footing with insertion

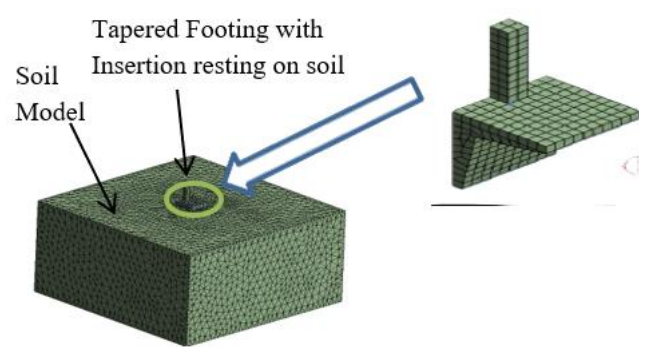


Fig. 6 - SSI Model of Tapered footing with insertion

2.7 Meshing Sensitivity Analysis

A combined mesh sensitivity analysis was performed by refining both footing and soil meshes. Table 5 shows that settlement values at points A and B stabilize as the mesh is refined. Noticeable changes occur between coarse (800/1600 mm) and medium (400/800 mm) mesh sizes. However, the results converge from mesh size 200 mm (footing) and 400 mm (soil) onward, beyond which further refinement shows negligible influence. Therefore, these mesh sizes were selected for all simulations to ensure both accuracy and computational efficiency.

Table 5- Meshing Sensitivity Analysis for Tapered Footing with Insertion

S.No.	Mesh Size (mm)		Settlement at A (mm)	Settlement at B (mm)
	Footing	Soil		
1	800	1600	-4.65	-3.01
2	400	800	-4.76	-3.17
3	200	400	-4.87	-3.26
4	100	200	-4.92	-3.28

3 Methodology

Footing performance improve by taking different depth of insertion, this study consists of various model of Isolated footing with insertion and tapered footing with insertion on ANSYS 2023 and evaluate the performance of footing.

The Flow Chart of methodology is given in Figure 7.

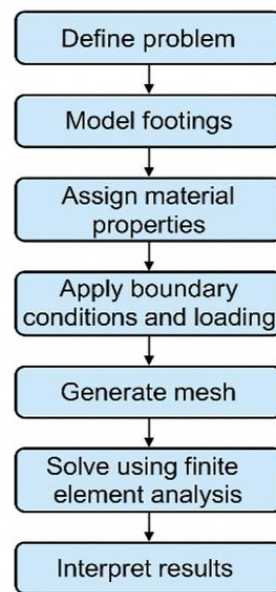


Fig. 7- Flow Chart of methodology

4 Result and Discussion

In the present study, the settlement and tilt behavior of different footing types, namely Isolated Footing (IF), Isolated Footing with Insertion (IFI), and Tapered Footing with Insertion (TFI), were compared under eccentric loading conditions. The relative settlement was determined by calculating the difference in settlement between two distant points, P and Q, located on opposite edges of the footing as shown in Figures 1 and 2, which reflects the unevenness of settlement beneath the foundation. The tilt was evaluated by dividing the relative settlement by the width of the footing, where a larger relative settlement indicated a greater tilt.

4.1 Comparative Analysis between Isolated footing (IF) and Isolated footing with insertion (IFI)

Table 6 presents a comparison between isolated footing with insertion (IFI) and isolated footing (IF) by analyzing the ratio of IFI to IF in terms of relative settlement and tilt. The $H/B = 0$ case corresponds to the isolated footing. As the H/B ratio increases, both relative settlement and tilt decrease, especially up to the load case of $x/B = 0.3$. Specifically, at $x/B = 0.1$, relative settlement reduces from 10.02 mm to 1.97 mm, at $x/B = 0.2$ it decreases from 8.28 mm to 1.18 mm, and at $x/B = 0.3$ it drops from 5.78 mm to 0.02 mm. Similarly, tilt values reduce from 5.01×10^{-3} to 1.97×10^{-3} at $x/B = 0.1$, from 4.14×10^{-3} to 0.59×10^{-3} at $x/B = 0.2$, and from 2.89×10^{-3} to 0.01×10^{-3} at $x/B = 0.3$. For the $x/B = 0.5$ case, where the load is applied 1 meter from the left edge, the performance of the isolated footing is better, and no insertion depth is needed. As the depth of insertion increases, both relative settlement and tilt increase. For $x/B = 0.4$, the tilt and settlement are minimized with a small insertion depth, with the best results observed at $H/B = 0.4$, where no tilt or settlement is produced. Standard codes, such as the IS code for concrete structures, specify a maximum tilt of 1.5×10^{-3} . This tilt limit can be met by adjusting the insertion depth based on the load position, considering the cost of work, and ensuring stability. This approach ensures both optimal performance and compliance with structural requirements.

The ratio of IFI to IF indicates the relative improvement in settlement and tilt when using IFI compared to IF. For $x/B = 0.1, 0.2$, and 0.3 , the relative settlement and tilt for IFI are 0.2, 0.14, and 0 times that of IF, respectively, as H/B increases up to 1. However, for $x/B = 0.4$, this ratio decreases up to $H/B = 0.4$ and then increases, suggesting that IFI provides better results at $H/B = 0.4$, where only a small insertion depth is needed. For $x/B = 0.5$, both relative settlement and tilt are zero for isolated footing, meaning the ratio is undefined, as isolated footing performs better in this case. This analysis demonstrates how insertion depth can be optimized to improve the performance of isolated footings depending on the load position while maintaining structural stability and meeting code requirements.

Table 6 Comparative Analysis between IF and IFI for different load locations and insertion depths

Particulars	x/B	H/B					
		0 (IF)	0.2	0.4	0.6	0.8	1
Settlement at P (mm)	0.1	-13.02	-10.62	-7.74	-6.75	-5.88	-5.22
Settlement at Q (mm)		-3	-3.15	-2.36	-3.39	-3.34	-3.25
Relative Settlement (mm)		-10.02	-7.47	-5.38	-3.36	-2.54	-1.97
Tilt (in 10^{-3})		-5.01	-3.735	-2.69	-1.68	-1.27	-0.985
Ratio of IFI / IF		1.00	0.75	0.54	0.34	0.25	0.20
Settlement at P (mm)	0.2	-11.34	-8.85	-7.19	-6.13	-5.39	-4.84
Settlement at Q (mm)		-3.06	-3.48	-3.76	-3.83	-3.78	-3.66
Relative Settlement (mm)		-8.28	-5.37	-3.43	-2.3	-1.61	-1.18
Tilt (in 10^{-3})		-4.14	-2.685	-1.715	-1.15	-0.805	-0.59
Ratio of IFI / IF		1.00	0.65	0.41	0.28	0.19	0.14
Settlement at P (mm)	0.3	-9.67	-7.66	-6.35	-5.51	-4.93	-4.48
Settlement at Q (mm)		-3.89	-4.35	-4.55	-4.55	-4.42	-4.42
Relative Settlement (mm)		-5.78	-3.31	-1.8	-0.96	-0.51	-0.02
Tilt (in 10^{-3})		-2.89	-1.655	-0.9	-0.48	-0.255	-0.01
Ratio of IFI / IF		1.00	0.57	0.31	0.17	0.09	0.00
Settlement at P (mm)	0.4	-8.08	-6.55	-5.59	-4.99	-4.55	-4.2
Settlement at Q (mm)		-5.12	-5.46	-5.57	-5.44	-5.22	-5.03
Relative Settlement (mm)		-2.96	-1.09	-0.02	0.45	0.67	0.83
Tilt (in 10^{-3})		-1.48	-0.545	-0.01	0.225	0.335	0.415
Ratio of IFI / IF		1.00	0.37	0.01	-0.15	-0.23	-0.28
Settlement at P (mm)	0.5	-6.55	-5.5	-4.92	-4.56	-4.27	-4
Settlement at Q (mm)		-6.55	-6.75	-6.71	-6.46	-6.12	-5.87
Relative Settlement (mm)		0	1.25	1.79	1.9	1.85	1.87
Tilt (in 10^{-3})		0	0.625	0.895	0.95	0.925	0.935

4.2 Comparative Analysis between Isolated footing (IF) and Tapered footing with insertion (TFI)

Table 7 compares tapered footing with insertion (TFI) and isolated footing (IF) under eccentric loading, where the tapering depth ratio (H/B) varies from 0.2 to 1, with $H/B = 0$ representing the isolated footing (IF). Volume of the TFI decreases as compared to the IFI, and its performance improves in terms of relative settlement and tilt. Variation in result similar to the isolated footing with insertion (IFI) Specifically, relative settlement decreases from 10.02 mm to 1.61 mm, 8.28 mm to 0.89 mm, and 5.78 mm to 0.09 mm, and tilt decreases from 5.01×10^{-3} to 0.805×10^{-3} , 4.14×10^{-3} to 0.445×10^{-3} , and 2.89×10^{-3} to 0.045×10^{-3} as H/B increases from 0 to 1 for load cases of $x/B = 0.1, 0.2$, and 0.3 , respectively. The TFI/IF ratio also decreases with increasing H/B , reaching 0.16, 0.11, and 0.02 for the same load cases. However, for $x/B = 0.4$, relative settlement and tilt initially decrease but then increase after $H/B = 0.2$, suggesting that smaller insertion depths are more effective in this range. In contrast, for $x/B = 0.5$, the performance of the isolated footing (IF) is better, indicating that no insertion depth is needed for improved performance. Overall, TFI generally outperforms IF, except for specific cases like $x/B = 0.5$.

Tables 6 and 7 together illustrate how insertion depth influences the performance of isolated footings under eccentric loading. The most critical case appears at $x/B = 0.1$, representing high eccentricity typical of boundary columns. In this range, both IFI and TFI footings show significant improvement in reducing tilt and settlement compared to the conventional footing.

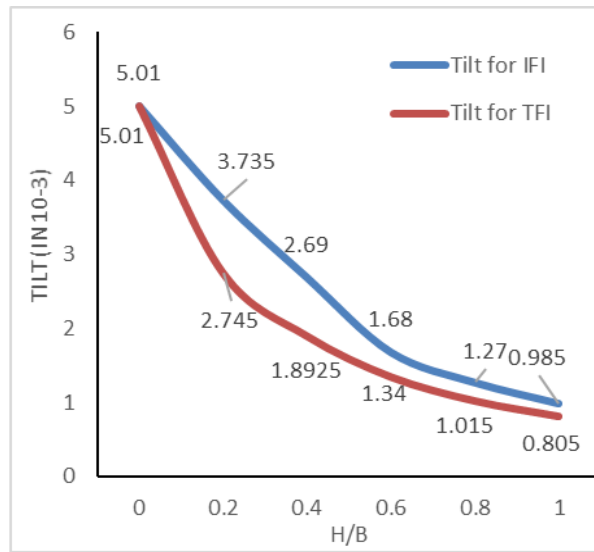
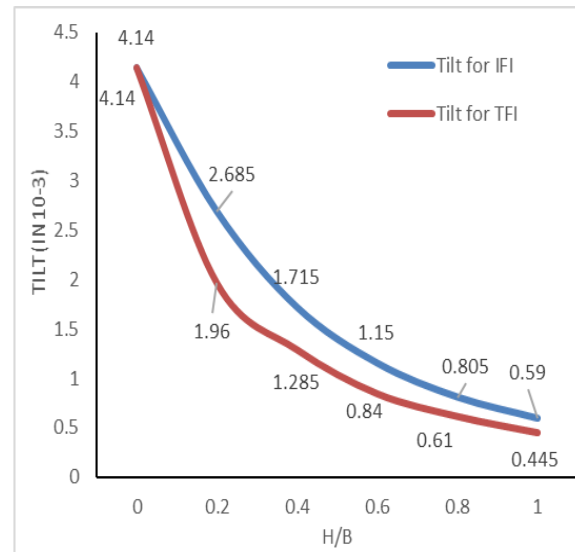
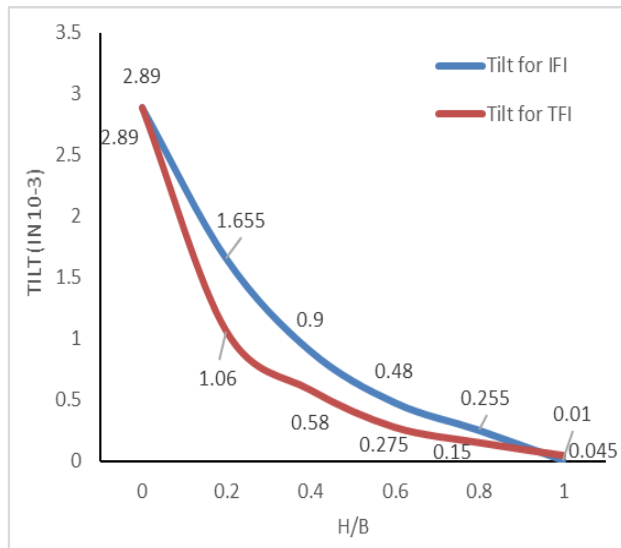
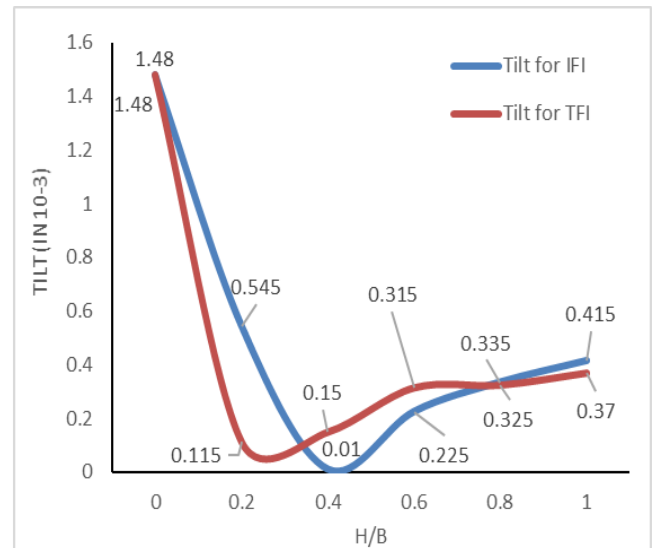
Among the two, TFI provides better results due to its tapered shape, which promotes a more uniform stress distribution. Variations in the sign of settlement values reflect direction relative to the reference point and do not indicate uplift or instability. At higher eccentricities, such as $x/B = 0.4$ and 0.5 , the benefits of insertion reduce, and the response becomes more dependent on footing shape and load position. Overall, the data confirm that modified footings, particularly TFI, are more effective at improving footing stability in eccentric loading conditions found near property lines.

Table 7 Comparative Analysis between IF and TFI for different load locations and insertion depths

Particulars	x/B	H/B					
		0 (IF)	0.2	0.4	0.6	0.8	1
Settlement at P (mm)	0.1	-13.02	-8.38	-7.02	-6.06	-5.39	-4.87
Settlement at Q (mm)		-3	-2.89	-3.235	-3.38	-3.36	-3.26
Relative Settlement (mm)		-10.02	-5.49	-3.785	-2.68	-2.03	-1.61
Tilt (in 10^{-3})		-5.01	-2.745	-1.8925	-1.34	-1.015	-0.805
Ratio of IFI / IF		1.00	0.55	0.38	0.27	0.20	0.16
Settlement at P (mm)	0.2	-11.34	-7.48	-6.38	-5.58	-5.02	-4.57
Settlement at Q (mm)		-3.06	-3.56	-3.81	-3.9	-3.8	-3.68
Relative Settlement (mm)		-8.28	-3.92	-2.57	-1.68	-1.22	-0.89
Tilt (in 10^{-3})		-4.14	-1.96	-1.285	-0.84	-0.61	-0.445
Ratio of IFI / IF		1.00	0.47	0.31	0.20	0.15	0.11
Settlement at P (mm)	0.3	-9.67	-6.59	-5.73	-5.11	-4.67	-4.29
Settlement at Q (mm)		-3.89	-4.47	-4.57	-4.56	-4.37	-4.2
Relative Settlement (mm)		-5.78	-2.12	-1.16	-0.55	-0.3	-0.09
Tilt (in 10^{-3})		-2.89	-1.06	-0.58	-0.275	-0.15	-0.045
Ratio of IFI / IF		1.00	0.37	0.20	0.10	0.05	0.02
Settlement at P (mm)	0.4	-8.08	-5.75	-5.16	-4.71	-4.38	-4.07
Settlement at Q (mm)		-5.12	-5.52	-5.46	-5.34	-5.03	-4.81
Relative Settlement (mm)		-2.96	-0.23	0.3	0.63	0.65	0.74
Tilt (in 10^{-3})		-1.48	-0.115	0.15	0.315	0.325	0.37
Ratio of IFI / IF		1.00	0.08	-0.10	-0.21	-0.22	-0.25
Settlement at P (mm)	0.5	-6.55	-4.96	-4.63	-4.37	-4.14	-3.9
Settlement at Q (mm)		-6.55	-6.23	-6.44	-6.19	-5.79	-5.49
Relative Settlement (mm)		0	1.27	1.81	1.82	1.65	1.59
Tilt (in 10^{-3})		0	0.635	0.905	0.91	0.825	0.795

4.3 Compare Isolated footing with insertion (IFI) and tapered footing with insertion (TFI)

When comparing a footing with insertion and a tapered footing with insertion, the tapered design shows superior performance in both settlement and tilt. While both types of footings reduce settlement compared to those without insertion, the tapered footing with insertion offers a more significant reduction due to its enhanced load distribution and resistance. In terms of tilt, footing with insertion generally remains within the acceptable limits of IS 1904 but may exhibit slightly higher tilt compared to a tapered footing. The tapered footing with insertion, on the other hand, maintains a lower tilt, consistently staying well within the permissible limits, providing better stability and performance overall.

(a) For the load case of $x/B = 0.1$ (b) For the load case of $x/B = 0.2$ (c) For the load case of $x/B = 0.3$ (d) For the load case of $x/B = 0.4$ **Fig. 8 Comparison of Tilt for IFI and TFI for different load location and insertion depths**

Here, H = Depth of insertion, B = Width of footing, x = Location of load from left edge of footing

Figures 8 (a, b, c and d) compare the tilt between TFI and IFI at different insertion depths, corresponding to load locations at $x/B = 0.1$, $x/B = 0.2$, $x/B = 0.3$, and $x/B = 0.4$, respectively. In Figure 7(a), the tilt reduces from 5.01×10^{-3} to 0.985×10^{-3} for IFI and from 5.01×10^{-3} to 0.805×10^{-3} for TFI. The reduction in tilt is higher for TFI, making it more stable than IFI in this case. Similarly, in Figure 7(b), the tilt reduces from 4.14×10^{-3} to 0.59×10^{-3} for IFI and from 4.14×10^{-3} to 0.445×10^{-3} for TFI. In Figure 7(c), at $x/B = 0.3$, the tilt reduction is higher for TFI compared to IFI up to $H/B = 0.8$. However, at $H/B = 1$, IFI has a lower tilt than TFI. In Figure 7(d), the reduction of tilt is more for IFI than TFI. The minimum tilt is achieved at a small insertion depth. For higher eccentricities ($x/B = 0.1$ and $x/B = 0.2$), the tilt can be reduced further by increasing the insertion depth, but this also increases the cost of the footing.

According to IS 1904:1986 Clause 6.6.2 (Table 1), the permissible angular distortion for isolated footings supporting framed structures is limited to 1 in 500 (≈ 0.002 radians). Although ACI 336.2R-88 provides generalized guidelines suggesting tilt should remain in the range of 1/500 to 1/300. However, BS 8004:2015 and Eurocode 7 do not state explicit

numerical tilt limits, instead relying on performance-based criteria to ensure structural serviceability. In this study, the modified footings (IFI and TFI) maintained tilt within the 1/500 limit, confirming the codal compliance.

5 Conclusion

This study highlights the significant advancements in footing design, particularly in the context of eccentric loading. By evaluating the performance of footings with insertion and tapered footings with insertion, the research demonstrates how modifications in footing design, such as increasing insertion depth and optimizing geometry, can greatly enhance stability and reduce settlement and tilt. The following sections summarize the key findings regarding the effectiveness of these footing designs, their performance under eccentric loading, material efficiency, and practical applications in foundation engineering.

- i. Increasing the depth of insertion shifts the center of gravity toward the inserted region in both isolated footings with insertion (IFI) and tapered footings with insertion (TFI). This shift reduces the eccentricity between the applied load and the center of gravity, which is especially beneficial for boundary columns. This effect is more pronounced in the case of TFI due to its tapered geometry. For the case of $x/B = 0.1$, the eccentricity reduces from 0.8 m to 0.4 m for IFI and from 0.8 m to 0.33 m for TFI as the insertion depth ratio (H/B) increases from 0 to 1.
- ii. IFI and TFI reduce tilt more effectively than conventional isolated footings (IF), especially when the load is near the edge and the insertion depth is higher. For $x/B = 0.1$, tilt is reduced from 5.01 to 0.985 in IFI and from 5.01 to 0.805 in TFI as H/B increases from 0 to 1.
- iii. TFI performs better than IFI at higher eccentricities (up to $x/B = 0.3$), while IFI performs slightly better than TFI at $x/B = 0.4$. For $x/B = 0.5$, the conventional isolated footing (without insertion) shows the best performance due to better balance and load transfer.
- iv. Although the TFI has a smaller volume compared to the IFI, it still demonstrates better performance under higher eccentricity conditions. This makes TFI a more efficient and structurally favorable option in situations where load eccentricity is significant.

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