Impact of Eccentric Loading on the Structural Performance of Reinforced Concrete Pad Footings: An Experimental Study

Abstract

Setting out of building footings are usually carried out using profile board. This method is usually not accurate in locating the position of columns. Hence, columns that are designed as a concentric columns to their respective footingsends up being columns having eccentricities to the pad footings that supports them.Since the stress distribution under pad footing with concentric column is different from that of pad footing with eccentric column, there is need to study the effect of these eccentricity on the load carrying capacity of the pad footing. In carrying out this work, four pad footings and a typical foundation were used. The pad footings were of sizes 230 mm x 230 mm x 150 mm, with columns of 150 mm x 150 mm cross-section. The first pad footing P_{1SH} was pad footing with short column and zero eccentricity, the second pad footing P_{2SL} was pad footing with slender column and zero eccentricity, the third pad footing P_{3SL} was footing with slender column with 40 mm eccentricity, while the forth pad footingP_{4SL} was footing with slender column with 80 mm eccentricity.The foundation comprises of sand which was contained in a sandbox. The sandbox was made of steel plate of dimensions 0.3 m × 0.3 m × 0.2 m of 4 mm thickness, was used to provide support for the foundation.The foundation was produced by compacting loose sand in three layers with 20 blows per layer in the steel box and with density of about 735 kg/m^3.The pad footings were placed on top of the foundation contained in the sandbox, and together were placed on the loading plate of Universal Testing Machine (UTM). Compressive load was applied on each of the pad footings through the columns till failure occurred, using UTM. It was found out that pad footing P_{1SH} have the highest load capacity of 261.25 kN, P_{2SL} pad footing with load capacity of 124.24 kN, P_{3SL} pad footing with load capacity of 39.34 kN, while P_{4SL} pad footing with load capacity of 23.30 kN.

Keywords: compressive strength; beams; service opening; geometrical shapes; flexural strength.

Type of Article: Original Research Article

1.0 INTRODUCTION

Structures that rest on the soil (the foundation)are carried by the footings. The footing is a structural building element that receives super-structure loads and transmits the load to an underlying suitable soil strata (Magar et al., 2020). The most prominent type of footing adopted for domestic/residential buildings is the pad footing. Pad footing is a type of shallow foundation that settles and spread over the bearing stratum easily within a depth of 1.5 to 3 m (BS 8004, 2015). The mode of transmission and distribution of stresses from the pad footing and to the foundation, to a large extent depends on the eccentricity of the column transmitting the load from the super-structure to the footing. Consequently, the eccentricity of the column with the shallow footings especially in pad footing should be an essential consideration in the design of many critical civil infrastructures. Hence the aim of this paper is to examine the effects of loading eccentricity on the strength of reinforced concrete square pad footings.

2. LITERATURE REVIEW

Many researchers (Badakhshan and Noorzad, 2017; Luo and Bathurst, 2018; Gill and Mittal, 2019; Wu *et al.*, 2020; Halder and Chakraborty, 2020; Komolafe *et al.*, 2021) have investigated the behaviour of footings subjected to eccentric loadings. The footings from these studies were subjected to only vertical loads from the dead and imposed loads, also uplift forces, inclined loads and overturning moments due to the structural asymmetry of the eccentric loading and the bearing strata. The degree of the foundation tilt and the base pressure depends upon the value of the eccentricity width ratio (Ornek, 2014). The effect of rotational pressures due to eccentric loadings on the stability of footings were studied by Ornek (2014), Sargazi and Seyedi (2017), and Sharma and Kumar (2018).

When the eccentricity of column load and footing is large enough to cause the footing base pressure to fall below zero, then there is a chance of an uplift. In order to limit the effect uplift pressure, the thickness of the base may have to be increased, which makes the footing to bemore expensive. The increase in footing thickness from the toe to the heel of the footing results in an increase in contact area which invariably decreases maximum contact pressure (Dhatrak*et al.*, 2016). As such, maximum contact pressure decreases proportionally with the decrease in eccentricity (Elsamny*et al.*, 2018).

In foundation design, two factors of safety must be considered, that is: an appropriate factor of safety against soil shear failure and differential settlement, which must constrained shear failure and differential settlement within the limits of superstructure tolerability. Geotechnical foundation design is essentially to determine the load that can be transferred from the structure in order to ensure the safe bearing capacity is not exceeded (Frank *et al.*, 2004). Soil confinement under axial load and foundation size can significantly boost the ultimate bearing capacity of footings (Prasad and Singh, 2011; Jahanandish*et al.*, 2012; Pusadkar*et al.*, 2016). The foundation failure affects the overall stability in a manner liable to slide, uplift or overturn in addition to axial loads transmitted from the column. To provide stability against soil uplift, there is a need to design an eccentric footing to assess the behaviour of different types of foundations with no negative bearing pressure.

In superstructures, the line of action of total load might not pass through the centre of gravity of the footing resulting in eccentric loading due to earthquake or wind loading (Kurre, *et al.*, 2020). The reduction of the bearing pressure by increasing the size of footing isuneconomical(Kurre, *et al.*, 2020). To mitigate the effect of eccentricity on the increased stresses on some part of the foundation, Kurre, *et al.*, (2020) used Geosynthetics to improve the bearing capacity of thefoundation soil. In their work, Kurre, *et al.*, (2020) conducted a series of tests and comparativestudy was made when Geotextile (Fibertex G-100) was used as planar reinforcementto improve the bearing capacity of sand. The test results indicate thatthere is significant improvement in the bearing capacity and reduction in thesettlement by providing planar reinforcement until the eccentricity is 0.1 timesthe width of footing.

In their research, Basha and Eldisouky (2023)studied how eccentric loads affect the behaviour of circularfootings on sand soil, both with and without skirts. The test results show thatwhen the skirtsare positioned at the depth of L/D = 4, it is found that the circularfooting's load-settlement behaviour is enhanced by 92% and 93% in case of using (e/D)ratio = 0.125 and 0.25 compared to the unreinforced case.

3. MATERIALS AND METHODS

3.1 Experimental Setup

The experiments for this work were carried out in the following manners.

3.1.1 The Pad Footings and the Sandbox

Four pad footings with different eccentricities were used for this work. Two footings were of zero eccentricity, but with short and slender columns, while the remaining two footings were of slender column with eccentricities of 40 mm and 80 mm respectively. The typical model geometry of the footing and the sandbox is shown in Figure 1. The dimensions of the pad footing were 230 mm by 230 mm size and of 150 mm deep, while that of the sandbox were 300 mm by 300 mm and 200 mm height. Also figures 2 and 3 show the pad footing with the column eccentricities.

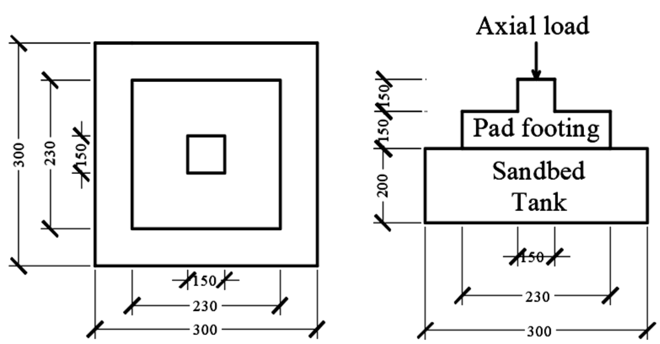

Figure 1: Schematics of sandbox tank and pad footing setup

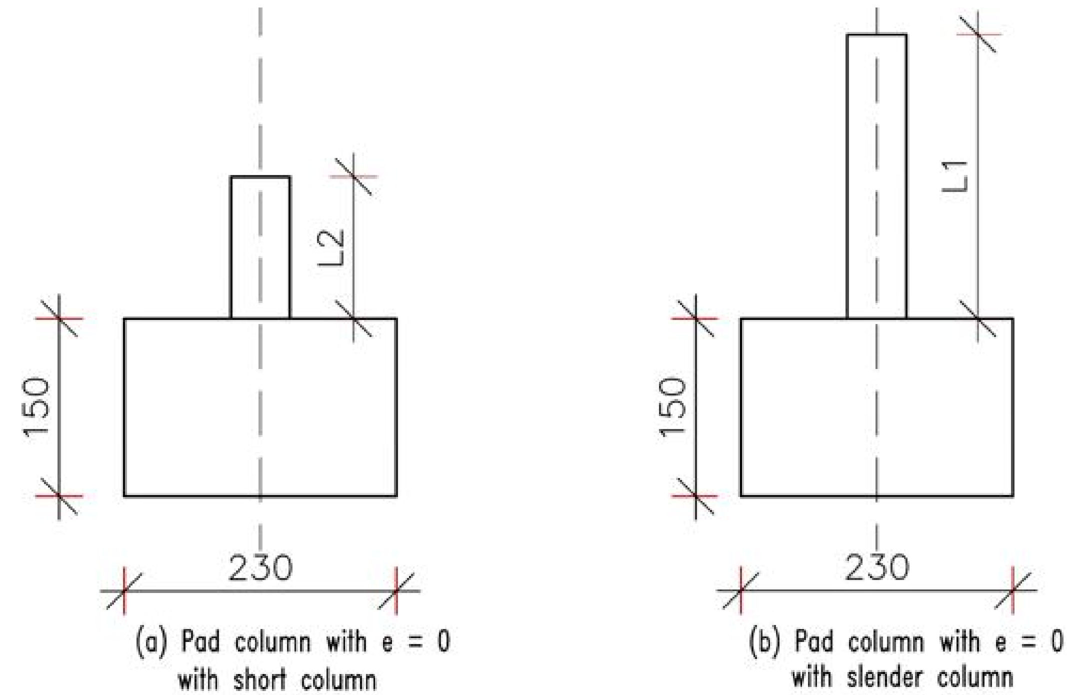

Figure 2: Pad Footings with concentric loading

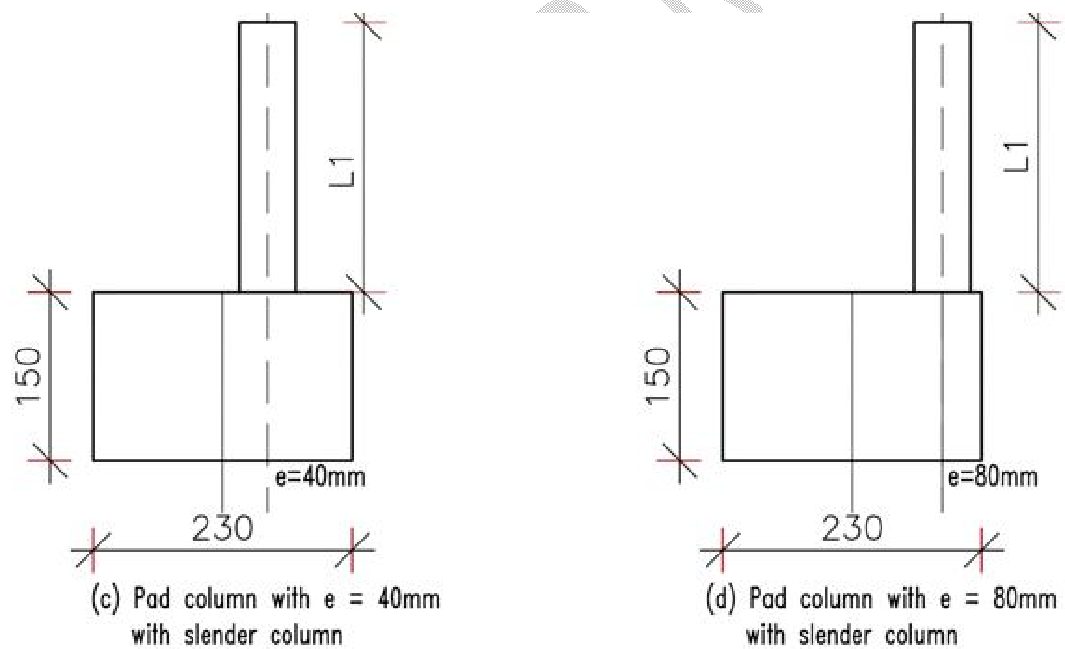

Figure 3: Pad Footings with eccentric loading

3.2.5 The Foundation

The foundation for this work was prepared by compacting loose sand in three layers with 20 blows per layer in the sandbox and with density of about735kg/m^3.

3.2 Materials

The materials used for this work are: cement, fine aggregate, coarse aggregate, steel bars and potable water. These materials are fully described in this section.

Cement: Grade 42.5 Portland Limestone Cement (PLC) was used as the binder for concrete mixing and was procured from a retail shop outlet opposite FUTA north-gate in Akure metropolis, Ondo state, Nigeria conforming to the NIS 444-1 (2018) and BS EN 197-1 (2011) specifications.

Fine aggregates: The fine aggregate used for this was sourced within the Akure metropolis, Ondo state, Nigeria.

Coarse aggregates: The coarse aggregate used, comprised of crushed rock (granite), which was sourced within the Akure metropolis, Ondo state, Nigeria.

Reinforcing bars: Hot-rolled steel/reinforcing bars of diameters 8 mm and 10 mm as recommended by BS EN ISO 15630-1 (2010) was used.

Concrete: The concrete used for this work was produced using concrete mix ratio of 1:1½:3, with water/cement ratio of 0.6.

Equipment: The equipment used for this work is the Universal Testing Machine (UTM).

3.3Testing Procedures

The tests for this work were carried out as outlined below.

3.3.1 Tests on Materials

Various tests were carried out on the materials to ascertain their suitability for use in this study. The tests that were performed on fine aggregate is the particle size distribution test. For coarse aggregate, particle size distribution test, aggregate impact value (AIV), aggregate crushing value (ACV) and specific gravity tests were carried out.

3.3.2 Tests on Concrete

Workability test was carried out on fresh concrete, while compressive test was carried out on the hardened concrete. Forty concrete cubes of size 150 mm x 150 mm x 150 mm were produced from the concrete mix used to cast the pad footings. Ten cubes each were tested at 7^{th}, 14^{th}, 21^{st} and 28^{th} days respectively using universal testing machine (UTM), to determine the characteristics strengths of the concrete.

The characteristic compressive strength of concrete cubes can be determined using Equation 1

$$f_k = \bar{x} - 1.64\sigma \quad (1)$$

Where f_k is the characteristic strength and σ is defined by Equation 2

$$\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{n}} \quad (2)$$

Where x – the strength of a sample

$\bar{x}$ – Average Concrete Cube Compressive Strength

n – The number of samples

σ – Standard deviation

3.3.3 Tests on Reinforcement Bars

For the reinforcement used for the work, tensile tests were carried out on steel reinforcing bars, according to BS 4449 (1997), to determine their characteristic strengths.

3.2.7 Loading of the pad footings

The loading of the pad footings was carried out by first putting the pad on the soil foundation inside sandbox, thereafter, the sandbox together with the pad footing were placed on the UTM for testing. The four pad footings types, together with the four foundations inside the sandbox were tested one after the other. The failure load, settlement and mode of failure were recorded.

4.0 RESULTS AND DISCUSSION

The results of the tests and the discussion of the results are presented below.

4.1 Test on Aggregates

The results of the tests on fine and coarse aggregates are presented and discussed below.

4.1.1 Test on Fine Aggregates

From the sieve analysis test carried out on fine aggregates, the size of the sand used was determined to be of metric sizes ranging 4.0 mm to 750 µm aperture. Also the uniformity coefficient (C_u) and the coefficient of gradation (C_c) were determined to be 14 and 2.93 respectively. For a well graded soil the value of coefficient of uniformity C_u must be greater than 4 and C_c should be between 1 and 3. Therefore the fine aggregate was well-graded.

The specific gravity of the fine aggregate used for the research was determinedto be 2.6, and the test was carried out in accordance to BS 812:2 (1995).

From result of the Bulk Density of Fine Aggregate carried out, the bulk density was determined to be 2156.58 kg/m^3.

4.1.2 Test on Coarse Aggregates

The tests carried out on coarse aggregates were Aggregate Impact Value (AIV) and, Aggregate Crushing Value (ACV). From the tests, the values of the AIV and ACV were determined to be 20.51% and 29.21% respectively.

Aggregate impact value of 20.51% is lower than 30% limit sets by the British Standard (BS812-112, 1990) shows that the aggregate satisfied the provisions of the British Standard (BS812-112, 1990). Also the 29.21% of ACV of the aggregate shows that the aggregate met the provisions of the British Standard (BS812:112, 1990).

4.2 Tensile Tests on Reinforcement Bars

From the results of the tensile tests carried out on the reinforcing bars, the yield strengths of the reinforcing bars were727.60MPa and 519.62MPa for 8 mm and 10 mm diameter respectively.

4.3 Tests on Concrete

4.3.1 Tests on Fresh Concrete

From the slump test of the fresh concrete, the slump was 66 mm, which shows that the slump was “true slump” and the degree of workability was “medium”.

4.3.2 Tests on Hardened Concrete

The summary of the results of the compressive tests carried out on the concrete cubes are presented in Table 1.

From Table 1, the characteristic strength of the concrete cubes are 9.06 N/mm^2, 10.44 N/mm^2, 11.98 N/mm^2 and 14.56 N/mm^2 for 7th, 14th, 21st, and 28th days respectively.

Table 1: Characteristic Strength of 150 x 150 x 150 mm Concrete Cubes

Days	**Cube Size (mm)**	**Average Comp. Strength (N/mm^2)**	**Standard Deviation (σ)**	**Characteristic Strength (f_k) (N/mm^2)**
7	150 x 150 x 150	10.51	1.56	9.06
14	150 x 150 x 150	11.84	1.56	10.44
21	150 x 150 x 150	13.09	0.68	11.98
28	150 x 150 x 150	16.02	0.89	14.56

4.4 Tests on Pad Footing

4.4.1 Density of the foundation

The size of the sandbox that contains the foundation was 300 mm × 300 mm × 200 mm, with the volume of 18 x 10^6 mm^3 (0.018 m^3). The weight of the steel box was 4.10 kg.

Respective weights of pad footings and foundations were obtained by direct weighing method using weighing balance. The pad footing result is presented in Table 2.

Table 2:Geometric Characteristics of the Pad Footing and Foundation

Sample	**Weight of Pad Footing (kg)**	**Weight of Steel Plate (kg)**	**Weight of Foundation and Steel Plate (kg)**	**Weight of Foundation without Steel Plate (kg)**	**Density of Foundation (kg/m^3)**
P_{1SH} (e = 0 mm)	19.800	4.10	17.334	13.234	735
P_{2SL} (e = 0 mm)	22.048	4.10	17.334	13.234	735

P_{3SL}(e = 40 mm)	20.144	4.10	18.066	13.966	776
P_{4SL} (e = 80 mm)	19.082	4.10	17.386	13.286	738

4.4.2 Effects of column eccentricity on the ultimate loads

The effects of column eccentricity on the compressive strength of the pad footings are presented in Table 3.

From Table 3, the failure load of the column of the pad footing of P_{1SH} with short column and concentric loading is 123.10 kN, with a corresponding settlement of 9.8 mm, while the column of P_{2SL} pad footing with slender column and concentric loading is 39.89 kN, with a corresponding settlement of 5.1 mm. Also the failure load of pad footing P_{3SL} column with eccentricity of 40 mm is 29.53 kN with corresponding settlement of 2.7 mm, while that of P_{4SL} column and eccentricity of 80 mm is 17.36 kN with corresponding settlement of 1.3 mm.

Also from Table 3, the failure load of P_{1SH} pad footing with short column and concentric loading is 261.25 kN, with a corresponding settlement of 12.5 mm, while that of P_{2SL} pad footing with slender column and concentric loading is 124.24 kN, with a corresponding settlement of 6.6 mm. Also the failure load of pad footing P_{3SL} with slender column and eccentricity of 40 mm is 39.34 kN with corresponding settlement of 3.5 mm, while that of P_{4SL} with slender column and eccentricity of 80 mm is 23.3 kN with corresponding settlement of 1.8 mm.

Table 3: Loads and settlement of foundation

Sample	Load of column failure/Settlement		Load at foundation failure/Settlement	
	Load (kN)	Settlement (mm)	Load (kN)	Settlement (mm)
P_{1SH} (E = 0)	123.10	9.8	261.25	12.5
P_{2SL} (E = 0)	39.89	5.1	124.24	6.6
P_{3SL} (E = 40mm)	29.53	2.7	39.34	3.5
P_{4SL} (E = 80mm)	17.36	1.3	23.30	1.8

The mode of failure of the pad footing P_{1SH} was the failure of the column first at the load of 123.10 kN, thereafter, the load rest directly the on the pad footing untilfailure of the pad footing occurred at load 261.25 kN.For pad footing P_{2SL}, the failure of the column occurred first, at the load of 39.89 kN due to buckling, which was accompanied by rotation or tilting of the footing.Thereafter, the load rest directly the on the pad footing until failure of the pad footing occurred at load 124.24 kN. The total failure of footing P_{1SH} occurred due to crushing of the pad footing with uniform settlement of the foundation, while that of P_{2SL} footing, occurred due to partly crushing of pad footing and partly due to tilting of the pad footing, with non-uniform settlement of the foundation.

However the failure of pad footings P_{3SL} and P_{4SL} were accompanied with rotation or tilting of the pad footings after the initial failure of the columns. The column of the pad footing P_{3SL}failed at load 29.53kN due to buckling, which together with the eccentricity of the column initiate the tilting of footing which finally failed due to tilting of the pad footing at a load of 39.34 kN.Like P_{3SL} footing, the column of the pad footing P_{4SL} failed at load 17.36 kN due to buckling, which together with the eccentricity of the column initiate the tilting of footing which finally failed due to tilting of the pad footing at a load of 23.30 kN.

From the above, it can be seen that the higher the eccentricity, the lower the ultimate loads forthe columns and the pad footing itself. Also the slenderness of the pad footing’s columns affects the ultimate loads of the columns and the pad footing. The ultimate loads of the pad footings with short columns are greater than that of the slender columns.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the investigations, experimental procedures, observations, analysis and the discussions on this research, the following conclusions were drawn:

Using locally available fine aggregates, coarse aggregates and Portland cement of grade 42.5, the characteristic strength of the concrete produced for the production of the pad footings was 14.15 N/mm^2. The mix ratio used for the production of the concrete was 1:1½:3.

The strength of the pad footing depends on the slenderness and eccentricity of the column transmitting load to the pad footing.

5.2 Recommendations

Based on the findings of this research, the following recommendations are hereby made:

Where possible, the column that transmits load directly to the foundation, should be designed as short column.

The eccentricity of column to pad footing should be reduced to the barest minimum.

Disclaimer (Artificial intelligence)

Authors(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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