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Comparative Design and Cost Assessment of Pad Foundations under Varying Soil Bearing Capacities

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Abstract-* Foundation performance and construction economy are strongly influenced by the engineering properties of the supporting ground, particularly allowable bearing capacity. This study comparatively evaluates the structural design and estimated cost of isolated reinforced-concrete pad foundations supporting a one-storey residential building under six allowable bearing-capacity conditions: 50, 100, 150, 200, 250 and 300 kN/m². The original design model was analysed using ProtaStructure and developed using Eurocode-based principles. Foundation dimensions, depths, reinforcement-related design actions, bending moments and shear responses were compared, after which the resulting quantities were assessed using a bill-of-quantities approach with constant study rates. The estimated foundation cost decreased substantially from ₦7,282,222 at 50 kN/m² to ₦3,014,905 at 250 kN/m². A further increase to 300 kN/m² produced a marginal increase to ₦3,015,128. This indicates that once practical minimum footing dimensions and structural detailing requirements become controlling, additional bearing capacity may provide little or no further economic benefit. Within the scenarios investigated, 250 kN/m² produced the lowest estimated cost. The findings demonstrate that foundation optimisation requires integration of geotechnical investigation, structural design and quantity surveying rather than consideration of bearing pressure alone.

Keywords: pad foundation; allowable bearing capacity; reinforced concrete; foundation design; construction cost; ProtaStructure; Eurocode; value engineering.

I. INTRODUCTION

1.1 Background

Foundations form the interface through which structural actions are transferred from a building to the ground. Their design must satisfy geotechnical and structural requirements, including adequate bearing resistance, acceptable settlement, structural strength and serviceability. Isolated pad foundations are appropriate where individual columns can be supported independently and competent founding material occurs at a suitable depth. The dimensions of a footing depend on the interaction between structural loading and the strength and deformation characteristics of the supporting soil (Das and Sivakugan, 2019; Knappett and Craig, 2019).

Allowable bearing capacity is a key parameter controlling the area required beneath a footing. For predominantly concentric loading, a higher allowable bearing pressure generally permits a smaller footing, whereas a lower allowable pressure requires a larger area to limit contact stresses. However, foundation cost does not reduce in direct proportion to bearing capacity because final dimensions can also be controlled by bending, one-way shear, punching shear, minimum reinforcement, practical minimum dimensions and excavation requirements (CEN, 2004a; CEN, 2004b). Eurocode 7 treats spread foundations through geotechnical verification of relevant limit states, while Eurocode 2 provides the structural basis for reinforced-concrete design (CEN, 2004a; CEN, 2004b).

This issue is particularly relevant to building projects in Nigeria, where ground conditions may vary considerably between sites and sometimes within the same development. A foundation that is economical on competent lateritic or dense granular soil may be unsuitable or uneconomical on weak or compressible deposits. Reliable site investigation is therefore essential before a design bearing capacity is adopted. The present study isolates the effect of allowable bearing capacity by keeping the selected building and structural actions constant while varying the design bearing capacity from 50 to 300 kN/m².

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1.2 Problem Statement

Preliminary foundation estimates can be misleading when the influence of soil bearing capacity on footing dimensions, structural actions and construction quantities is not explicitly considered. Over-conservative assumptions can increase construction expenditure, while under-estimation can create structural and financial risks. Moreover, the relationship between bearing capacity and foundation cost is not necessarily linear because several interacting design variables become controlling at different stages. A systematic comparison is therefore required to determine how far increases in allowable bearing capacity continue to provide meaningful economic benefits for the selected building.

1.3 Aim and Objectives

The aim of the study is to determine how variations in allowable soil bearing capacity affect the structural design and estimated cost of pad foundations and to identify the lowest-cost condition within the investigated range.

- Design the pad foundations for allowable bearing capacities of 50, 100, 150, 200, 250 and 300 kN/m².
- Compare footing dimensions, depths and governing structural actions.
- Quantify the principal foundation construction items using a bill-of-quantities approach.
- Compare the estimated foundation costs across the six bearing-capacity scenarios.
- Identify the bearing-capacity condition associated with the lowest estimated cost.

1.4 Scope of the Study

The study is limited to the selected one-storey residential building and the isolated pad foundations supporting its columns. The superstructure geometry and applied actions are held constant so that the effect of allowable bearing capacity can be examined in a controlled manner. Structural analysis and foundation design were undertaken using ProtaStructure and Eurocode-based design principles. The cost comparison covers excavation, backfilling and compaction, plain/blinding concrete, reinforced concrete, reinforcement steel, formwork and blockwork, using the study rates supplied in the original analysis.

1.5 Significance of the Study

The study links geotechnical parameters with structural design and construction economics. It demonstrates the practical value of integrating foundation calculations with quantity measurement and cost analysis. It also illustrates an important value-engineering principle: the highest bearing capacity does not necessarily produce the lowest total foundation cost once minimum practical dimensions and structural detailing requirements become dominant.

II. LITERATURE REVIEW

2.1 Pad Foundations and Soil–Structure Interaction

An isolated pad foundation spreads the load from an individual column over an area of soil capable of providing the required resistance. Preliminary footing sizing is related to applied load and allowable bearing pressure, but final design must also consider eccentricity, settlement and structural actions. Eurocode 7 provides the framework for geotechnical design of spread foundations and requires appropriate ground data and verification of relevant limit states (CEN, 2004a).

Bearing resistance and settlement are distinct design considerations. A footing can possess adequate ultimate bearing resistance while still producing unacceptable settlement. Soil type, density or consistency, groundwater, drainage, stress history, footing dimensions and embedment all influence foundation behaviour (Das, 2022; Knappett and Craig, 2019). Consequently, economical foundation design should be based on reliable ground investigation rather than assumed bearing pressure alone.

2.2 Structural Requirements for Pad Foundations

Once a footing has been sized geotechnically, the reinforced-concrete element must be checked for flexure, one-way shear and punching shear. Eurocode 2 covers the design and detailing of reinforced-concrete structures, including requirements associated with resistance, serviceability and durability (CEN, 2004b). As footing dimensions increase on weaker soil, the projection beyond the column face may increase and produce larger bending demands. Conversely, when the footing becomes smaller on stronger soil, local shear and punching requirements may become increasingly influential.

2.3 Foundation Cost and Value Engineering
Foundation cost is affected by excavation, disposal, backfilling, concrete, reinforcement, formwork and other construction operations. The relationship between soil strength and cost is therefore not purely geometric. Minimum practical dimensions and structural requirements can maintain a significant portion of total cost even after footing areas have reduced. Foundation selection should consequently consider engineering suitability and construction economy together (Tomlinson and Woodward, 2008).

2.4 Research Gap
Much conventional foundation literature concentrates on bearing capacity, settlement or comparison between foundation systems. The present study contributes a more focused economic comparison by keeping the same building and foundation type while evaluating six bearing-capacity scenarios. This controlled approach permits the influence of soil capacity on footing dimensions, structural actions and estimated total cost to be examined consistently.

III. MATERIALS AND METHODS

3.1 Building Description
The analysed structure is a one-storey reinforced-concrete residential building with a plan area of approximately 132 m² and a storey height of 3.30 m. The column grid transfers superstructure actions to isolated pad foundations. Similar loading characteristics permit representative columns to be grouped for foundation comparison.

3.2 Structural Actions
Four representative column groups were considered. PB1 comprises A1, D1, A4 and D4; PB2 comprises B1, C1, B4 and C4; PB3 comprises A2, A3, D2 and D3; and PB4 comprises B2, B3, C2 and C3. PB1 has a permanent axial action of 77.2 kN and a variable axial action of 5.4 kN, whereas PB4 has 136.9 kN and 22.2 kN respectively. The grouping reflects the loading patterns used in the submitted structural analysis.

3.3 Design Parameters

Parameter	Adopted value
Design standards	Eurocode 7 for geotechnical design; Eurocode 2 for reinforced concrete
Concrete	C25/30
Reinforcement	High-yield reinforcement
Nominal cover	50 mm
Allowable bearing capacities	50, 100, 150, 200, 250 and 300 kN/m²
Building type	One-storey residential building
Analysis/design software	ProtaStructure

The six bearing-capacity values are comparative design cases. They should not be interpreted as measured soil properties for an actual site unless supported by an appropriate geotechnical investigation (CEN, 2004a).

3.4 Foundation Design Procedure
For each bearing-capacity scenario, a trial footing size and depth were selected. The design procedure included assessment of ultimate actions, eccentricity, foundation contact pressures, flexural demand, required reinforcement, one-way shear and punching shear. Dimensions and depths were adjusted until the relevant checks were satisfied. The final designs were then used to obtain the quantities required for the cost analysis. This approach is consistent with the principle that spread-foundation design requires both geotechnical and structural verification rather than bearing-pressure sizing alone (CEN, 2004a; CEN, 2004b).

3.5 Cost Analysis
A bill-of-quantities approach was used for the cost assessment. Unit rates were kept constant across all

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scenarios so that changes in estimated cost reflected changes in design quantities rather than market-price fluctuations. Principal items included excavation, backfilling and compaction, plain/blinding concrete, reinforced concrete, reinforcement steel, formwork and blockwork. The rates are study assumptions and should not be interpreted as current Nigerian market rates.

3.6 Data Analysis

The principal comparison indicators were total estimated foundation cost, footing dimensions, footing depth, bending moment and shear-related design responses. The objective was not simply to identify the smallest footing, but to determine the scenario producing the lowest total estimated cost while satisfying the adopted design requirements.

IV. RESULTS AND DISCUSSION

4.1 Foundation Dimensions and Detailing

Bearing capacity (kN/m²)	PB1: L×W, depth	PB2: L×W, depth	PB3: L×W, depth	PB4: L×W, depth
50	2.25×2.25 m, 300 mm	2.05×2.45 m, 300 mm	1.70×2.70 m, 300 mm	2.85×2.85 m, 300 mm
100	1.45×1.45 m, 300 mm	1.55×1.55 m, 300 mm	1.85×1.65 m, 200 mm	1.75×1.75 m, 300 mm
150	1.15×1.50 m, 300 mm	1.25×1.25 m, 300 mm	1.35×1.35 m, 300 mm	1.40×1.40 m, 300 mm
200	1.00×1.00 m, 300 mm	1.05×1.05 m, 300 mm	1.15×1.15 m, 300 mm	1.20×1.20 m, 350 mm
250	1.00×1.00 m, 350 mm	1.00×1.00 m, 350 mm	1.05×1.05 m, 350 mm	1.05×1.05 m, 350 mm
300	1.00×1.00 m, 300 mm	1.00×1.00 m, 300 mm	1.00×1.00 m, 350 mm	1.00×1.00 m, 400 mm

The results show a pronounced reduction in plan dimensions as allowable bearing capacity increases. At 50 kN/m², PB4 reaches 2.85 m × 2.85 m, whereas several footing types reach the practical 1.0 m plan dimension at 200–300 kN/m². Footing depth does not follow a simple decreasing trend because structural shear and punching-shear requirements can become controlling after the geotechnical area has been reduced. This helps explain why the 300 kN/m² case is not automatically the cheapest.

4.2 Bending Moment

Bearing capacity (kN/m²)	PB1 (kNm)	PB2 (kNm)	PB3 (kNm)	PB4 (kNm)
50	56.63	75.13	92.81	111.45
100	25.81	32.39	37.60	49.92
150	17.99	22.68	30.40	34.62
200	14.58	17.16	23.78	26.89
250	14.31	15.90	18.39	21.65
300	14.58	15.90	15.31	19.92

Bending moments generally decrease as bearing capacity increases, with the most pronounced reduction occurring between 50 and 150 kN/m². Beyond approximately 200 kN/m², the reduction becomes smaller because practical minimum dimensions and structural detailing increasingly control the design. PB4 generally records the highest bending moments because it represents the larger

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column actions. The trend is consistent with footing mechanics: a larger footing can have a greater projection beyond the column, while a smaller footing reduces the effective cantilever length.

4.3 Shear Capacity

Bearing capacity (kN/m²)	PB1 (kN/m²)	PB2 (kN/m²)	PB3 (kN/m²)	PB4 (kN/m²)
50	0.161	0.191	0.210	0.230
100	0.162	0.183	0.200	0.226
150	0.143	0.176	0.208	0.224
200	0.129	0.149	0.192	0.143
250	0.087	0.087	0.108	0.113
300	0.193	0.193	0.107	0.035

The shear-related results are not strictly monotonic because footing depth and plan dimensions were modified to satisfy the structural checks. The variation reinforces the fact that foundation design is iterative: once a footing becomes small, local shear and punching-shear requirements can become more influential, preventing concrete quantities and cost from falling in direct proportion to increases in soil capacity.

4.4 Foundation Cost Comparison

Bearing capacity (kN/m²)	Total estimated cost (₦)	Change from previous case
50	7,282,222	—
100	3,938,093	−45.9%
150	3,469,948	−11.9%
200	3,125,395	−9.9%
250	3,014,905	−3.5%
300	3,015,128	+0.01%

The estimated foundation cost decreases sharply from 50 to 100 kN/m² and continues to decline through 250 kN/m². The lowest estimated cost in the submitted analysis is ₦3,014,905 at 250 kN/m². Increasing the assumed bearing capacity to 300 kN/m² produces a marginal increase to ₦3,015,128. Thus, 250 kN/m² is the least-cost condition among the six scenarios examined. Importantly, this is a project-specific optimum rather than a universal recommendation.

4.5 Cost Components

Cost item	50 kN/m² (₦)	150 kN/m² (₦)	250 kN/m² (₦)	300 kN/m² (₦)
Excavation	1,592,690	759,110	656,370	672,210
Backfilling/compaction	756,720	340,380	285,750	295,650
Plain/blinding concrete	502,400	271,200	265,200	247,600
Reinforced concrete	2,149,550	604,500	467,350	431,600
Steel reinforcement	1,084,582	298,478	213,915	197,228
Formwork	290,160	290,160	276,720	280,440
Blockwork	906,120	906,120	849,600	890,400
Total	7,282,222	3,469,948	3,014,905	3,015,128

Reinforced concrete and excavation are major contributors at low bearing capacity because larger footing dimensions require greater quantities. As footing dimensions reduce, less-sensitive items such as blockwork and some formwork become a larger proportion of total expenditure. Cost optimisation should therefore consider the complete foundation work package rather than concrete volume alone.

4.6 Economic Optimum and Value Engineering

The lowest total estimated cost occurs at 250 kN/m² rather than 300 kN/m². At 300 kN/m², several footing plan dimensions have already reached the adopted practical minimum of 1.0 m, while some depths increase to satisfy structural requirements. Additional bearing capacity therefore cannot produce a proportional reduction in quantities. The near-identical costs of the 250 and 300 kN/m² cases demonstrate diminishing economic returns from further increases in assumed bearing capacity under the study assumptions.

The result should not be interpreted as evidence that 250 kN/m² is an inherently optimum soil bearing capacity for all projects. The optimum depends on structural loading, footing type, minimum dimensions, geotechnical conditions, design standards, construction methods and local cost rates.

4.7 Implications for Nigerian Construction Practice

For Nigerian building projects, the findings reinforce the need for reliable geotechnical information before foundation dimensions are finalised. Where soil improvement is considered, its cost should be compared with alternatives such as raft, combined, strip or pile foundations. If the cost of improving weak soil exceeds the cost of adopting another foundation system, the alternative may be more economical. Such decisions should be based on site-specific geotechnical, structural and economic evidence rather than generalised bearing-capacity thresholds.

V. CONCLUSIONS

The study demonstrates a clear relationship between allowable soil bearing capacity, pad-foundation geometry, structural actions and estimated construction cost for the selected one-storey residential building. Increasing allowable bearing capacity from 50 to 250 kN/m² substantially reduces footing dimensions and the quantities of excavation, concrete and reinforcement required. The estimated total foundation cost falls from ₦7,282,222 at 50 kN/m² to ₦3,014,905 at 250 kN/m², a reduction of approximately 58.6%.

At 300 kN/m², the estimated cost increases marginally to ₦3,015,128. The 250 kN/m² case is therefore the lowest-cost scenario within the six cases studied. This outcome results from the interaction of reduced footing area with minimum practical dimensions and structural depth/detailing requirements. Bending moments generally decrease as bearing capacity increases, while shear-related responses are not strictly monotonic because the footing geometry and depth are adjusted to satisfy structural checks.

Overall, the findings confirm that the most economical pad foundation is not necessarily associated with the highest assumed soil bearing capacity. Foundation optimisation should instead balance geotechnical performance, structural safety, constructability and total cost.

VI. RECOMMENDATIONS

- Conduct a site-specific geotechnical investigation before adopting an allowable bearing capacity for design. Both bearing resistance and settlement should be assessed from appropriate field and laboratory data.
- Use the current edition of the applicable Eurocodes together with relevant national requirements for live projects. The numerical results presented here are based on the design framework and assumptions in the submitted study.
- Do not select a foundation solely because it corresponds to the highest bearing capacity. Compare footing size, depth, reinforcement, excavation, concrete, labour and other relevant cost items.
- For weak soils in the approximate 50–100 kN/m² range, compare isolated pads with raft, combined, strip and deep-foundation solutions before final selection.
- For medium-to-high bearing capacities, optimise pad dimensions while maintaining practical minimum dimensions and satisfying structural shear and punching requirements.
- Update all cost rates using current, location-specific quotations before applying the analysis to tendering or project budgeting.
- Future studies should compare pad, strip, combined, raft and pile foundations under common structural loads and site conditions and should incorporate settlement, life-cycle cost and, where appropriate, ground-improvement alternatives.

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