Effect of Slenderness Ratio on Group Efficiency in Gypseous Soil

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Abstract. The paper investigates the impact of the slenderness ratio (L/D) on the group efficiency of a four-pile configuration in gypseous soil, emphasizing L/D ratios of 10, 20, and 30. Employing steel pipes with a diameter of 15mm and a wall thickness of 1.2 mm, the piles underwent surface roughening using sandpaper to simulate realistic field conditions and enhance friction with the surrounding soil. The group, arranged in a square pattern, was subjected to vertical loading. The test apparatus featured a cap for uniform load distribution. Dry and soaked conditions were considered for load-settlement behavior analysis at a constant pile spacing of 4D. In the dry state, the group pile load demonstrated a proportional increase with increased L/D ratios, due to increased embedded depth, surface area, loading level, lateral earth pressure, and bearing capacity factor. A nearly linear relationship between ultimate load and L/D ratio was observed.

Keywords: Piles, foundation, gypseous soil, group, efficiency.

1. INTRODUCTION

The field of civil engineering has long been interested in the behavior of pile groups in various types of soil, particularly in challenging conditions such as gypseous soil. Gypseous soil, prevalent in arid and semi-arid regions, is considered a collapsible soil that exhibits high resistance to settlement and high bearing capacity when dry, but loses these characteristics when inundated [1,2]. The efficiency of pile groups, defined as the ratio of the load capacity of the pile group to the total load capacity of each individual pile, is a critical factor in the design and performance of foundations. Previous studies have shown that the efficiency of pile groups can be influenced by various factors, including pile spacing, pile length, and the geology of the soil layer. In particular, the pattern of pile groups has been identified as a significant factor affecting group efficiency [1,3,4].

Several studies have explored the behavior of piles in various soil conditions, highlighting the significance of factors like slenderness ratio. Senna et al. [5], Gebreselassie [6], Karlsson and Moritz [7], Alielahi et al. [8], and Gunnvard [9] have contributed valuable results into pile behavior and the influence of geometric parameters on load-settlement characteristics. Moreover, pioneering works by Terzaghi [10], Vesic [11], and Tomlinson [12] laid the foundation for understanding soil-structure interaction and pile design principles. This paper focuses on experimental findings, incorporating three L/D ratios (10, 20, and 30), to comprehensively examine the effect of slenderness ratio on group efficiency. The experiments involve steel piles with specified dimensions and surface roughness, simulating realistic conditions to enhance friction and soil-pile interaction. By investigating both dry and soaked states, the study aims to contribute novel insights that can inform optimized design practices for pile foundations in gypseous soil.

2. MATERIALS AND METHODS

2.1 Soil

Gypseous soil used in the current study with gypsum content (G.C61%) taken from Tikrit city center of Salah Al-Deen Governorate north of Baghdad city (Iraq). These soils are used to study the effect of pile spacing on group efficiency subjected to axial loading. The properties of engineering, chemical and physical of gypseous soil are carried out as shown in Tables 1 and 2. Moreover, Figures 1 and 2 revealed the results of the laboratory tests conducted on the soil used in current study. In addition, the test of relative density is not applicable for these soils (ASTM D4254-00). Furthermore, the initial water content test is obtained under the temperature at (40-50) °C to avoid losing crystal of gypseous soil. The sample of gypseous soil (G.C61%) are classified as Moderately severe respectively (ASTM D5533-2003) as shown in Figure 2.

Table 1. Results of chemical properties of gypseous soil used for testing based on (BS 1377: 1990, Part 3).

Composition	Magnitude %
Total soluble salts (T.S.S.) %	66.2
Sulphate content (SO3) %	31.4
Gypsum content %	61
Organic matters (O.M) %	0.22
Chloride content (CL) %	0.063
pH value	8.5

Table 2. Physical properties of gypseous soil used for testing.

Property		Value	Specification
Grain size analysis	D10 (mm)	0.07	ASTM D422-02
	D30 (mm)	0.14	
	D60 (mm)	0.35	
	Classification of soil based on (USCS)	SM	
Specific gravity, Gs		2.428	ASTM D 854 (2006)
Direct Shear Test	Angle of Internal Friction (Ø) in dry	38	ASTM D 3080-98
	Angle of Internal Friction (Ø) in soaked	32	
	Inetial void ratio, e_{test}	0.72	
Initial water content %		0.5	ASTM D2216-02
Compaction characteristics	Max. Dry unit weight (kN/m^3)	16.63	ASTM 698-00
	Optimum Moisture content (%)	11.20	
Test unit weight (kN/m^3), $\gamma_{d\ test}$		14.13	
Field density ((kN/m^3), γ_{field}		14.06	ASTM D1556-07
Collapse Potential		7.9	ASTM D5533-2003

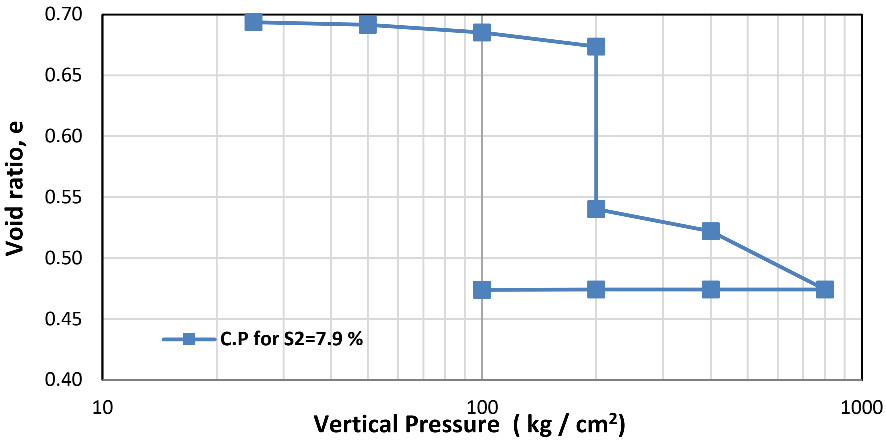

Figure 1. Results of single oedometer collapse test of soil used.

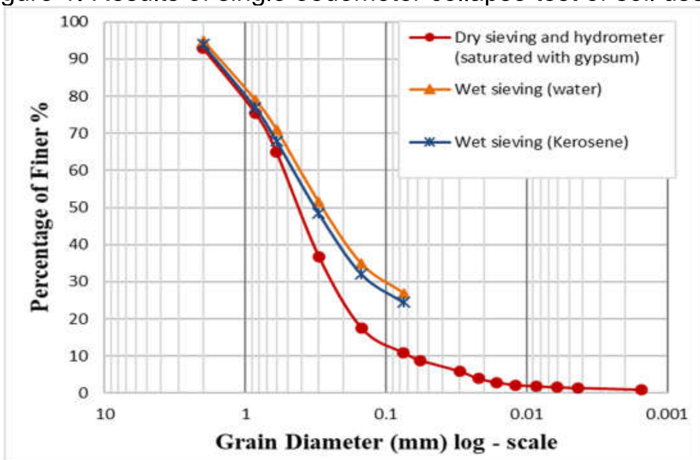

Figure 2. Grain Size Distribution for gypseous soil of (G.C61%).

2.2 Model Pile

The pile's model used in the current study is made of steel circular pipe having outer diameter of 15 mm and inner diameter of 12.2 mm. The slenderness ratio (L/D) length to diameter of piles is 10, 20, and 30 the pile tip is cone-shaped of 1.5 cm in length and cone angle of 60°. The properties of used piles are illustrated in Table 3 and results of interface friction angle between soil and pile are shown in Table 4.

Table 3. Properties of steel piles used.

Properties	Value	Specification
Length of pile cm	20, 35, 50	
Embedded length of pile (L)	15,30,45	
Diameter of pile (D) cm	1.5	
L/D ratio (embedment)	10, 20, 30	
Wall thickness of pile (mm)	1.4	
Poisson ratio	0.3	ASTM A36
Compressive yield strength (MPa)	135	
Tensile strength (MPa)	207	

Table 4. Results of interface shear test between gypseous soil and steel pile according to ASTM D5321/D5321M–17.

Sample	S1 (G.C 30%)		S2 (G.C61%)	
Status	Dry	Soaked	Dry	Soaked
δ, deg.	23	21	26	22
δ/ϕ	0.703	0.70	0.72	0.69

3. EXPERIMENTAL PROGRAM

The tests are carried out in the laboratory of civil engineering in the faculty of Engineering in Diyala University using a self-design laboratory model as shown in Figure 3 which is fabricated with a steel plate 4mm in thickness. The steel tank is square with diameter equal to 500mm and height 650mm. The inner face of the steel tank is painted to reduce the friction. The effective zone of influence that affected by the installation and loading of pile specified by a many of researchers about 3-8 times piles diameter. Consequently, the dimensions for the steel tank fabricated to provide a clear distance between the perimeter and tip of piles to tanks internal satisfies the requirements. For axial loading test, the apparatus is designed in such a manner that the applying compression in the pile head by mean of 4 tons hydraulic jack as shown in Figure 3. The sliding piston is move in x-direction and the mechanical jack is moving the steel tank in z-direction to desired distance of pile spacing as revealed in Figure 3.

3.1 Ancillary Equipment

Numbers of ancillary equipment were attached with the apparatus, as described below: (i) Compression Load Cells: To measure the axial load applied on the model pile during test in progress, a load cell with 3 tons capacity. Calibration for load cells are performed using mode "load cells' max load "and "Rated output value (mV)". (ii) Two Digital Dial Gauges: To measure the pile head deflection in the axial direction with sensitivity 0.001mm. (iii) Digital Indicators: Digital indicators are used to display and record the load cell reading as shown in Figure 3.

Figure 3. Manufactured testing equipment: a) Sliding piston and manual jack, b) Setup of test.

3.2 Group Configuration of Piles and Piles Cap

A steel pipe piles with constant diameters and different length, with configuration of four piles (2x2) as square pattern. In addition, of single pile. These configurations are arranged to achieve the testing program of the laboratory study. The piles are bolted to rigid steel plate pile cap. The cap of single and pile group is made from steel plate having a thickness of (10 mm), the piles cap is rigid to keep the load transferred equally to each pile. In addition, the cap is free of 5 cm above the soil and kept of 2D minimum edge distance from face of piles as shown in Figure 4.

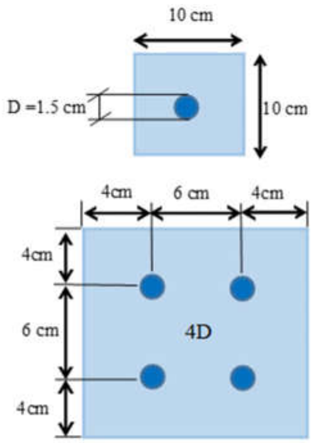

Figure 4. Model piles cap and configuration of group piles.

3.3 Testing Procedure

The study initiated with the careful layering of gypseous soil in a model box, with specific dimensions and layering to replicate realistic conditions. Soil weight calculations were based on dry unit weights for soil (S2). A thorough compaction process followed, ensuring uniform density in each layer. In the soaking state, a filter material facilitated water movement, mirroring field conditions. Next, model group piles were installed. The steel tank, placed in a steel frame, underwent manual jack installation. Piles were inserted using a compression load cell, and a cap was bolted onto them. Load application was monitored by a digital weighing indicator during pile embedment. Loading cases involved applying vertical loads through a 3-ton load cell, following specified standards. The test continued until a 20 mm displacement was achieved. Digital gauges measured central settlement, and stress readings were obtained from the load indicator in the dry state. For soaked conditions, saturation was confirmed with a piezometer tube, followed by axial pile load tests after 24 hours of soaking.

4. RESULTS AND DISCUSSION

4.1 Dry State Behavior

In the dry state, the load of the group pile exhibited a consistent increase with an elevated slenderness ratio (L/D). This behavior was attributed to the amplified embedded depth, surface area, loading level, lateral earth pressure, and bearing capacity factor resulting from the transmission of stresses from the piles to the surrounding soil. The incremental pattern of ultimate load with L/D ratio was approximately linear. The square pattern persisted from L/D ratio 20 to 30, indicating a 55% to 68% increase as compare to L/D ratio 10 as shown in Figure 5.

4.2 Ultimate Load Variation in Dry State

Figure 6 detailed the ultimate load variations with different L/D ratios in dry conditions. The ultimate load increments were 74%, and 68% for the L/D ratios 20 and 30 as compared to L/D ratio10. As the L/D ratio increases, the pile embeds deeper into the soil, thereby mobilizing a larger surface area along the shaft. This increased contact enhances the contribution of skin friction to the load-carrying capacity. Additionally, a greater pile embedment leads to higher confinement of the surrounding soil, which promotes densification and elevates the effective lateral earth pressure acting on the pile shaft. Both effects result in an increase in the mobilized shear resistance and, consequently, a higher apparent friction angle of the soil–pile system. In addition, the difference in ultimate load capacity between a single pile and a pile group was observed to increase progressively with the L/D ratio. Specifically, the group capacity exceeded the single pile capacity by factors of 2.37, 3.20, and 3.40 for L/D ratios of 10, 20, and 30, respectively as shown in Figure 6.

This trend indicates that the collective interaction effects that develop in pile groups. At lower embedment (L/D = 10), the group effect is relatively modest, since the shallower piles mobilize less shaft friction and the surrounding soil experiences limited confinement. However, as the L/D ratio increases, each pile mobilizes more shaft resistance and tip resistance, while the soil within and around the group block becomes more confined. This confinement amplifies the shear strength of the soil mass and enhances the load transfer efficiency of the group as a whole. The higher factors observed at L/D ratios of 20 and 30 demonstrate that the beneficial group interaction becomes more pronounced with deeper embedment. Nevertheless, the incremental increase between L/D = 20 and L/D = 30 (from 3.20 to 3.40) suggests a tendency toward stabilization, implying that beyond a certain depth, the efficiency of additional embedment on group performance approaches a limiting value.

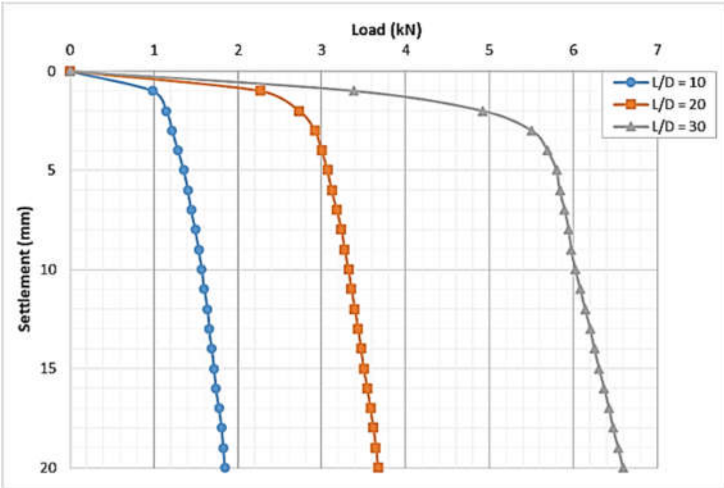

Figure 5. Load versus settlement for different L/D ratio at dry state of 4D spacing.

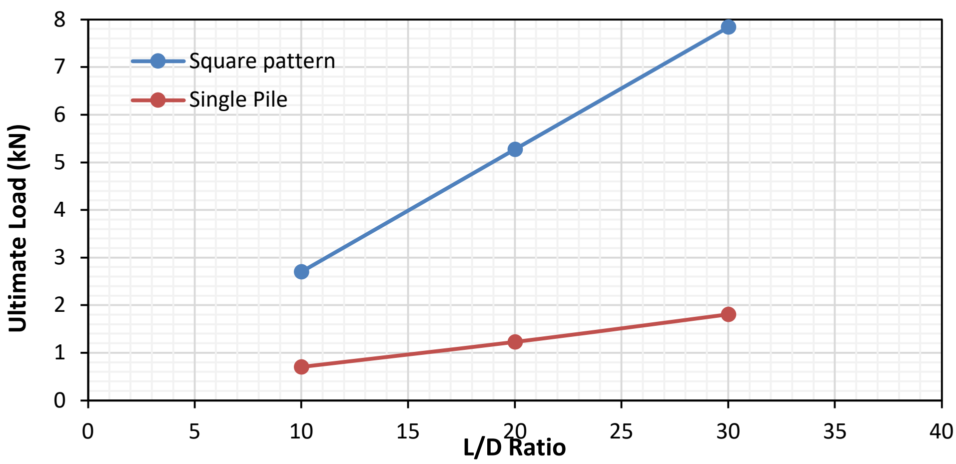

Figure 6. Ultimate load versus L/D ratio for different pattern at dry state.

4.3 Soaked State Behavior

Figure 7 detailed the ultimate load variations with different L/D ratios in Soaked conditions. The ultimate load increments were 87%, and 180% for the L/D ratios 20 and 30 as compared to L/D ratio10. As the L/D ratio increases, the pile embeds deeper into the soil, thereby mobilizing a larger surface area along the shaft. This increased contact enhances the contribution of skin friction to the load-carrying capacity. Additionally, a greater pile embedment leads to higher confinement of the surrounding soil, which promotes densification and elevates the effective lateral earth pressure acting on the pile shaft. Both effects result in an increase in the mobilized shear resistance and, consequently, a higher apparent friction angle of the soil–pile system.

4.4 Ultimate Load Variation in Soaked State

Figure 8 provided a detailed account of ultimate load variations with different L/D ratios in soaked conditions. In addition, the difference in ultimate load capacity between a single pile and a pile group was observed to increase progressively with the L/D ratio. Specifically, the group capacity exceeded the single pile capacity by factors of 1.88, 4.83, and 3.40 for L/D ratios of 10, 20, and 30, respectively. Figure 9 presents the influence of the L/D ratio on group efficiency. The results indicate that group efficiency increases almost linearly with increasing L/D ratio. In the dry condition, the efficiency improved by approximately 12% and 13% at L/D ratios of 20 and 30, respectively, compared to the reference case of L/D = 10. Under soaked conditions, the corresponding improvements were 8% and 10%. The behavior indicate that the deeper embedment associated with higher L/D ratios, which enhances shaft resistance and mobilizes greater confinement of the soil within and around the pile group. In dry soils, the higher effective stress and the contribution of matric suction lead to stronger soil–pile interaction, thereby yielding a greater increase in efficiency compared to soaked soils. Conversely, in the soaked state, the reduction of effective stress and loss of suction diminish the soil's shear strength, which moderates the improvement in group efficiency even though the overall trend with L/D ratio remains positive.

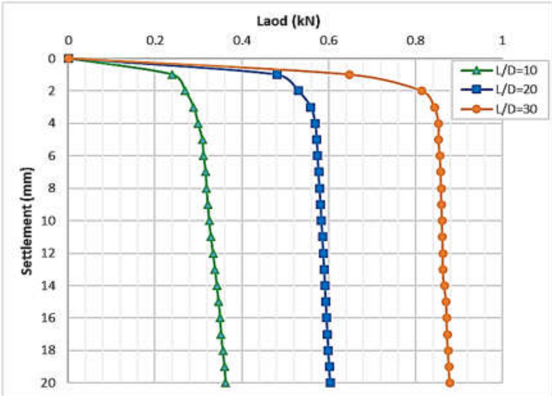

Figure 7. Load versus settlement for different L/D ratio at soaked state of 4D spacing in S1, square.

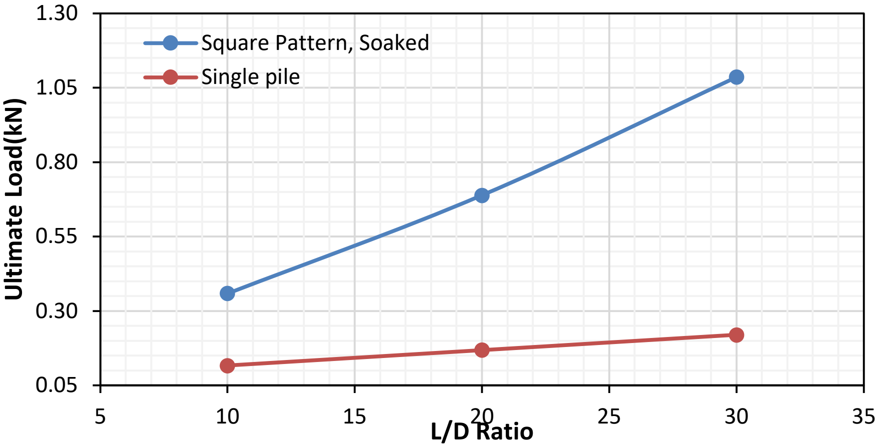

Figure 8. Ultimate Load Versus L/D Ratio for Different Pattern at Soaked State for 4D spacing, a) S1, b) S2.

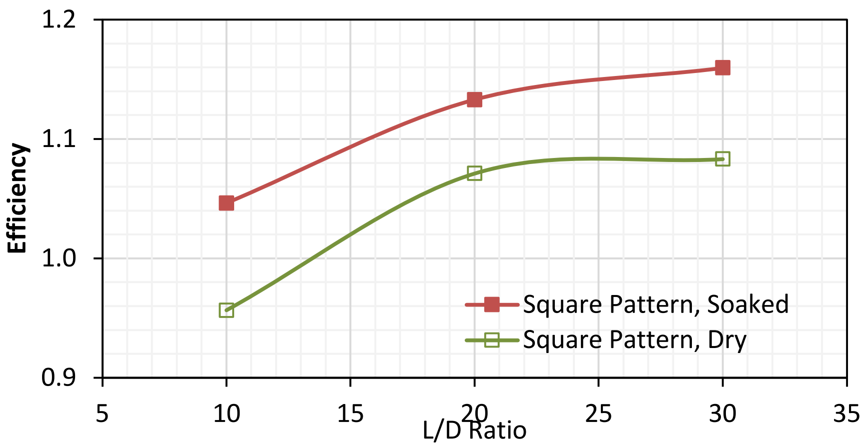

Figure 9. Effect of L/D ration on Group efficiency in dry and soaked state.

5. CONCLUSIONS

- The ultimate load capacity of pile groups increased almost linearly with higher L/D ratios.
- At L/D = 20 and 30, the ultimate load improved by 55–74% compared with L/D = 10.
- Greater embedment enhanced soil confinement and densification, which in turn increased the mobilized shear resistance and apparent friction angle of the soil–pile system.
- Group capacity was significantly higher than that of a single pile, with factors of 2.37, 3.20, and 3.40 for L/D = 10, 20, and 30, respectively.

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