

Experimental and Numerical Assessment of the Bearing Capacity of Square and Circular Footings on Basanite Rock

—Cape Verde Peninsula, Dakar

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Abstract

Estimating the bearing capacity of rock masses through in situ testing is costly. This study experimentally and numerically evaluates the bearing capacity of footings on three basanite facies from Senegal. Reduced-scale model tests on rock blocks (150 × 150 × 75 mm and 100 × 100 × 50 mm) with square footings (32 mm side length) and circular footings (32 mm diameter) were performed until failure, under centered and eccentric configurations. The results show that experimentally, the allowable bearing capacity ranges from 16.27 to 37.32 MPa (type A blocks) and from 14.63 to 35.24 MPa (type B blocks). Including eccentric configurations, type A values reach up to 53.71 MPa. Circular footings exhibit higher bearing capacity than square footings. Two failure mechanisms are observed: punching-splitting (weathered basanites) and splitting (vacuolar and healthy basanites). Numerical modeling using PLAXIS 2D with the Hoek-Brown criterion validated the experimental trends, yielding a numerical-to-experimental capacity ratio between 1.05 and 3.01, with the best agreement observed for vacuolar basanite. The combined approach constitutes a reliable and economical alternative to in situ testing for foundation design in the Dakar region.

Keywords

Dakar Peninsula, Bearing Capacity, Basanite, Plaxis 2D, Square Footing, Circular Footing

1. Introduction

Rock masses are generally considered safe materials for civil engineering construc-

tion. The design of shallow foundations on rock requires a reliable estimation of their bearing capacity, an essential parameter to ensure the stability of structures. However, determining this capacity through in situ testing on rock masses proves to be very costly, time-consuming, and technically difficult to implement. This issue is particularly acute in regions such as the Cape Verde Peninsula in Senegal, where increasing urbanization requires both economical and reliable foundation solutions, justifying the development of alternative methods such as laboratory-scale model testing.

Numerous experimental and numerical studies on reduced-scale models have been conducted to estimate the bearing capacity of shallow foundations on rock. De Beer *et al.* [1] studied the bearing capacity of sand under circular foundations, while Meyerhof [2] developed a theoretical formulation for the bearing capacity of rock and concrete blocks. The influence of rock discontinuities was examined by Bishnoi [3] on Indian sandstones, resulting in a semi-theoretical expression for circular and rectangular foundations. Von Kolnitz [4] investigated fractured rock blocks, and more recent studies by Bindlish *et al.* [5] and Raizamzamani Md Zain *et al.* [6] analyzed the capacity of concrete blocks and their failure mechanisms.

Despite these advances, the mechanical behavior of basalts specific to the Cape Verde Peninsula remains poorly documented. In particular, no study has systematically investigated the combined influence of footing shape, block thickness, and rock alteration state for these specific materials, nor validated reduced-scale model results through Hoek-Brown-based finite element simulations. The present work addresses these gaps.

This study aims to fill these gaps by experimentally and numerically evaluating the allowable bearing capacity of shallow footings on basalts from the Cape Verde Peninsula. The objectives are to experimentally determine the allowable bearing capacity of three basalt facies under square and circular footings, in centered and eccentric configurations, to analyze the influence of block thickness and footing shape, to observe failure mechanisms, and to validate experimental results through numerical modeling with Plaxis 2D according to the Hoek-Brown criterion. By combining experimental and numerical approaches, this study will provide essential quantitative data for the design of shallow foundations in the Dakar region, while proposing a reliable and economical alternative methodology to in situ testing.

2. Materials and Methods

2.1. Rock Block Specimens

The rock specimens analyzed are olivine basalts from the Tertiary and Quaternary periods of the Cape Verde Peninsula [7]–[9]. These rock blocks were cut using a saw equipped with a 50 mm diameter diamond blade. Two types of block sizes were prepared: type A, measuring 150 mm × 150 mm × 75 mm, and type B, measuring 100 mm × 100 mm × 50 mm (Figure 1).

Uniaxial compressive strength (UCS) and tensile strength were obtained from

direct laboratory tests performed on cylindrical specimens cored from the same blocks. Cohesion and internal friction angle were derived from the Mohr-Coulomb linearization of the Hoek-Brown failure envelope. Three facies were identified and characterized.

Weathered basanite has a uniaxial compressive strength ranging from 18 to 28 MPa with a unit weight between 24 and 26.67 kN/m³. Vacuolar basanite exhibits a uniaxial compressive strength between 24.27 and 30 MPa and a unit weight varying from 24.26 to 29.51 kN/m³. Healthy basanite shows compressive strengths ranging from 30 to 45 MPa with unit weights between 21.67 and 30.10 kN/m³. The physical and mechanical properties of these different rock types are summarized in **Table 1**.



Figure 1. Pictures of specimens of rock blocks, types A (150 mm × 150 mm × 75 mm) and B (100 mm × 100 mm × 50).

Table 1. Physical and mechanical parameters of rock blocks.

Samples	N° Sampling	Block Size (mm)	Natural Unit Weight (kN/m ³)	Compressive Strength (MPa)	Tensile Strength	Cohesion (MPa)	Internal Friction Angle ϕ (°)
Weathered Basanite	A0I		24.00				
	A0II	150 × 150 × 75	26.67	28.00	1.12	2.98	65.92
	A0III		26.02				
	A0IX		26.63				
	B0VII	100 × 100 × 50	25.00	18.00	0.72	1.92	65.92
	B0VIII		26.63				
Vacuolar Basanite	A0IV		29.51				
	A0V	150 × 150 × 75	25.00	24.27	0.96	2.57	66.01
	A0VI		27.80				
	A0X		24.26				
	B0II	100 × 100 × 50	29.33	30.00	1.20	3.20	65.92
	B0IV		30.25				

Continued

Healthy Basanite	A0VII	150 ×	21.67				
	A0VIII	150 ×	25.69	45.00	1.80	4.80	65.92
	A0XII	75	27.74				
	B0V	100 ×	30.10				
	B0III	100 ×	32.00	1.28	3.41	65.92	
		50	24.26				

2.2. Loading Press and Displacement Measurement Device

The experimental setup consists of a uniaxial hydraulic press with a maximum capacity of 1500 kN (**Figure 2(a)**). The press frame is composed of two rigid steel platens maintained parallel by four steel columns, ensuring axial load application without eccentricity. The applied load is measured by a load ring (accuracy of ± 0.5 kN) mounted in series between the jack and the distribution beam. Displacements are recorded using a precision displacement gauge with a resolution of 0.01 mm per division. The gauge needle is attached to a non-deformable steel plate to ensure accurate measurements. A dedicated mounting device was introduced to hold the displacement gauge (**Figure 2(b)**). During loading, as the footing penetrates the rock surface, the bracket maintains gauge contact with the reference plate, enabling continuous and uninterrupted settlement monitoring throughout the test. All tests were conducted using rigid steel footings to prevent any deformation during loading.

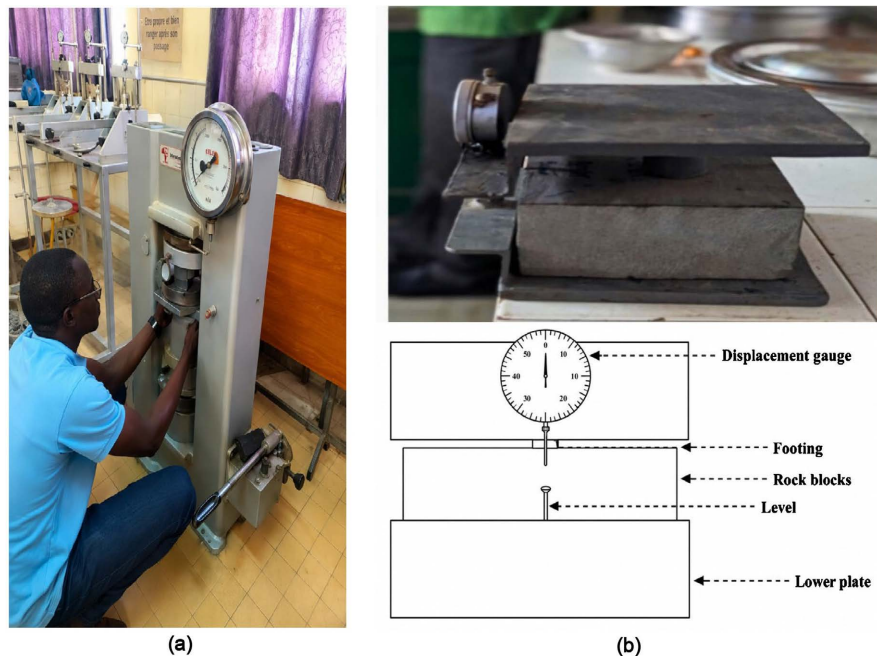


Figure 2. Experimental setup: (a) loading press, (b) displacement measurement system.

2.3. Test Program

All tests were conducted using rigid steel square footings (32 mm side length) and

circular footings (32 mm diameter). Two series of tests were performed (**Figure 3**). The first series involved footings centered on the rock block (**Figure 3(a)**), while the second series examined footings placed eccentrically on different blocks (**Figure 3(b)**). This experimental design aims to investigate the influence of footing eccentricity on bearing capacity, as well as the effects of block height and footing shape. In the eccentric configuration, the footing was offset from the block center by a distance $e = 16$ mm along the longitudinal axis of the block, corresponding to a normalized eccentricity $e/B = 0.5$, where B is the footing side length (32 mm).

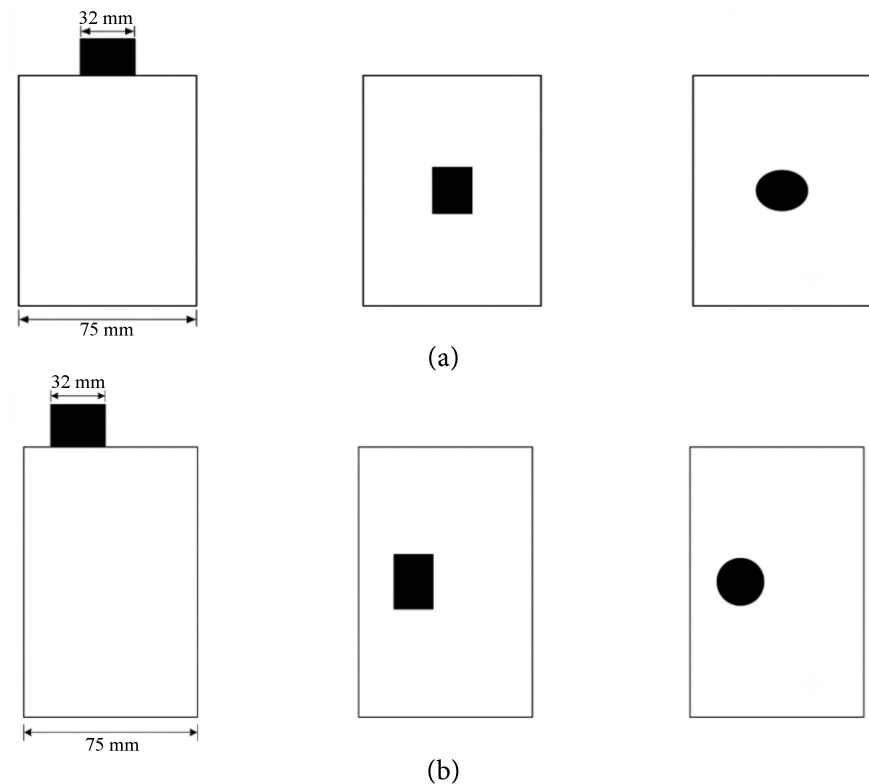


Figure 3. Example schematic representation of footing configurations applied on the rock block type A. (a) centered footing configuration: from left to right, front view showing the centered footing on the block, top view of a centered square footing, and top view of a centered circular footing; (b) eccentric footing configuration: from left to right, front view showing the eccentric footing position on the block, top view of an eccentric square footing, and top view of an eccentric circular footing.

2.4. Ultimate and Allowable Bearing Capacity Determination

The applied load was measured using a 1500 kN capacity load ring, while displacements were recorded with a displacement gauge having a 10 cm measuring range and an accuracy of 0.01 mm. The testing procedure began by gradually bringing the upper press plate, which holds the footing, into contact with the rock surface using discs placed beneath the lower plate. Once contact was established and all gauges were set to zero, load was applied incrementally to the footing until complete rock failure. Each load increment was maintained until settlement stabilized, at which point displacement was recorded from the gauge.

As loading progressed, initial punching of the rock beneath the footing was observed, followed by crack propagation indicating impending failure. The load at which the rock could no longer sustain additional loading was considered the ultimate bearing capacity, determined from the load-displacement curve [10]. The allowable bearing capacity (q_a) is the maximum pressure that can be safely applied to the rock under service conditions [11]. It is computed as:

$$q_a = q_u / F$$

In the present study, $F = 3$ is adopted, consistent with standard geotechnical practice for shallow foundations on rock [11] [12].

2.5. Numerical Modeling with Plaxis 2D Studies

Numerical simulations were performed using Plaxis 2D [13], which incorporates the Hoek-Brown constitutive law for rock behavior and plate elements for footings [14] [15]. The rock blocks used for numerical modeling are weathered, vacuolar, and healthy basanites with no major joints present. Furthermore, these rock blocks are considered isotropic and homogeneous. An intact rock constant $m_i = 25$ was adopted for basalt [16]. The disturbance factor $D = 0$ was used throughout (specimens obtained by sawing, no blasting). The model geometry matched the tested block dimensions exactly. Square footings were modeled under plane strain conditions; circular footings under axisymmetric conditions. Boundary conditions consisted of horizontal fixity on the vertical sides of the model and full fixity at the base. Interface conditions assumed a rough contact between the footing and the rock surface. Finally, 15-node triangular elements were selected after sensitivity analysis showed 6-node elements overestimated the allowable bearing capacity. A very fine mesh was adopted after convergence analysis between fine and very fine meshes. The geometric model and mesh are shown in **Figure 4**.

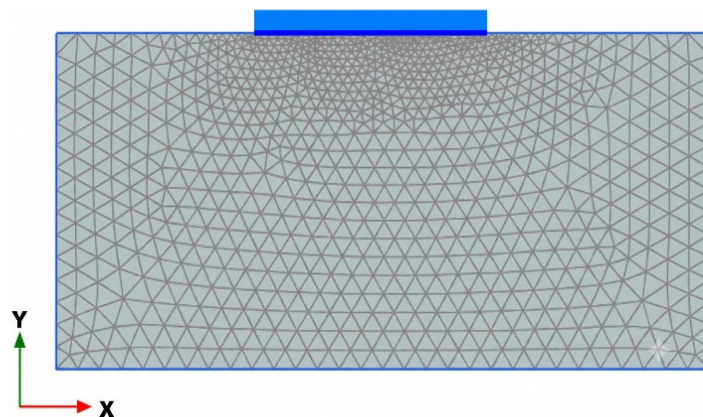


Figure 4. Example of the geometric model and a very fine mesh type.

3. Results and Discussions

3.1. Experimental Results

The experimental bearing capacity-displacement curves obtained for centered

footings (Figure 5) and eccentric footings (Figure 6) show distinct behavioral patterns for each facies. The initial stiffness decreases with increasing alteration. Healthy basanites exhibit the steepest load-displacement response, whereas weathered basanites display a more gradual curve with greater displacement before failure. For weathered basanites (samples A0II, A0I, A0III, A0XIII, B0IV, and B0II), initial punching of the footing is observed at the beginning of load application, characterized by a slight concavity in the bearing capacity curves. As loading progresses, transverse cracks develop, eventually separating the rock block into two parts. The fracture inclination angles β range from 15° to 55° , well below the theoretical Mohr-Coulomb angle ($\theta = 45^\circ + \varphi/2 \approx 78^\circ$), confirming that tensile splitting rather than shear failure governs the collapse. The failure mechanism is punching-splitting (Figure 5(a)-(b)). For the vacuolar basanites (samples A0VI, A0IV, A0V, A0X, B0IV, and B0II), the allowable bearing capacity curves show a short clamping phase, followed by linear and then non-linear response before sudden failure through a single transverse crack parallel to the block sides (Figure 6(c)-(d)). Measured inclination angles $\beta = 20^\circ - 50^\circ$. The failure mechanism is identified as cleavage fracture. The tensile character of failure is again confirmed by angles falling well below 78° . In the healthy basanites (samples A0VII, A0VIII, A0IX, A0XII, B0III, and B0VIII), two distinct behavioral modes are observed.

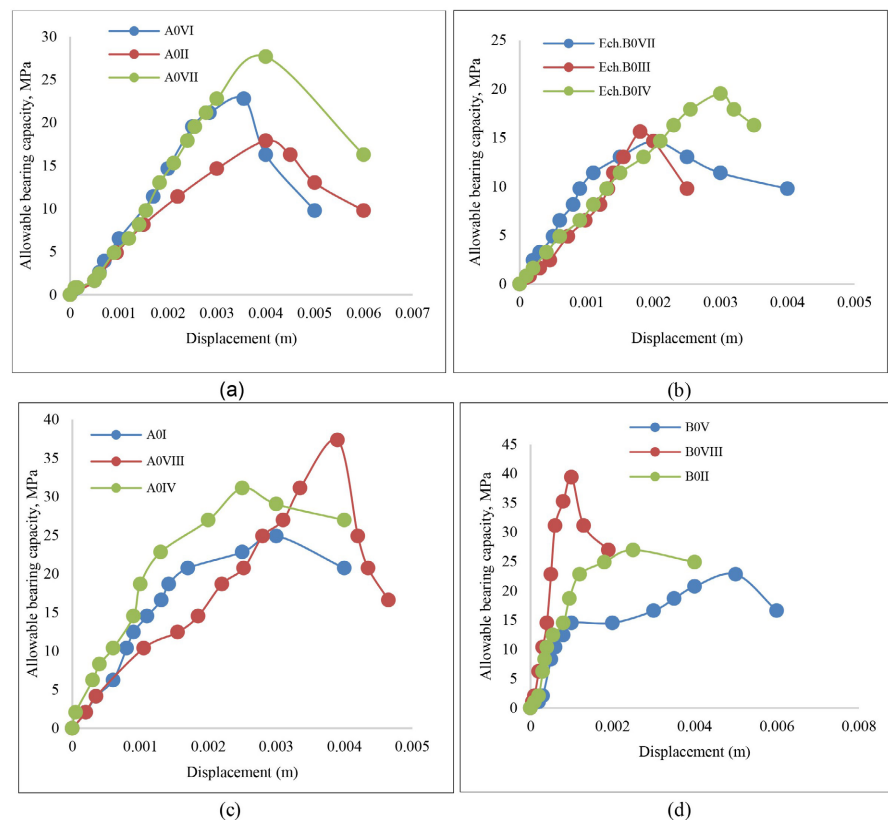


Figure 5. Allowable bearing capacity-displacement curves for centered footings: (a) square spread footing, type A specimen; (b) square spread footing, type B specimen; (c) circular spread footing, type A specimen; (d) circular spread footing, type B specimen.

Coarse-grained specimens show concavity followed by linear behavior until failure. In contrast, fine-grained specimens display rapidly increasing deformation with increasing load, culminating in sudden brittle failure. Fracture occurs by splitting, with inclination angles varying between 22° and 55° (**Figure 7(e)-(f)**).

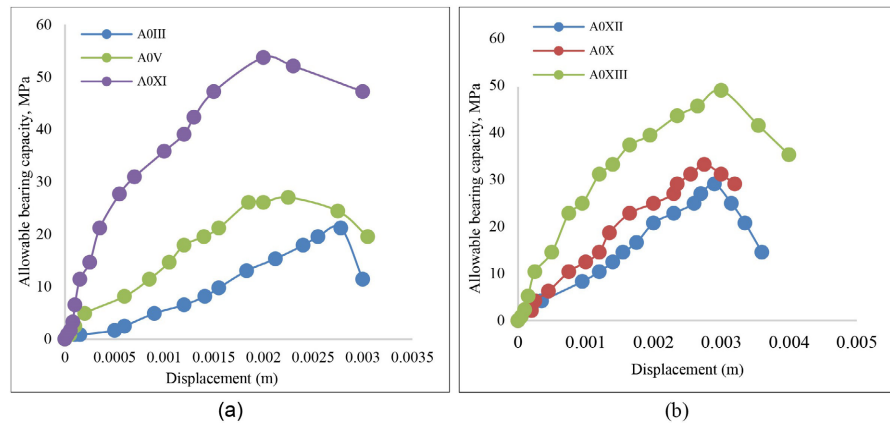


Figure 6. Allowable bearing capacity-displacement curves for eccentric footings (type A specimens): (a) square spread footing; (b) circular spread footing.



(a) Weathered Basanite specimen A



(b) Weathered Basanite specimen B



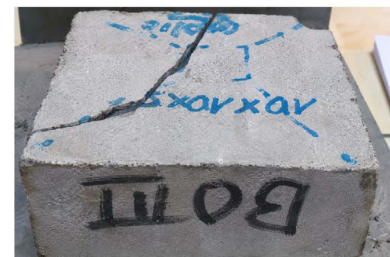
(c) Vacuolar Basanite specimen A



(d) Vacuolar Basanite specimen B



(e) Healthy Basanite specimen A



(f) Healthy Basanite specimen B

Figure 7. Failure mechanisms of rock block (a, b, and c: failure by punching and splitting; d, e, and f: failure by splitting).

Quantitative results are summarized in **Tables 2-4** for square-centered, circular-centered, and eccentric configurations, respectively, presenting allowable bearing capacity. The results demonstrate that bearing capacity is significantly influenced by rock block thickness, footing shape, and alteration state. Type A specimens ($150 \times 150 \times 75$ mm) exhibited 15% - 40% higher capacities than type B specimens ($100 \times 100 \times 50$ mm), confirming that larger rock volumes mobilize greater resistance. Circular footings outperformed square footings by 35% - 53%, with experimental capacities reaching 24.88 - 37.32 MPa for type A blocks compared to 16.27 - 27.66 MPa for square footings, consistent with theoretical solutions where axisymmetric stress distribution reduces edge effects. In the case of eccentric footings on type A specimen (**Table 4**), the bearing capacity ranges from 21.15 to 53.71 MPa for square footings and 29.02 to 45.61 MPa for circular footings. It is noteworthy that for the healthy basanite, the eccentric allowable bearing capacity (53.71 MPa) exceeds the centered footing capacity (27.66 MPa). This result is attributed to asymmetric confinement. This effect is most pronounced for high-strength intact rocks and should not be extrapolated to field conditions where discontinuities reduce the total allowable bearing capacity [3] [4].

3.2. Numerical Results

The numerical allowable bearing capacity-displacement curves are presented in **Figure 8** for type A rock blocks and in **Figure 9** for type B.

Table 2. Square-centered footing allowable bearing capacity results.

Rocks Facies	Specimens Type A			Specimens Type B		
	Numerical (MPa)	Experimental (MPa)	Ratio	Numerical (MPa)	Experimental (MPa)	Ratio
Weathered Basanite	28.50	16.27	1.75	25.19	14.63	1.72
Vacuolar Basanite	24.02	22.78	1.05	27.29	19.53	1.39
Healthy Basanite	63.16	27.66	2.28	47.13	15.62	3.01

Ratio = Numerical/Experimental.

Table 3. Circular centered footing allowable bearing capacity results.

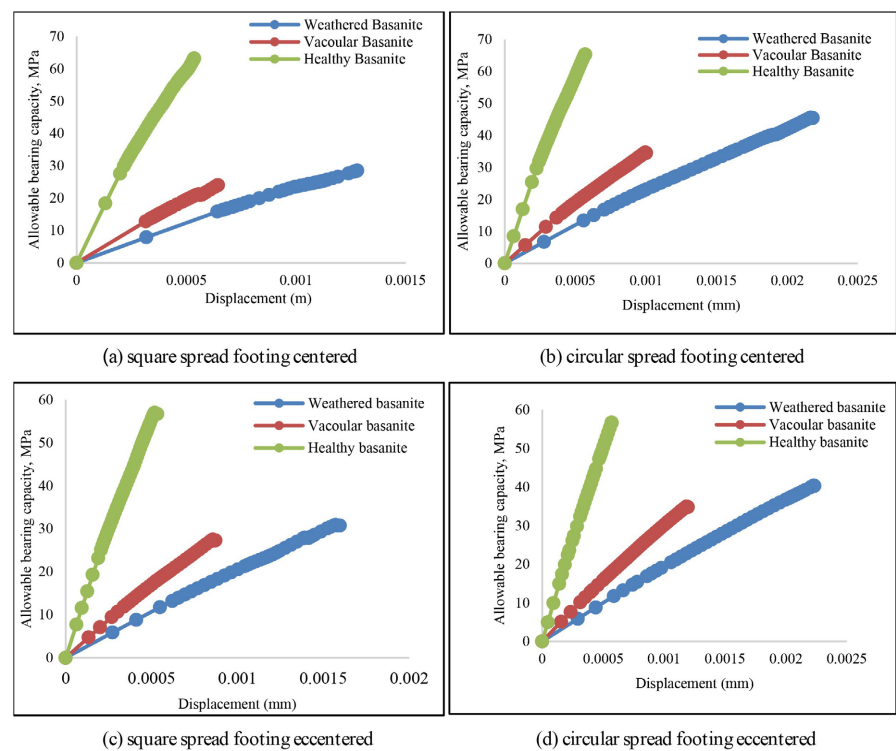
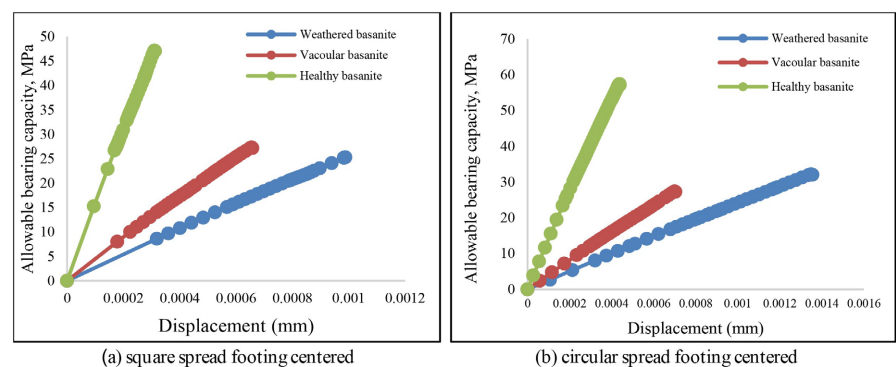
Rocks Facies	Specimens Type A			Specimens Type B		
	Numerical (MPa)	Experimental (MPa)	Ratio	Numerical (MPa)	Experimental (MPa)	Ratio
Weathered Basanite	45.50	24.88	1.82	35.15	22.80	1.54
Vacuolar Basanite	34.59	31.10	1.11	27.37	24.80	1.10
Healthy Basanite	65.29	37.32	1.74	57.34	35.24	1.62

Ratio = Numerical/Experimental.

Table 4. Eccentered footing allowable bearing capacity results (type A specimens).

Rocks Facies	Square Footing			Circular Footing		
	Numerical (MPa)	Experimental (MPa)	Ratio	Numerical (MPa)	Experimental (MPa)	Ratio
Weathered Basanite	30.88	21.15	1.46	40.36	29.02	1.39
Vacuolar Basanite	27.47	26.04	1.05	34.51	33.17	1.09
Healthy Basanite	56.67	53.71	1.05	56.71	45.61	1.24

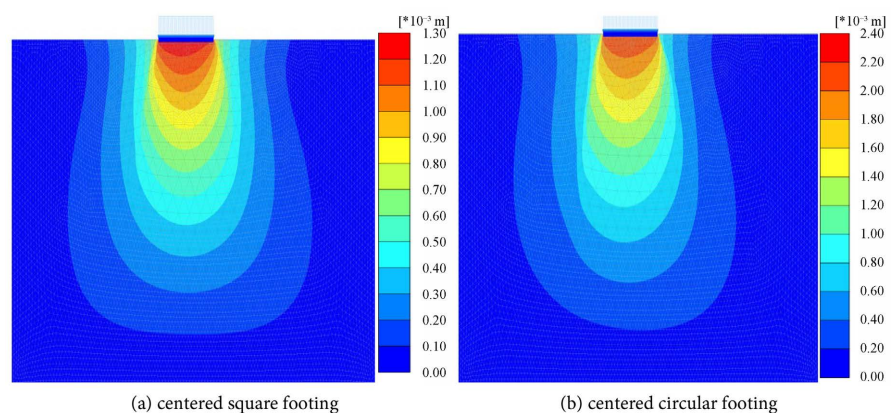
Ratio = Numerical/Experimental.

**Figure 8.** Allowable bearing capacity for block type A.**Figure 9.** Allowable bearing capacity for block type B.

The allowable bearing capacity from numerical simulations is summarized in **Tables 2-4**, alongside the experimental values for comparison. **Table 2** presents the allowable bearing capacities obtained with centered square footings. Weathered basanites exhibit capacities of 28.50 MPa and 25.19 MPa for type A and type B specimens, respectively. In vacuolar basanites, the corresponding values are 24.02 MPa and 27.29 MPa. Healthy basanites provide significantly higher capacities, reaching 63.16 MPa in type A specimens and 47.13 MPa in type B specimens. The numerical results obtained for centered circular footings (**Table 3**) indicate an overall increase in bearing capacity. Allowable bearing capacity for weathered basanites ranges between 35.15 MPa and 45.50 MPa, depending on specimen type. Vacuolar basanites show values from 34.59 MPa and 27.37 MPa in type A and type B specimens, respectively. The highest capacities are again observed in healthy basanites, with values reaching 65.29 MPa and 57.34 MPa. For eccentric footings on type A specimens (**Table 4**), the allowable bearing capacity for square footings is 30.88 MPa in weathered basanite, 27.47 MPa in vacuolar basanite, and 56.67 MPa in healthy basanite. For eccentric circular footings, the values are 40.36 MPa, 34.51 MPa, and 56.71 MPa, respectively. The numerical-to-experimental allowable bearing capacity ratios range from 1.05 to 3.01, depending on the rock facies. The closest correlation is obtained for vacuolar basanites, with ratios between 1.05 and 1.11. This strong agreement indicates that the Hoek-Brown elasto-plastic criterion is most appropriate for moderately altered rocks exhibiting progressive failure.

The total displacement fields obtained from numerical simulations for type A and B rock blocks are presented in **Figure 10** and **Figure 11** for weathered, vacuolar, and healthy basanites, respectively. For Type A blocks ($150 \times 150 \times 75$ mm), maximum displacements range from 5.58×10^{-4} to 5.99×10^{-4} m for healthy basanite, increase to 6.64×10^{-4} - 1.05×10^{-3} m for vacuolar basanite, and reach 1.29×10^{-3} - 2.23×10^{-3} m for weathered basanite.

A similar trend is observed for Type B blocks ($100 \times 100 \times 50$ mm), although the displacement levels are generally lower, ranging from 3.94×10^{-4} - 4.93×10^{-4} m for healthy basanite, 7.29×10^{-4} - 7.42×10^{-4} m for vacuolar basanite, and 7.29×10^{-4} - 1.29×10^{-3} m for weathered basanite. This behavior reflects the



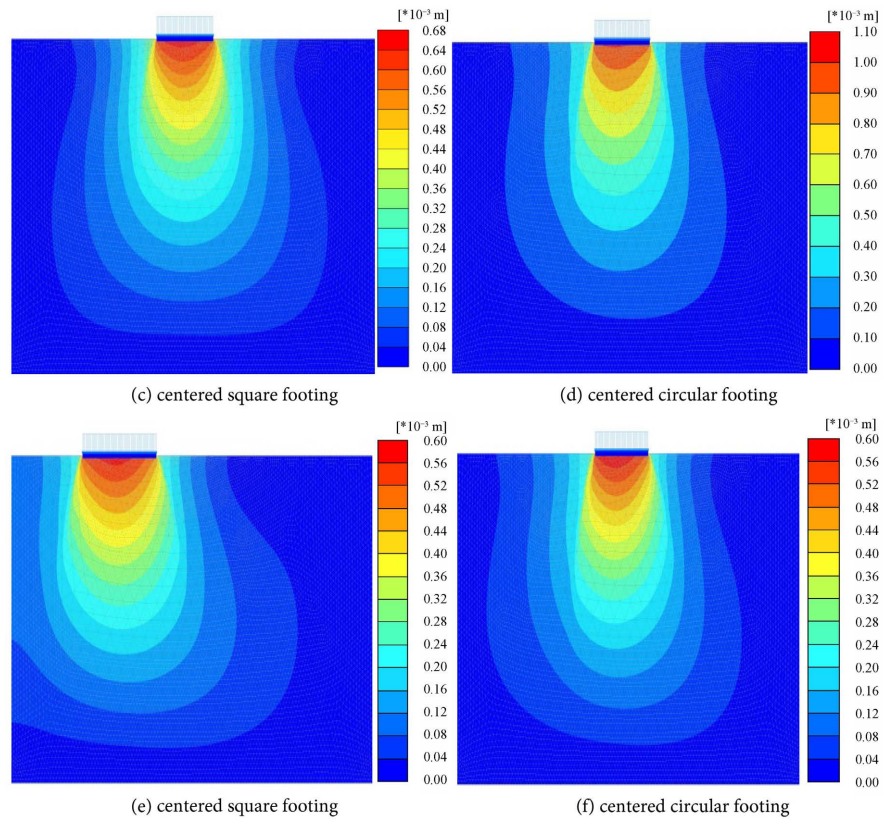
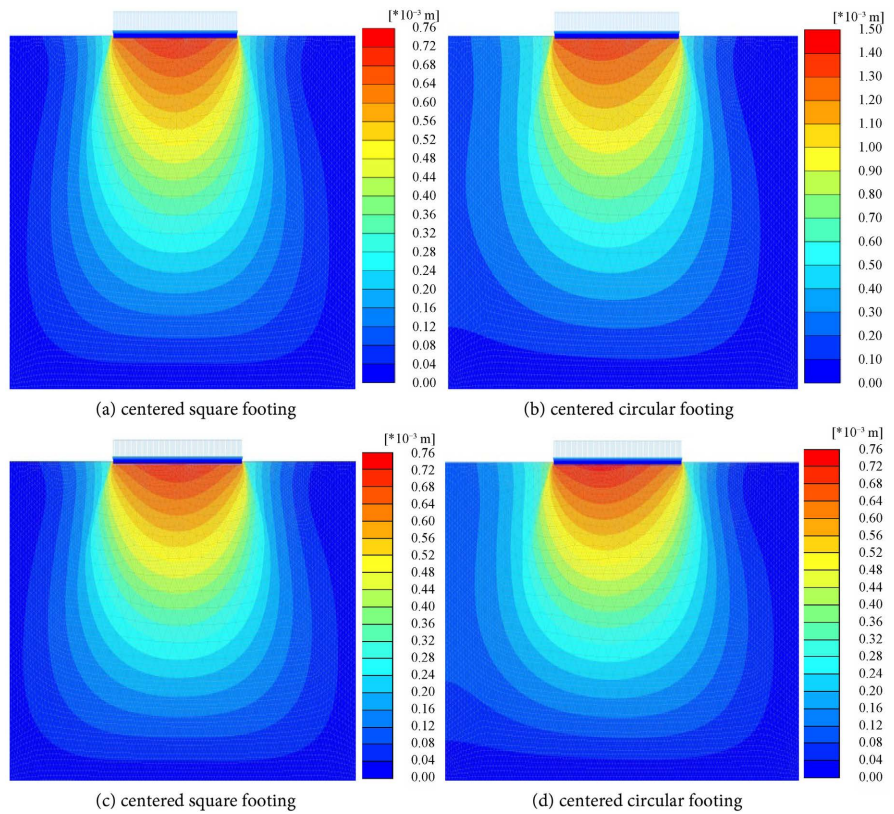


Figure 10. Total displacement types A rock blocks (a - b: weathered basanite; c - b: vacuolaire basanite; e - f: healthy basanite).



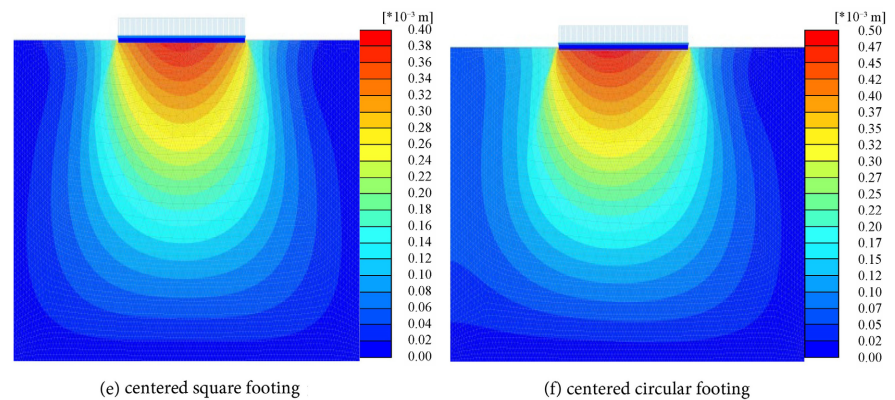


Figure 11. Total displacement types B rock blocks (a - b: weathered basanite; c - b: vacuolaire basanite; e - f: healthy basanite).

progressive degradation of rock stiffness with increasing weathering and the additional stress concentration induced loading. Numerical results indicate a punching failure mechanism in all configurations, characterized by total displacement contours concentrated directly beneath the footing and the absence of extended shear zones propagating toward the free surface, which are typically associated with general shear failure. This localized deformation pattern is consistent with the brittle failure behavior of intact rock, as described by Wyllie (1999).

4. Conclusions

This study investigated the bearing capacity of shallow footings on Cape Verde Peninsula basanites through experimental scale model testing and numerical simulations with Plaxis 2D.

The following conclusions are drawn:

1) Footing shape and block size: Circular footings outperformed square footings across all facies and block types, with the largest advantage for weathered basanites (ratio = 1.82). The axisymmetric stress distribution beneath circular footings mobilizes a larger failure volume. Circular foundations are recommended for marginal rock conditions in the Dakar region. Additionally, Type A (150 × 150 × 75 mm) specimens exhibited higher bearing capacities than Type B (100 × 100 × 50 mm) specimens, which is qualitatively consistent with Meyerhof's observation that bearing capacity increases with the block thickness-to-footing width ratio (H/B).

2) Failure mechanisms: A Punching-splitting mechanism governs the failure of weathered basanites; cleavage fracture governs vacuolar and healthy basanites. The observed fracture angles (15° - 55°) fall well below the Mohr-Coulomb theoretical value (78°), confirming that tensile splitting, rather than shear, controls failure.

3) Numerical model: The Hoek-Brown-based Plaxis 2D model validates experimental trends satisfactorily for vacuolar basanites, yielding numerical-to-experimental ratios between 1.05 and 1.11 but overestimates bearing capacity for intact

healthy basanites (ratios up to 3.01), reflecting the limitation of continuum models for brittle rock fracture.

Further research should investigate joint scale effects using larger block assemblies, examine the impact of footing eccentricity on bearing capacity, and develop 3D numerical models to properly simulate the geometric effects of square footings. Additionally, specific design charts should be established for Cape Verde basanites to incorporate joint spacing as a third parameter alongside UCS and GSI.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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