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Experimental Investigation on the Bearing Capacity of Loose Sand: Effects of Footing Geometry and Cemented Layer Thickness

Ali Jabbar Mutar, Mohammed Khachi Hatem

[1,2,] Civil Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

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ABSTRACT

Shallow foundations constructed on loose sand deposits frequently face significant geotechnical challenges, primarily characterized by low bearing capacity and excessive settlement due to the soil's punching shear failure mechanism. This study presents a comprehensive experimental investigation to quantify these behaviors and evaluate the efficacy of surface cement stabilization as a ground improvement technique. The experimental program was conducted in two distinct phases. The initial phase established a baseline for untreated loose sand (Dr=30%) by examining the "scale effect" through square footings of varying widths (B=60,70,80,and 100 mm) and analyzing the "shape effect" by comparing square and circular geometries. The results demonstrated a non-linear increase in bearing capacity with footing size, confirming the stress-level dependency of granular soils. Furthermore, square footings exhibited superior performance, yielding approximately a 19% higher ultimate capacity than circular footings of equivalent dimensions due to enhanced confinement at the corners.

In the second phase, the study investigated the performance of a rigid square footing (B=60 mm) resting on a finite cement-stabilized crust (3% cement content, cured for 7 days). The width of the improved zone was fixed at twice the footing width (W=2B), while the layer thickness was systematically varied to thickness ratios (H/B) of 0.5, 1.0, 1.5, and 2.0. The inclusion of the cemented layer fundamentally altered the load-settlement response, transforming the failure mode into a rigid slab action that effectively distributed stresses over the weaker subgrade. The improvement efficiency was substantial, with the ultimate bearing capacity rising from 104.2 kPa at a thin layer of H/B=0.5 to a peak of 325.3 kPa at H/B=2.0. These findings indicate that optimizing the thickness of a finite cemented crust offers a highly effective and economical alternative to deep foundations for structures on marginal granular soils.

1. Introduction

In the contemporary landscape of civil engineering, the scarcity of competent construction sites has increasingly compelled geotechnical engineers to utilize marginal lands, where loose sand deposits pose a formidable challenge due to their inherent structural inadequacy. These granular soils are characterized by a high void ratio and a metastable fabric, rendering them highly susceptible to excessive differential settlement and catastrophic bearing capacity failure under shallow foundations [1], [2]. The failure mechanism in such cohesionless media is typically governed by "punching shear," a mode wherein the footing penetrates the soil mass vertically with minimal lateral yielding, leading to unpredictable foundation performance that often defies the predictions of classical plastic

[*] Corresponding author E-mail address: alijabbar@uomustansiriyah.edu.iq
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equilibrium theories [3], [4]. Consequently, the development of economic and robust ground improvement techniques has transcended from a mere option to a critical design imperative for ensuring the serviceability and longevity of infrastructure [5].

Among the spectrum of amelioration strategies, surface stabilization using cementitious agents has emerged as a scientifically proven and practically viable solution. The incorporation of Portland cement into the upper horizon of loose sand initiates a complex hydration process, precipitating calcium silicate hydrate (C-S-H) gels that bind the inert quartz particles into a coherent, rigid matrix [6], [7]. This artificially cemented crust functions fundamentally differently from the underlying natural soil; it acts through a "slab action" or "load-spreading" mechanism, effectively distributing concentrated structural loads over a broadened area of the weaker subgrade, thereby reducing contact stresses and mitigating the risk of localized shear failure [8], [9]. However, the successful design of such composite systems is predicated not merely on the strength of the improved layer, but on a rigorous understanding of the interaction between the foundation geometry and the soil's baseline behavior.

A critical lacuna in conventional design practice lies in the over-reliance on traditional bearing capacity equations (such as those by Terzaghi [10] and Meyerhof [11]) which often treat soil strength parameters as intrinsic constants independent of the footing size. This assumption frequently overlooks the profound "scale effect" inherent in granular mechanics, where the bearing capacity factor (N_γ) exhibits a non-linear inverse dependency on the footing width (B) due to the stress-level dependency of the friction angle [12]. Furthermore, the interplay between this scale effect and the "shape effect"—specifically the distinct failure kinematics of square versus circular footings—creates a complex reference behaviour that remains insufficiently characterized in the literature. Therefore, establishing an accurate, multi-scale baseline for untreated soil is not an academic exercise but a fundamental prerequisite for quantifying the true efficiency of any subsequent finite-layer improvement technique.

Consequently, this study adopts a systematic, two-phase experimental approach to investigate the performance of shallow foundations on loose sand. The initial phase focuses on establishing a comprehensive baseline by examining the load-settlement response of untreated loose sand. This phase specifically scrutinizes the "scale effect" by testing square footings of varying widths (60, 70, 80, and 100 mm) and investigates the "shape effect" by comparing circular and square footings of equivalent dimensions. Building upon this established baseline, the second phase evaluates the efficacy of a finite cement-stabilized replacement layer in enhancing the bearing capacity. In this stage, the footing geometry is standardized to a 60 mm square plate to isolate the influence of the improvement parameters. The study investigates a practical, localized improvement scheme where the width of the treated zone is fixed at twice the footing width (W=2B), utilizing a sand-cement mixture with 3% cement content cured for 7 days. The primary variable in this phase is the thickness of the cemented layer, which is varied systematically (depth ratios H/B=0.5,1.0,1.5, and 2.0) to identify the optimal geometric configuration for effective load distribution.

2. Test materials and apparatuses

The materials used in this study were locally sourced clean natural sand and sulfate-resistant Portland cement. Further details on each material are provided in the following subsections.

2.1 Sand

The soil used in this study was clean, yellowish, dry sand procured from a local source. To ensure material homogeneity, the sand was air-dried and passed through a No. 10 (2.00 mm) sieve to eliminate any coarse aggregates or impurities. The physical properties of the soil were determined through standard tests conducted at the Geotechnical Laboratory of Mustansiriyah University. The particle size distribution and physical properties of the used sand are presented in Figure 1 and Table 1, respectively.

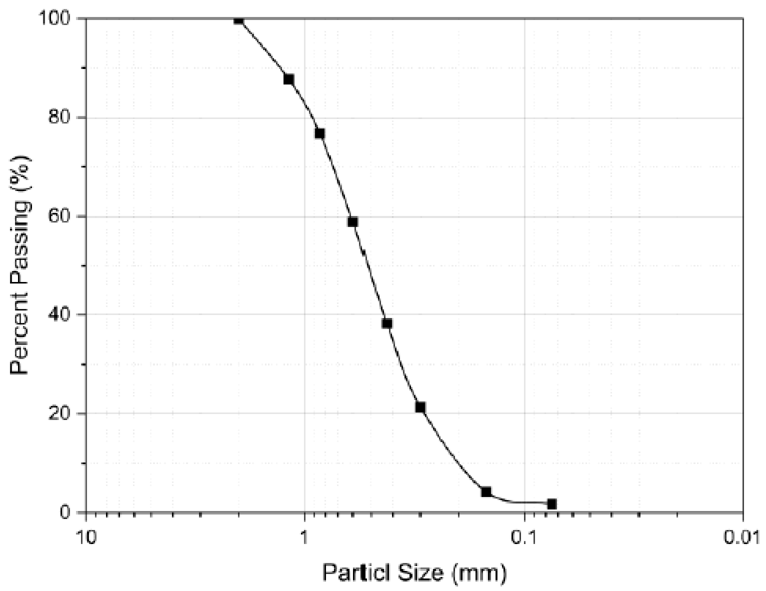

Figure 1. Tthe grain size distribution of the sandy soil

Table 1 physical and chemical properties of soil

Property	Unit	Value	Standard Specifications
Gravel	%	0.00	
Sand	%	98.30	
Fines	%	1.70	
D_{10}	mm	0.20	
D_{30}	mm	0.36	ASTM D6913 (2017)
D_{50}	mm	0.٥٢	
D_{60}	mm	0.62	
Coefficient of Uniformity (Cu)	~	3.08	
Coefficient of Curvature (Cc)	~	1.07	
Classification (USCS)	~	SP	ASTM D2487 (2017)
Specific Gravity (Gs)	~	2.66	ASTM D854 (2023)
Minimum Dry unit weigh (γ_{dmin})	kN/m³	13.24	ASTM D4254 (2006)
Maximum Dry unit weigh (γ_{dmax})	kN/m³	17.03	ASTM D4253 (2019)
Dry unit weight (at Dr=30%)	kN/m³	14.18	~
Dry unit weight (at Dr=95%)	kN/m³	16.78	
Friction angle (φ) (at Dr=30%)	degree	31.7	ASTM D2850 (2025)
Friction angle (φ) (at Dr=٩٥%)	degree	42.8	
Cohesion (c)	kPa	3	
sulphate content (SO_3)	%	0.38	IQS 45/1984

2.2. Cement

Locally manufactured sulfate-resisting Portland cement (SRPC), commercially known as “Al-Gesr”, was utilized in this study. This cement is classified as CEM I 42.5 R – SR and conforms to the specifications of the Iraqi Standard IQS 5/2019 [13].

2.3. Specimen Preparation of Treated Soil

The treated soil specimens were prepared by thoroughly dry-mixing oven-dried sand with a cement content of 3% by dry weight. Distilled water was then gradually added to the mixture to achieve the Optimum Moisture Content (OMC). Standard Proctor compaction tests were conducted in accordance with ASTM D698 (2021) [14] to determine the compaction characteristics. As shown in Figure 2, the mixture with 3% cement yielded a Maximum Dry Density (MDD) of 18.09 kN/m³ and an OMC of 10.2%.

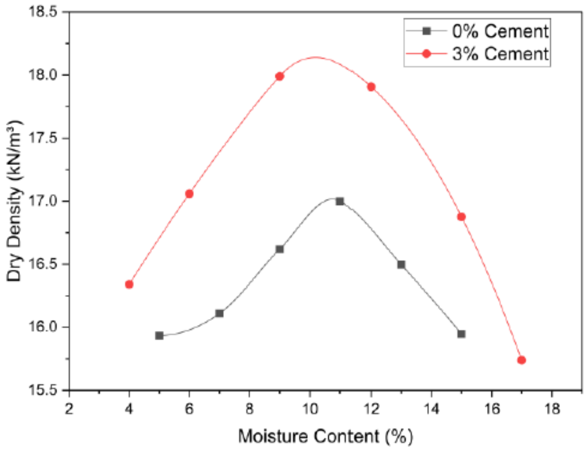

Figure 2 Compaction results of the cemented sand.

2.3. Experimental Model

The experimental program was conducted using a custom-designed setup illustrated in Figure 3. The apparatus comprises a soil container, a reaction frame, and a loading system. The test tank consists of a rigid cubic steel box with internal dimensions of 600×600×600 mm and a wall thickness of 4 mm. These dimensions were carefully selected to minimize boundary effects and ensure that the stress isobars extend freely within the soil mass [15].

The reaction frame, designed to support the hydraulic jack, was fabricated from steel channel sections to form a rigid structure with a clear height of 1200 mm and a width of 800 mm. This frame is welded to a stable 800×800 mm square base. Vertical loads were applied using a manually operated hydraulic jack (2-ton capacity) capable of delivering controlled incremental loading. The resulting settlement was monitored using two precision digital dial gauges (0.002 mm resolution) mounted on an independent reference beam to isolate them from any system deformations.

To investigate the influence of foundation geometry, a series of rigid steel plates were manufactured with a thickness of 10 mm. The testing program included different footing shapes (square and circular) as shown in Figure 4, and various sizes to examine the scale effect, as detailed in Figure 5.

For the baseline tests, a square footing of 60×60 mm was utilized. The selection of footing dimensions was guided by the criteria proposed by Bolton et al. [16] to eliminate particle size effects. They suggested that the ratio of footing width (B) to the mean grain size (D50) should exceed 20. In this study, with a D50 of 0.52 mm, the B/D50 ratio is approximately 115, ensuring that the model behaves as a continuum rather than individual particles.

Figure 3 The model setup

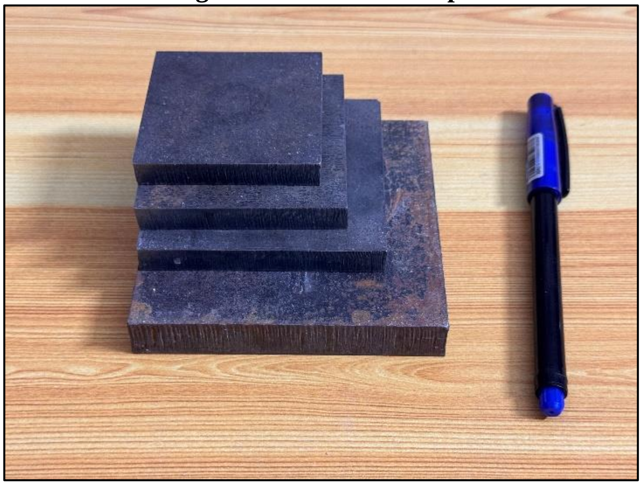

Figure 4 Model footings with different sizes.

Figure 5 Model footings with different shapes.

3. Results and discussion

3.1. Effect of Foundation Size

To examine the influence of footing size on the bearing capacity of loose sand (prepared at a relative density Dr=30% and a corresponding dry unit weight γd=14.18 kN/m³), a series of loading tests were conducted on four square footings with varying widths (B) of 60, 70, 80, and 100 mm. The load-settlement behaviors for all tested sizes are compared in Figure 6.

The experimental results demonstrate a clear dependency of the bearing resistance on the footing geometry. As the footing width increased, the mobilized bearing capacity (q10) at the failure criterion (s/B=10%) showed a consistent upward trend. Specifically, the bearing capacity values were recorded as 19.2, 24.3, 27.5, and 51.8 kPa for footing widths of 60, 70, 80, and 100 mm, respectively. This substantial increase indicates that larger footings mobilize higher shear resistance per unit area compared to smaller ones in loose sand deposits.

This behavior aligns with Terzaghi's bearing capacity theory [10] for surface footings on cohesionless soils, which posits that the ultimate bearing capacity is directly proportional to the footing width (B) when the soil unit weight is constant. Physically, this phenomenon is attributed to the expansion of the stress influence zone (pressure bulb) beneath the foundation [2]. As the footing size increases from 60 mm to 100 mm, the stress bulb extends deeper into the soil mass, providing greater confinement and engaging a larger volume of sand in the shear resistance mechanism, thereby enhancing the overall bearing capacity.

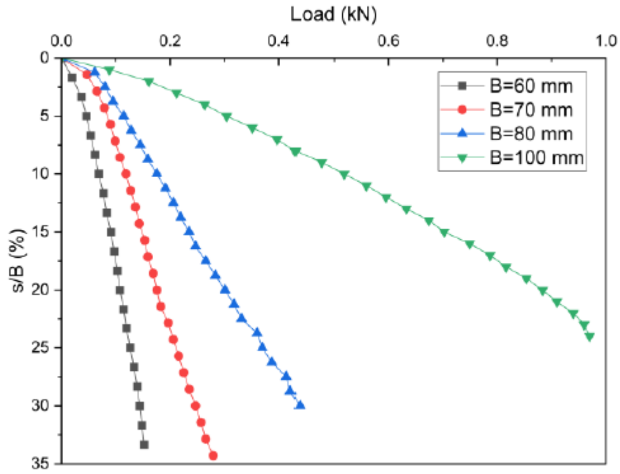

Figure 6 Load–settlement response of loose sand for different footing sizes.

3.2. Effect of Foundation Shape

The influence of footing geometry was investigated by comparing the performance of circular footings (D=60 and 100 mm) against square footings of equivalent widths (B=D). All tests were conducted on loose sand prepared at a relative density Dr=30% (γd=14.18 kN/m³).

The variation of the settlement ratio (s/B) with applied load for the different geometries is presented in Figure 7. For the smaller model size (B=D=60 mm), the square footing sustained a load of 0.069 kN, slightly exceeding the 0.065 kN sustained by the circular footing. However, the influence of shape became significantly more pronounced as the footing scale increased. For the 100 mm footings, the square geometry mobilized a bearing capacity of 51.8 kPa, whereas the circular footing sustained only 43.7 kPa. These results indicate that the square footing provides approximately a 19% increase in bearing capacity compared to its circular counterpart of the same dimension.

This behavior aligns with Terzaghi's bearing capacity theory [10]. In the context of cohesionless soils, the shape factor (sγ) associated with the soil weight term contributes more effectively to the capacity of square footings than to circular ones. According to Terzaghi, the shape factor for a square footing is sγ=0.8, while for a circular footing, it reduces to sγ=0.6. From a physical perspective, the square geometry mobilizes a larger volume of soil in the shear failure zone due to "corner effects," thereby offering higher resistance compared to the axisymmetric failure mode of circular footings [12].

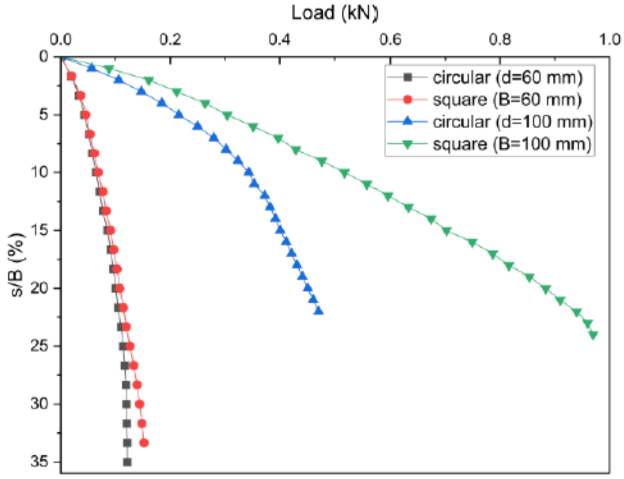

Figure 7 Load–settlement curves for square and circular footings on loose sand.

3.3. Effect of Cement Treatment on Sand

To determine the impact of the improved layer depth on the bearing capacity, a series of model tests were conducted using a square footing (B=60 mm). The width of the improvement zone was fixed at W=2B (120 mm), while the thickness of the cemented layer (H) was varied to correspond to thickness ratios (H/B) of 0.5, 1.0, 1.5, and 2.0. In all these tests, the cement content was maintained at 3% with a 7-day curing period.

Figure 8 presents the load-settlement behaviors for the treated sand layers in comparison to the untreated loose sand. The results indicate a substantial and continuous enhancement in the bearing capacity as the layer thickness increases. Starting from the baseline ultimate load of 0.069 kN for the untreated sand (at s/B=10%), the inclusion of a thin cemented layer (H/B=0.5) raised the capacity to 0.375 kN. Doubling the layer thickness to H/B=1.0 resulted in a further increase to 0.657 kN. This upward trend continued for the thicker layers, with the ultimate load reaching 0.944 kN at H/B=1.5 and peaking at 1.171 kN for the thickest layer tested (H/B=2.0).

In terms of improvement efficiency, these values correspond to Bearing Capacity Ratios (BCR) of approximately 5.4, 9.5, 13.7, and 17.0 for thickness ratios of 0.5, 1.0, 1.5, and 2.0, respectively. This significant improvement is attributed to the structural benefit of the cemented crust, which acts as a rigid slab distributing the applied stresses over a wider area of the underlying loose sand. Indicating that a sufficient volumetric improvement ratio mitigates the progressive compressibility of the underlying soil [17].

Even with a finite width of W=2B, increasing the thickness enhances the flexural rigidity of the improved layer, thereby preventing premature punching failure and mobilizing greater shear resistance within the soil system. This plateau suggests a geometrical saturation point where the improved width fully encompasses the stress bulb. This finding is consistent with recent numerical studies by Hamid and Alnuaim [18],

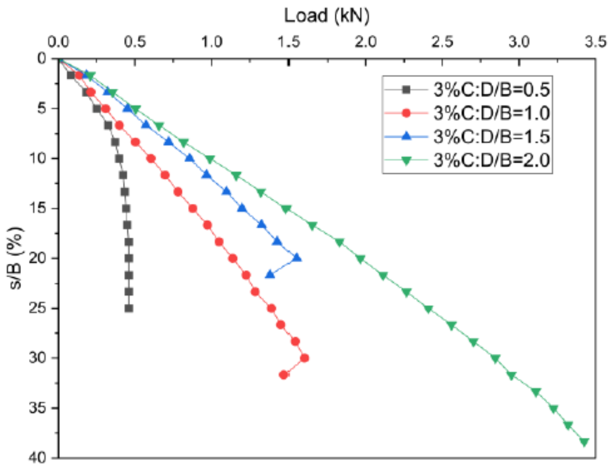

Figure 8 Load–settlement curves of 3% cement-treated sand at varying improvement depths H/B.

Visual observation of the deformed model, as depicted in Figure 9, indicates that at a shallow depth of D/B=0.5, the failure surface penetrates vertically through the improved layer. This behavior confirms that the layer thickness is insufficient to redistribute the stress fully, resulting in a punching shear mechanism into the underlying weak soil [19].

Figure 9 Failure pattern for 3% cement-treated sand at D=0.5B.

4. Conclusion

This study presented a systematic experimental investigation into the bearing capacity of shallow foundations resting on loose sand deposits improved by a surface cement-stabilized layer. By isolating the effects of footing geometry (size and shape) on untreated soil and subsequently evaluating the structural contribution of a finite cemented crust (W=2B) with varying thicknesses (H/B), several critical conclusions can be drawn regarding the behaviour and design of such composite systems:

1. The baseline tests on untreated sand confirmed that ultimate bearing capacity is size-dependent. Increasing the footing width from 60 mm to 100 mm resulted in a significant rise in bearing capacity from 19.2 kPa to 51.8 kPa, highlighting the necessity of accounting for the scale effect in granular soils.
2. Foundation geometry played a critical role in performance. Square footings consistently demonstrated superior resistance, achieving approximately 19% higher bearing capacity compared to circular footings of equivalent width. This enhancement is attributed to the additional confinement provided by the corner zones in square geometries.
3. Introducing a rigid cemented crust (3% cement) effectively mitigated the punching shear failure mode of loose sand. Even a minimal layer thickness of H/B=0.5 yielded a substantial improvement, increasing the ultimate load to 0.375 kN.
4. The system's efficiency is directly governed by the thickness of the improved layer. Increasing the thickness ratio from H/B=0.5 to 2.0 resulted in a continuous capacity increase, peaking at an ultimate load of 1.171 kN.
5. The finite cemented layer functions as a rigid slab that distributes stresses over a wider area of the subgrade. For practical design on loose sand, a layer thickness of at least the footing width (H/B≥1.0) is recommended to fully mobilize this "slab action" and ensure a robust composite system.

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