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# Bearing capacity of square footing resting on lime-sand soil

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**Keywords:** bearing capacity, square footing, plate load, lime-sand, treated layer

**Abstract.** This study aims to evaluate the bearing capacity of shallow square footing resting on an artificially treated lime-sand soil layer, considering the influence of the treated layer thickness (H) and different dry unit weights of the soil layer beneath the treated layer. Additionally, the effect of lime content on the unconfined compressive strength (UCS) of lime-treated sand was also investigated. The data were obtained from loading tests carried out on a square steel plate model (89 mm length, 89 mm width, and 23 mm thick) placed on the top of an artificial lime-sand layer with H/B = 0.1, 0.3, 0.6, 1, where B is the width of the footing. The sand under the artificial layer was compacted with two dry unit weight values (14.4 and 15.8 kN/m$^3$), thus, achieving the loose (33 %) and dense (77 %) states, respectively. Different percentages of lime (5, 7, 10, and 15 %) were added to examine the strength of treated sand soil with lime. The results showed that the increased H/B ratio affected the stress-settlement curves and improved bearing capacity with the bearing capacity ratio (BCR) rising from 1 to 2 in loose state and from 1 to 1.9 in dense state. Small scale load tests of square footing resting on lima-sand treated layer on the top of sand with different dry unit weights revealed two failure modes. For H/B = 1 with the lowest dry unit weight, the treated layer punched through to the sand soil without visible fissures until reaching the bearing capacity of the underlaying sand. For lower H/B ratios (0.1, 0.3), the lime-treated soil layer fractured, forming cracks near the footing edge and central axis, whereas higher H/B ratios (0.6, 1) resulted in cracks primarily near the footing edge.

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## 1. Introduction

Sandy soils cover certain areas of Iraq, presenting challenges, such as low bearing capacity, excessive settlement, and others. Therefore, this study aims to enhance the characteristics of clayey soil through chemicals or additives to improve its strength and durability, among other improvements [1].

Recently, various methods of soil stabilization through chemicals or various natural and synthetic materials have occurred. Chemical stabilization is the process of changing soil characteristics by adding chemically active element to improve its characteristics and increase its bearing capacity [2]. The soil improvement by chemical stabilization is more successful than deep foundations because, while reducing settlement, it can be expensive. The most common construction materials used for soil stabilization include lime, cement and pozzolanic materials [3].

Lime stabilization is a cost-effective method that reduces soil plasticity, improves soil workability, and enhances mechanical properties, such as California Bearing Ratio (CBR) values, unconfined compressive strength (UCS), shear strength, and tensile strength. This technique has a significant impact on fine soil and has many benefits [4, 5].

Soil stabilization with lime is not a new technique. In fact, the Chinese and Indians have used this particular mixture for centuries to build dams, bridge footings, and underground chambers [6]. Similarly, the Romans utilized lime-soil mixture for road sub-base [6]. The effectiveness of lime stabilization depends on several factors, including clay mineralogy, soil pH, silica-alumina content, lime type, water content, temperature, and curing duration [7].

Over the years, various methodologies [5, 8, 9] have been developed to determine the proper amount of lime required to adjust properties of soil and provide suitable durability and strength. Such methodologies usually aim to establish a threshold value that is intended to meet soil chemical requirements for lime, often serving as the baseline for construction purposes.

In [10], the effectiveness of applying quick and hydrated lime at different percentages (0, 2.5, 7.5, and 10 %) on the soil of tropical and subtropical regions (separately) was examined. The results showed that, regardless of lime type, it generally improves the compressive strength. In [11], the uncured effects of lime stabilization on fine-grained cohesive soil with 2, 4, and 6 % lime content were examined. The early strength and deformation properties (cone index, CBR, shear strength, and deformation moduli) of uncured lime-soil mixtures compacted wet of optimum showed substantial improvement compared to untreated natural soils. In [3], the impact of various lime and natural pozzolanic dosages on the geotechnical characteristics of silt sand soil has been studied. The results showed that lime improves compressive strength of the soil, while a combination of both lime and pozzolan significantly increased compressive strength – up to sixteen times that of untreated soil.

There have been several studies of shallow foundations in layered systems, most of them focus on sandy layer treated with cement or other stabilized agents [12–14]. Only a few [7, 15] dealt with lime-sand layers.

Plate load tests were conducted [15] on soil layers that had been compacted with lime and fly ash, resulting in increased bearing capacity and reduced settlement. As the H/D ratio increased, the test plates exhibited stiffer and stronger behavior.

In [7], plate load tests on layered systems consisting of compressible residual soil layer overlaid by three different top layers (sandy soil – bottom ash – carbide lime mixture, bottom ash – cement mixture, residual soil – cement mixture) that have been artificially cemented into place were studied. The results showed that using bottom ash and carbide lime on the treated top layer enhanced ultimate load capacity and reduced foundation settlements on processed cemented soil. The tensile cracking began at various locations according to the H/D ratio and maximum H/D value of about 1.0.

The main objective of this study is to investigate the bearing capacity and settlement of the shallow foundation resting on a lime-stabilized sand layers of varying thicknesses, considering two distinct states.

## 2. Materials and Methods

### Materials

The sand air-dried soil used in this study was collected from a site near Nasiriya city, Iraq. The sand's physical properties are given in Table 1. The sand used in the study is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Fig. 1 shows sieve analysis test results [16]. Hydrated lime (calcium hydroxide $Ca(OH)_2$), in a form of fine white powder was supplied by the Karbala lime plant. The characteristics of hydrated lime are given in Table 2. Tap water was used for all experimental procedures, with the exception of the specific gravity test, for which distilled water was used.

***Table 1. Physical properties of sand.***

| GS | Cu | Cc | Classification of soil (USCS) | $\gamma_d$ min., kN/m³ | $\gamma_d$ max., kN/m³ | $e_{min.}$ | $e_{max.}$ | Angle of internal friction (φ) at | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $\gamma_d$ =15.8 kN/m³ | $\gamma_d$ =14.4 kN/m³ |
| 2.61 | 2.6 | 1.24 | SP | 13.5 | 16.6 | 0.54 | 0.89 | 35.6 | 31 |

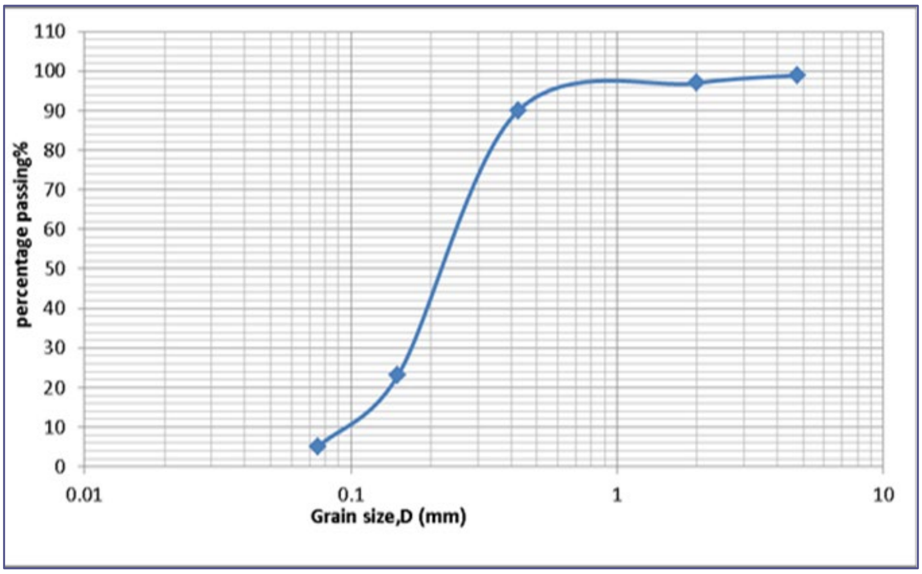


**Figure 1. Sieve analysis test results.**

***Table 2. Characteristics of hydrated lime.***

| Property | Value |
|---|---|
| Form | fine white powder |
| CaO, % | 66.851 |
| $Ca(OH)_2$, % | 88.572 |
| $CO_2$, % | 2.731 |
| Specific gravity | 2.321 |
| Fineness of grinding on a sieve of 90 microns, % | 6 |

***UCS tests***

UCS tests were conducted [17] on eight specimens of soil with lime contents of 5, 7, 10, and 15 %. Two different values of dry unit weights (14.4 and 15.8 kN/m$^3$) and a moisture content of 10 % were used. Cylindrical specimens measuring 42 mm in diameter and 84 mm in height were also used.

The lime and sand were thoroughly mixed to achieve a homogeneous mixture. The lime and water were weighed with the lime content for each mixture determined by the dry soil mass. After that, the water was added. The mixing continued until the mixture became homogenous. Each specimen was compressed in three layers within a greased cylindrical plastic mold, once each layer achieved the required dry density.

After molding, the specimens remained in the plastic mold, wrapped in a plastic sheet, and stored in airtight container for 28 days at a temperature of 22±1 °C. Fig. 2 shows the specimens during the curing. Prior to testing, the weight, diameter, and height of each specimen were measured. Fig. 3 shows the UCS test.

**Figure 2. Specimens during the curing.**

a) b)

**Figure 3. UCS test: a) a specimen under load, b) a failed specimen.**

***Small-scale model tests***

A steel model footing measuring 89 mm in diameter and 23 mm thickness was used in all tests as a shallow footing model. The soil container measuring 600 mm in length, 600 mm in width, and 600 mm in height was manufactured from 6-mm-thick steel.

To apply static vertical load to the footing, a testing frame was designed and manufactured. The 2-ton capacity piston of a hydraulic jack was supported by the testing frame. The hydraulic jack was attached to a 180 mm long nickel shaft with a hole on the other end that connected to the stainless-steel load cell with 2-ton capacity. The hydraulic jack contained a gauge that measured the applied pressure. Load measurements were recorded using a digital weighing indicator SI 4010. Settlement was measured using two dial gauges connected to magnetic supports with 0.01 mm precision (Fig. 4). Fig. 5 shows a sketch of the cross-section for the small-scale model test.

**Figure 4. Complete test setup.**

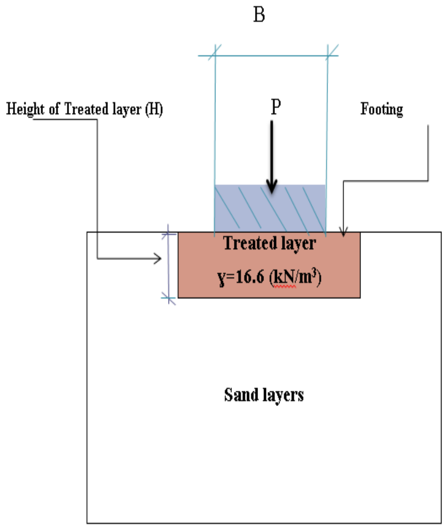


**Figure 5. Sketch of the cross-section for small-scale model test.**

***Preparation of sand layers***

Two series of models were tested using two different values of dry unit weights (14.4 and 15.8 kN/m$^3$). The first series examined untreated soil layers, while the second series evaluated artificially lime-stabilized soil layer. The soil tank was filled in five 120-mm-height layers. Each layer was filled with a certain weight of soil and compacted using a 10 kg steel hammer measuring 130 mm in diameter. The number of blows for every layer was not specified. The compaction continued until each layer was filled with a certain weight and the required dry unit weight was achieved. The sands exhibited effective peak strength values of $c$ = 0 kPa with φ = 35.6° at $\gamma_d$ =15.8 kN/m³ and φ = 31° at $\gamma_d$ =14.4 kN/m³.

The soil was treated with 10 % hydrated lime content and compacted to 16.6 kN/m$^3$ dry unit weight after adding 10 % of moisture content as optimum value. The treated soil was cast in wooden mold outside the soil container to prevent disturbing loose sand. The molding method was essentially similar to UCS testing. Following the mixing, the treated soil was manually compacted in layers with equal thickness, ensuring that each layer satisfied the required dry density and water content requirements. To prevent moisture loss, the sample was wrapped in a plastic sheet. The samples were removed from the mold after 7 days of curing, and their dimensions and mass were measured with accuracy of around 0.1 mm and 0.01 g.

The sample was positioned at the center of the tank. Additional soil was manually added to the treated soil sides until it was level with the top. After that, the displacement gauges and loading piston were installed, and the small-scale square footing model was set up on the treated layer with thickness represented as the H/B ratios: 0.1, 0.3, 0.6, and 1. The treated layer width, curing period and foundation width were kept constant. Table 3 summarizes all experimental parameters considered in this investigation.

***Table 3. Experimental parameters.***

| Test No. | Sand layers | Type and percent of stabilization agent | Dry unit weight of sand layers, kN/m$^3$ | H/B |
|---|---|---|---|---|
| 1 | Untreated | _ | 14.4 | 0 |
| 2 | Treated | Lime 10 % | 14.4 | 0.1 |
| 3 | Treated | Lime 10 % | 14.4 | 0.3 |
| 4 | Treated | Lime 10 % | 14.4 | 0.6 |
| 5 | Treated | Lime 10 % | 14.4 | 1 |
| 6 | Untreated | _ | 15.8 | 0 |
| 7 | Treated | Lime 10 % | 15.8 | 0.1 |
| 8 | Treated | Lime 10 % | 15.8 | 0.3 |
| 9 | Treated | Lime 10 % | 15.8 | 0.6 |
| 10 | Treated | Lime 10 % | 15.8 | 1 |

# 3. Results and Discussion

## 3.1. Results of UCS Tests

Table 4 contains some details of UCS tests, such as percentage of lime, dry unit weights, and results of UCS tests after 28 days of curing. The axial stress increases from 121.7 to 411 kPa for soil with $\gamma_d$ = 14.4 kN/m$^3$ and from 714.6 to 1985.4 kPa for soil with $\gamma_d$ = 15.8 kN/m$^3$ with increasing lime content from 5 to 15 % (Figs. 5, 6).

Fig. 7 shows that the strength increases almost linearly with increasing lime content for both treated soils. It is worth noting that with a higher sand density, the strength of the sample with a higher dry unit weight increases rapidly, while the strength of the sample with a lower dry unit weight increases at a slower rate.

***Table 4. Details of UCS tests.***

| Samples No. | Percentage of lime, % | $\gamma_d$, kN/m$^3$ | UCS for curing time = 28 days, kPa |
|---|---|---|---|
| 1 | 5 | 14.4 | 121.7 |
| 2 | 7 | 14.4 | 235.7 |
| 3 | 10 | 14.4 | 352.3 |
| 4 | 15 | 14.4 | 411 |
| 5 | 5 | 15.8 | 714.6 |
| 6 | 7 | 15.8 | 801.5 |
| 7 | 10 | 15.8 | 1227 |
| 8 | 15 | 15.8 | 1985.4 |

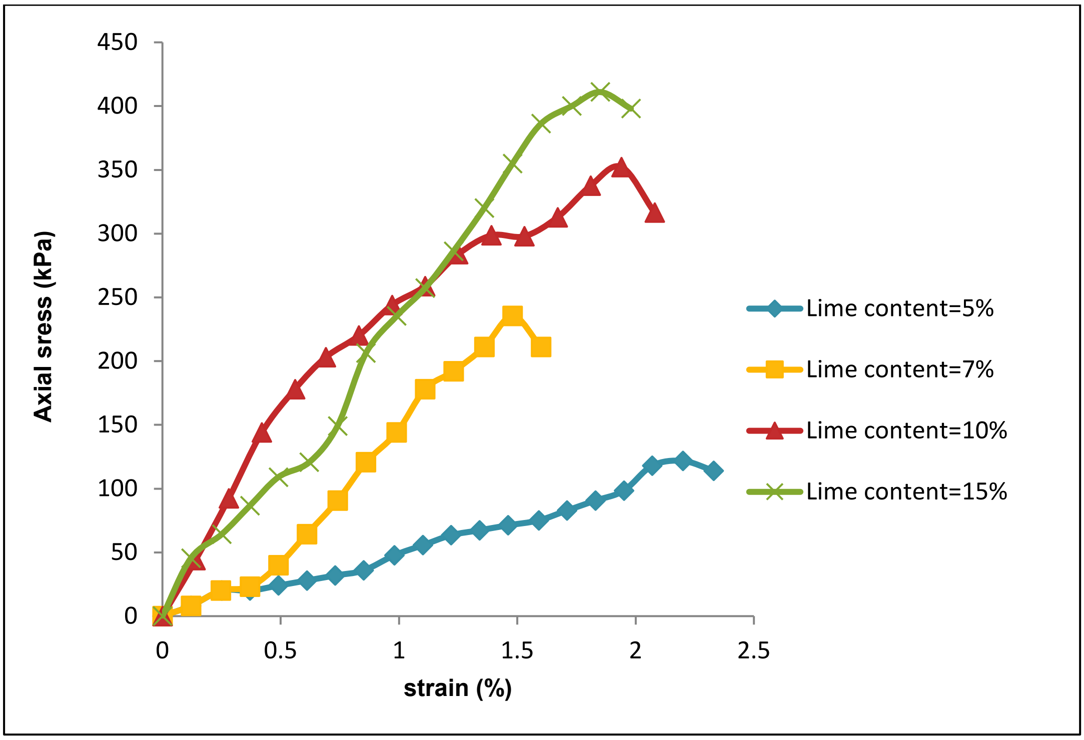


**Figure 5. Stress-strain relationship for soil with $\gamma_d$ = 14.4 kN/m$^3$ and different percentages of lime.**

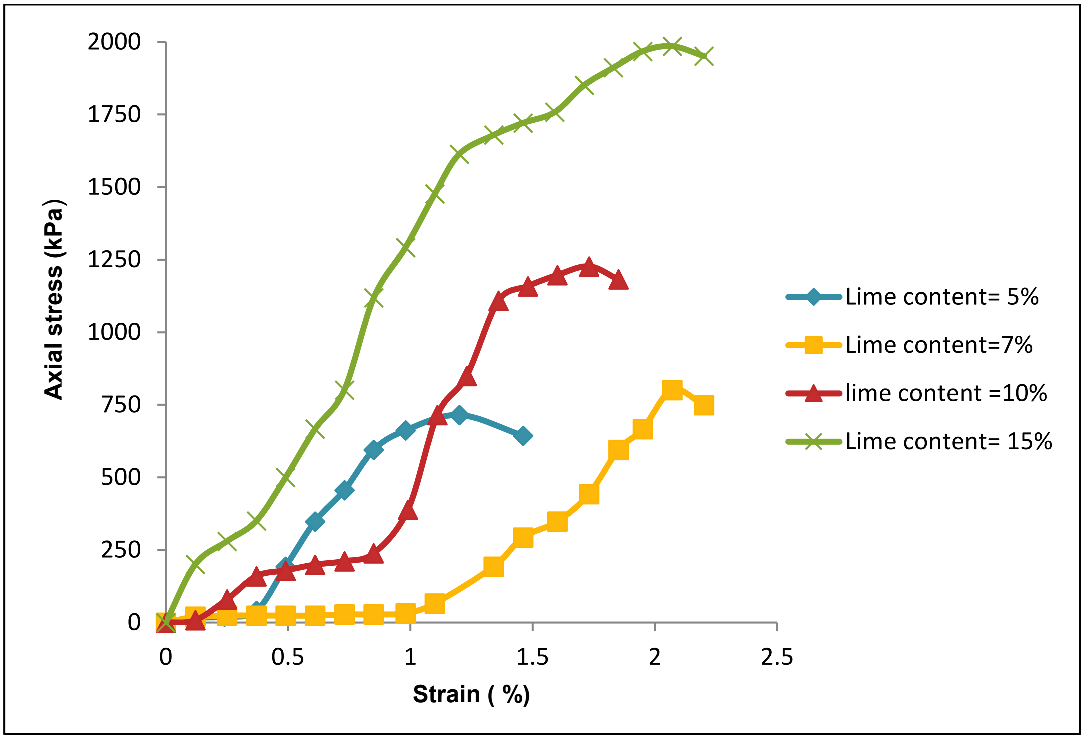


**Figure 6. Stress-strain relationship for soil with $\gamma_d$ = 15.8 kN/m$^3$ and different percentages of lime.**

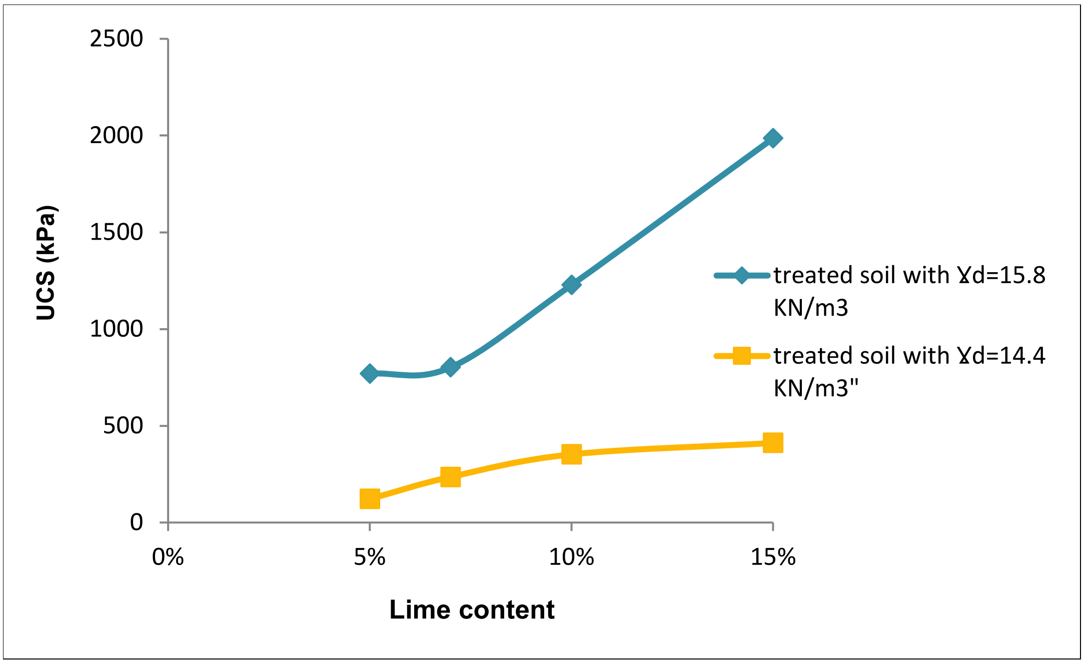


**Figure 7. Axial stress for both treated soils with different dry unit weights and lime content.**

### *3.2. Results of Plate Load Test*

Plate load tests were performed on both natural and lime-treated sandy soils. The results of these tests are shown in Figs. 8, 9. Table 5 summarizes the key characteristics of the results, such as bearing capacity values, bearing capacity ratios (BCRs), failure modes, and the test sequences for each treated layer.

In this study, the bearing capacity was determined from plate load tests. The sand bearing capacity at $\gamma_d$ = 14.4 kN/m$^3$ measured 70 kPa and at $\gamma_d$ = 15.8 kN/m$^3$ – 255 kPa. Figs. 8 and 9 show stress-settlement curves for soils with $\gamma_d$ = 14.4 kN/m$^3$ and 15.8 kN/m$^3$, respectively. Fig. 8 demonstrates how bearing increased from 70 to 76, 83, 118, and 144 kPa for treated layers varying in H/B ratios of 0.1, 0.3, 0.6, and 1, respectively. Fig. 9 demonstrates how bearing capacity increased from 255 to 268, 320, 396.2, and 473 kPa for treated layers varying in H/B ratios of 0.1, 0.3, 0.6, and 1, respectively.

Two distinct failure modes were observed in untreated soils during plate load tests. For foundation on sandy soil with $\gamma_d$ = 15.8 kN/m$^3$, the failure appeared suddenly at the sand surface and significant bulging of the sheared mass of sand occurred with the failure. This type of failure was similar to general shear failure [13, 30]. For foundation on sandy soil with $\gamma_d$ = 14.4 kN/m$^3$, penetration without bulging of the sand occurred, indicating punching failure [19]. The sand-lime layer exhibited fracturing at specific settlements. A sudden stress drop in the stress-settlement curves indicated the start of cracking. Cracking patterns varied by H/B ratio: near footing edges at H/B = 0.6 and 1, along the central axis and edges at H/B = 0.1 and 0.3, with no cracking observed at H/B = 1 in loose soil.

Increased layer thickness produced higher failure loads and stiffer stress-displacement responses. Greater stabilized soil height resulted in larger failure zone covered by resistant soil, thereby enhancing shallow foundation's bearing capacity. The test results showed stiffer and stronger behavior with increasing H/B ratio in both soils with different dry unit weights. Fig. 10 shows the increase in bearing capacity with increasing H/B ratios of treated soil in both dry unit weights, reaching maximum vertical stress of 140 kPa for lower dry unit weight, and maximum vertical stress of 473 kPa for higher dry unit weight. The BCR values increased from1 to 2 in loose state and from 1 to 1.9 in dense state. While lime stabilization is more common for fine-grained soils, its effectiveness in coarse-grained soils depends significantly on soil mineralogy. According to it, lime stabilization can lead to accelerated or moderate strength gain [20–26].

***Table 5. Results of small-scale test.***

| Test No. | $\gamma_d$, kN/m$^3$ | Lime content, % | H/B | S/B 10 % | | Failure modes |
|---|---|---|---|---|---|---|
| | | | | $q_u$, kPa | BCR | |
| 1 | | | 0 | 70 | 1 | Punching |
| 2 | | | 0.1 | 76 | 1.08 | Fissure |
| 3 | 14.4 | 10 | 0.3 | 83 | 1.2 | Fissure |
| 4 | | | 0.6 | 118 | 1.7 | Fissure |
| 5 | | | 1 | 140 | 2 | Punching |
| 6 | | | 0 | 255 | 1 | General |
| 7 | | | 0.1 | 268 | 1.05 | Fissure |
| 8 | 15.8 | 10 | 0.3 | 320 | 1.25 | Fissure |
| 9 | | | 0.6 | 396.2 | 1.6 | Fissure |
| 10 | | | 1 | 473 | 1.9 | Fissure |

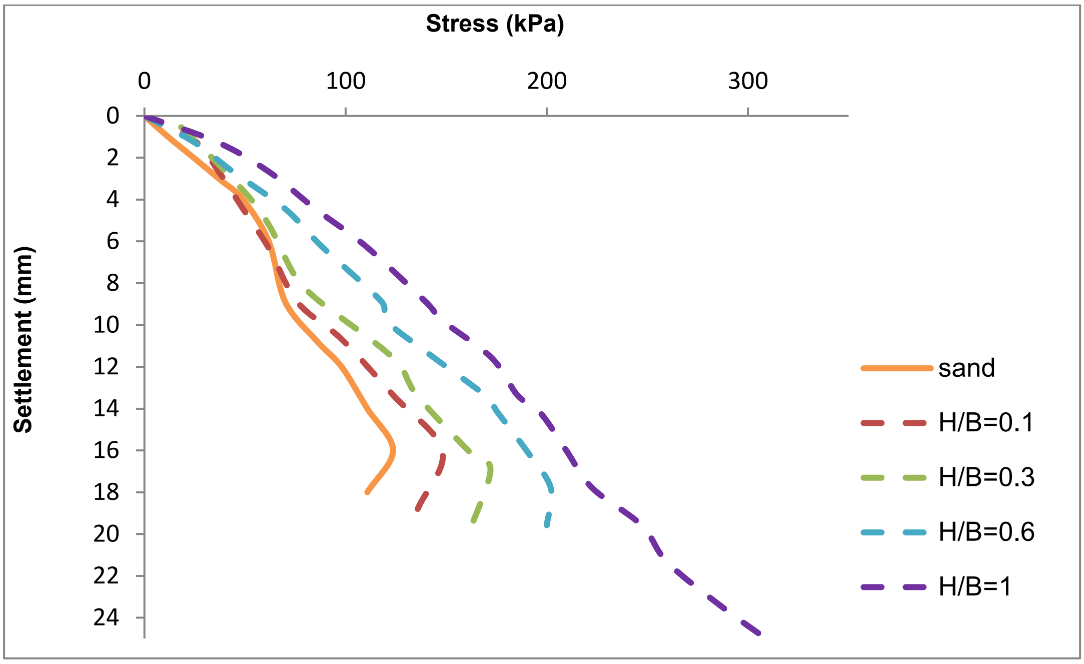


**Figure 8. Stress-settlement curves for model footing trials with various H/B ratios. Lime treated layers and sand layer with $\gamma_d$ = 14.4 kN/m$^3$.**

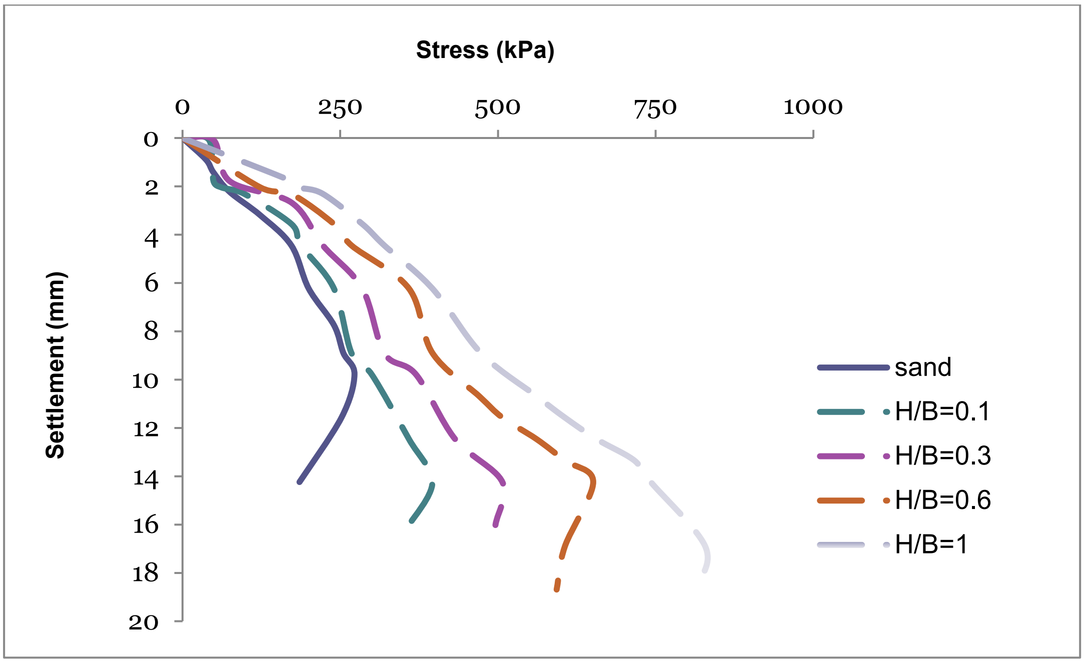


**Figure 9. Stress-settlement curves for model footing trials with various H/B ratios. Lime treated layers and sand layer with $\gamma_d$ = 15.8 kN/m$^3$.**

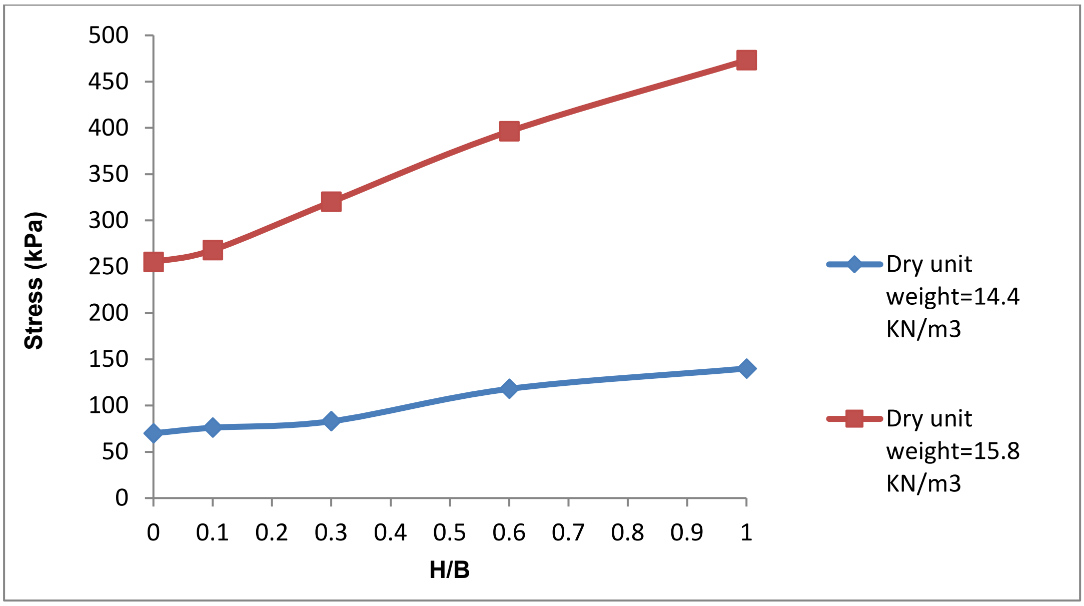


**Figure 10. Relationship between bearing capacity and H/B ratio for lime-treated soil.**

### *3.3. Bearing Capacity Analysis*

***Bearing capacity of untreated soil***

According to [27], BCR represents the enhanced ultimate bearing capacity in non-dimensional form:

$$BCR = q_{u(R)} / q_u , \quad (1)$$

where $q_{u(R)}$ is the ultimate bearing capacity of treated soil and $q_u$ is the ultimate bearing capacity of untreated soil.

The most commonly used bearing capacity equations for untreated soil, based on both practical and theoretical studies, define the ultimate bearing capacity as the pressure causing shear failure in the supporting soil beneath and adjacent to the foundation.

Historically, K. Terzaghi [18] proposed a superposition approach to calculate footing bearing capacity by summing contributions from various soil and load characteristics. Later, G.G. Meyerhof [28] modified Terzaghi's equation with following key differences:

– footing dimensions determine the shape factors;
– shear zone extends above the foundation level.

Additionally, G.G. Meyerhof [28] introduced the method of effective width (dimensions modification) for eccentrically loaded footings. Table 6 compares bearing capacities from plate load tests with theoretical values calculated using [18] and [28].

***Table 6. Different methods of calculating the bearing capacity.***

| $\gamma_d$, kN/m$^3$ | $q_u$ theoretical, kPa, at $Df = 0$ | | $q_u$ experimental, kPa |
|---|---|---|---|
| | [18] | [28] | |
| 15.8 | 34.4 | 49.3 | 255 |
| 14.4 | 14.5 | 19.3 | 70 |

***Bearing capacity of treated soil***

Unlike traditional methods, where bearing capacity factors depend solely on internal angle of friction, P. Purushothamaraj et al. [21] proposed factors that consider both layer cohesions in addition to internal angle of friction and $\phi$ for $\phi - c$ soils. The modified $\phi$ and $c$ values are obtained as follows:

1. Calculating depth $H$ = 0.5 B tan (45 + $\phi/2$) using $\phi$ for the top layer.
2. If $H > d1,$ computing modified $\phi$ as:

$$\phi' = \frac{d1\phi1 + \left(H - d1\right)\phi2}{H}. \tag{2}$$

3. Similarly determining $c'$.
4. Using the bearing-capacity equation for $q_{ult}$ with $\phi'$ and $c'$.

These steps will give us $q'_{ult}$ as:

$$q'_{ult} = q''_{ult} + \frac{ppvks \tan\phi}{A_f} + \frac{Pd1c}{A_f} \leq q_{ult}, \tag{3}$$

where $q''_{ult}$ is the ultimate bearing capacity of the lower layer; $p$ = 2(B + L) is the total perimeter for punching; $p_v$ is the total vertical pressure computed as $p_v = \bar{q}d_1 + \int_0^{d_1} \gamma h dh;$ $k_s$ is the lateral earth pressure coefficient; $p_{d1c}$ is the perimeter cohesion force; $A_f$ is the footing area.

Table 7 demonstrates that when using method described in [21] at H/B = 1, the bearing capacity in the soil with lower dry unit weight is approximately equal to the bearing capacity in the soil with higher dry unit weight. This indicates comparable effectiveness of treatment thickness in both loose and dense states. Table 8 presents the treated layer properties.

***Table 7. Geometrical properties of lime-sand layers, soils parameters, experimental bearing capacity, and method described in [21].***

| H/B | $\gamma_{d1}$, kN/m$^3$ | $\gamma_{d2}$, kN/m$^3$ | $\phi_1$, ° | $\phi_2$, ° | $\phi'$, ° | $c_1$, kPa | $c'$, kPa | Plate load test ($q_u$), kPa | [21], kPa |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 16.6 | 15.8 | 53 | 35.4 | 36.6 | 550 | 37.7 | 268 | 51.6 |
| 0.3 | | | | | 39 | | 44.2 | 320 | 90.6 |
| 0.6 | | | | | 43.7 | | 228.4 | 396.2 | 597.5 |
| 1 | | | | | 47.4 | | 376.5 | 473 | 1561.4 |
| 0.1 | 16.6 | 14.4 | 53 | 31 | 32.5 | 550 | 37.6 | 76 | 29.7 |
| 0.3 | | | | | 35.5 | | 114.2 | 83 | 154.9 |
| 0.6 | | | | | 40.1 | | 228 | 118 | 574.7 |
| 1 | | | | | 46 | | 376.5 | 140 | 1541.4 |

***Table 8. Properties of treated layers.***

| Type of additives | Dimensions, cm | H/B | $c$, kPa | $\phi$, ° | WC, % |
|---|---|---|---|---|---|
| Lime | 12×12 | 0.1, 0.3, 0.6, 1 | 550 | 53 | 10 |

# *4. Conclusions*

This study investigated the bearing capacity of shallow square footing resting on lime-sand soil, yielding the following conclusions:

1. The H/B ratio and dry unit weight are seen as identical parameters regarding the bearing capacity of sand soil. They demonstrate comparable influence on sandy soil's bearing capacity, with both parameters showing positive correlation – as they increase, bearing capacity improves while settlement decreases. Specifically, the bearing capacity ratio increased from 1 to 1.9 for dense sand and from 1 to 2 for loose sand.
2. The artificial layer with H/B = 0.1 showed a very slight improvement, whereas H/B = 0.6 produced significant bearing capacity enhancement in both different dry unit weights of the sand used.
3. Axial stress analysis revealed that increased lime content (5–15 % for higher dry unit weight; 7–15 % for lower dry unit weight) leads to greater brittleness in treated soil.
4. The small-scale load tests identified two modes of failure:
   - untreated cases where the layer punched through to the sand without fissuring at H/B = 1 and lowest density,
   - treated cases exhibiting fractures – with cracks appearing near the footing's edge and central axis at low H/B ratios (0.1, 0.3) or solely near the edge at higher ratios (0.6, 1).
5. Based on method described in [21], it was confirmed that, at larger thickness of treated layer, loose and dense sands achieve nearly equal bearing capacities.

For future research, replicating this experimental approach with cement stabilization would be valuable as cement typically demonstrates superior sandy soil stabilization compared to lime, enabling direct performance comparison with these findings.

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