Experimental Testing and Mathematical Modeling of Grout Treated Kirkuk Soft Clay Soil

Aram Mohammed Raheem
Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq.
aram_raheem@uokirkuk.edu.iq

Abstract. In this study, the untreated and treated grout soft clay soil behaviors have been investigated using both consolidation and unconfined compression stress laboratory tests. Soft soil samples have been obtained from the central zone of Kirkuk city, where this soil has been treated with different schemes of cement grout and cured for two weeks. The used grout has water to the cement of 5 where this ratio has been determined after several laboratory trials. Two nonlinear mathematical models, including second-order polynomial and p-q models, have been utilized to predict the void ratio-vertical effective stress and unconfined compression stress relationships. As the soft soil was treated with five grouts, the void ratio has decreased by 30.6%, and the unconfined compressive strength has increased by 97%. In addition, both used models have good agreements with the experimental data where the maximum recorded R^2 for nonlinear polynomial and p-q models were 0.9991 and 0.973, respectively.

Keywords: Experimental testing; mathematical modeling; grout; consolidation; unconfined compressive strength; nonlinear models; p-q model

1. Introduction
Cement grouting is a technique that is used extensively to enhance soil properties represented by permeability, strength, and deformability. In geotechnical engineering, the permeation grouting technique is very popular for improving the soil in soil beds and reinforcing the underlying foundations of structures. Several reports have been performed in recent years on the stabilization of sands that use cement-based grout to strengthen the properties of the soil. The strength properties of microfine cement-grouted sand samples were analyzed by Mollamahmutoglu and Yilmaz [1]. The findings revealed that the unconfined compressive capacity (UCS) of the grouted samples enhanced as the curing time is increased. The intensification degree of the UCS was shown to be extraordinary up to the 28 curing day, whereas the UCS was decreased suddenly after that. In addition, it was noticed that the UCS is independent of the average size of the sand particles (D_{50}).

Experimental research was carried out [2] to produce a comparatively fine-grained substance produced by the pulverization of ordinary cement. It was observed that after a 28-day curing time, the UCS of the grouted sand samples improved by decreasing the water-to-cement ratio (W/C) of the grout. Markou and Droudakis [3] tested the grouting efficiency on sand samples of varying grain sizes grouted with a suspension comprising W/Cs of 1, 2, and 3 by conducting unconfined compressive checks. The findings revealed that the W/C constituents and the sand's productive grain size are very significant parameters. Cemented soils show higher cement content and lower initial mean successful stresses with more brittle stress-strain behavior [4]. Because of the porous behavior of cemented soils, which may cause their foundations to collapse abruptly, it might not be permissible to use them in certain situations. In particular, the risk of brittle actions due to low confining stress is strong where cemented soils are
used at shallow depths. Due to the water content above its liquid limits, the shear strength of the soft soil deposits is very low, contributing to an inability to sustain upper buildings and/or structures [5-7].

Grouting technologies have been widely embraced to enhance the mechanical properties of the soft soil deposits [8-9] to solve this core engineering challenge. Nevertheless, the efficacy of grouting can be greatly influenced by the design of the grouting system in specific geological environments. In the circumstance that the grouting scheme is built primarily to strengthen the properties of the composite material, resulting in a lack of appropriate interaction forces generated by the successive soils, the jacking of the tilted building will not be successfully applied. Also, the grout infiltration will swell the cohesive soil and produce the positive excess pressure of pore water. Grout products may be injected across the upper portion of tunnel linings during the soft earth shield tunneling phase to improve the soil’s resilience and minimize the extent of surface settlements. In recent years, in several large tunneling ventures, restitution grouting and grout jacking have been effectively implemented to restrict land settlements under substantial frameworks. Grout is injected at positions between the tunnel and the building foundations in this process to compensate for tension relief and lack of land caused by tunnel excavation [10-11].

The method of injecting a massive body of soft soil involves maintaining a low injecting pressure to ensure deep access to voids without destructing the soil structure. Moreover, for a full-scale or real field use, the cement grout can be prepared with high water to cement ratio, making the cost low. The cement grout injection can be remotely utilized for structures with existing engineering facilities. Thus, the main objective of this study is to check the effectiveness of small amounts of cement grouts in Kirkuk city in the northern region of Iraq. This study has also focused on investigating the effect of different schemes of cement grouts on the variation of the void ratio and unconfined compression stress behaviors. Furthermore, the study has used both nonlinear polynomial and p-q models to predict the variation of void ratio, and unconfined compression stress of untreated and grout treated soft soil, respectively.

2. Materials and methods

2.1 Materials

Specimens of soft clay were locally collected from a two-meter depth at the central zone of Kirkuk city in the northern region of Iraq. In this experimental analysis, the basic soil properties have been summarized in Table 1. The grain-size arrangement of the collected soil is shown in Figure 1. The soil is above the A-line in the plasticity graph. Thus it is categorized according to the Unified Soil Classification scheme as low plasticity clay soil [12].

| Property                      | Value |
|-------------------------------|-------|
| Specific gravity, Gs          | 2.76  |
| Grain size (%)                |       |
| Gravel (2-75 mm)              | 0     |
| Sand (0.075-2 mm)             | 5     |
| Silt (0.002-0.075 mm)         | 56    |
| Clay < (0.002) mm             | 39    |
| Atterberg limit (%)           |       |
| Liquid limit                  | 33    |
| Plastic limit                 | 20    |
| Plasticity index              | 13    |
| Activity                      | 0.333 |
| Compaction parameters         |       |
| Optimum moisture content (%)  | 12.5  |
| Maximum dry density (kN/m³)   | 19.5  |
| Soil classification           | USCS  |
To produce a low-density grout cement-water mixture, locally usable cement was combined with sufficient water. After multiple experiments, the most effective grout mixture was the one with a water-cement ratio of 5.

2.2 Sample Preparation
The soft soil samples have been prepared depending on the natural water content, which was determined to be 14.7%. The samples have been arranged in two cylindrical sizes, including 20×70 mm and 70×70 mm for both consolidation [13] and unconfined compression [14] tests, respectively. After completing sample preparation, small holes have been made on the sample to inject the grout cement-water mixture where each small hole can take between one to two grams of the mixture. The prepared cement grout has been injected under low applied pressure using a medical syringe. All the treated soft soil samples have been cured for two weeks before performing both consolidation and unconfined compression tests.

3. Laboratory experimental tests
The experimental laboratory program has included executing consolidation, and unconfined compression tests for untreated and cement grouted soft soil samples. The treated soft soil samples have been treated using different schemes that vary between one to five grouted cement holes. All the treated samples have tested after two weeks of curing.

4. Results and analysis
Conventional consolidation measurements were used to explore the variation of the void ratio with effective vertical stress for untreated, and grout treated soft clay, as shown in Figure 2. One entire period of loading and unloading was used in the assessment phase. During the loading stage and as the effective vertical stress increased from 625 to 10000 kPa, the void ratio has decreased by 13.2% and 30.6% for untreated and five grout-treated soft soil, respectively. It is indicated that the grout has accelerated the consolidation process under the effect of the same applied load. However, the grouts have almost no effect on the void ratio change during the unloading stage than untreated soft soil.
Figure 2. The consolidation behavior of untreated and grouted soft soil (a) untreated soft soil, (b) treated with 1 grout, (c) treated with 3 grouts, and (d) treated with 5 grouts.

The consolidation apparatus collection with both untreated and grout-treated soft soil samples has been shown in Figure 3. The variation of stress-strain behavior for untreated and grout-treated soft clay using an unconfined compression test has been shown in Figure 4. It is clearly shown that the untreated and grout-treated soft soils have different unconfined compressive strengths with different corresponding strains. As the soft soil treated with different grouts, the unconfined compressive strength has increased by 210, 200, and 97% for one, three, and five grouts, respectively. The strains correspond to the unconfined compressive strength by 64, 36, and 197% as the soft soil was treated by one, three, and five grouts. Both one and three grout treatments have sharp peak points due to alteration in the material behavior to the brittle condition prior to peak state with lower observed corresponding strain.

Figure 3. The consolidation device collection with grouted soft soil sample.
Figure 4. The unconfined compression behavior of untreated and grouted soft soil (a) untreated soft soil, (b) treated with 1 grout, (c) treated with 3 grouts, and (d) treated with 5 grouts.

The prepared untreated and grout treated soft samples before and after performing unconfined compression tests have been shown in Figure 5.

Figure 5. The untreated and treated grout soft clay soil samples before and after the unconfined compression test.

5. Mathematical modeling

5.1 Consolidation Behavior

The nonlinear polynomial has been used to model the loading and unloading stages for untreated and treated soft soil with different grouts. The proposed model can be represented as follows:

\[ e = A \times \log(\sigma_v)^2 + B \times \log(\sigma_v) + C \]  

(1)

Where A, B, and C are model parameters.

The proposed second-order nonlinear model has been obtained using the trail minimizing error procedure. The modeling for the variation of the void ratio with the effective vertical stress for untreated and grout treated soft soil has been shown in Figure 6. All the polynomial nonlinear model coefficients have been summarized in Table 2. It is noticeably shown that the proposed mathematical model has a good agreement with the experimental data where the R^2 range was from 0.8311 to 0.9991.
Figure 6. Modeling the consolidation behavior of untreated and grouted soft soil (a) untreated soft soil, (b) treated with 1 grout, (c) treated with 3 grouts, and (d) treated with 5 grouts.

Table 2. Polynomial parameters for the consolidation model.

| Soil                  | A      | B      | C      | R²     |
|-----------------------|--------|--------|--------|--------|
| Untreated soft soil   | Loading| 4.00E-10| -9.00E-06| 0.3371| 0.9948|
|                       | Unloading| 3.00E-10| -5.00E-06| 0.3065| 0.8311|
| One grout treated soil| Loading| 2.00E-09| -3.00E-05| 0.3378| 0.9983|
|                       | Unloading| 3.00E-10| -4.00E-06| 0.2447| 0.8694|
| Three grouts treated soil| Loading| 2.00E-09| -3.00E-05| 0.3157| 0.9433|
|                       | Unloading| 2.00E-10| -3.00E-06| 0.2331| 0.9991|
| Five grouts treated soil| Loading| 1.00E-09| -2.00E-05| 0.2915| 0.9983|
|                       | Unloading| 2.00E-10| -4.00E-06| 0.2272| 0.9911|

5.2 Unconfined Compression Behavior
The unconfined compression behavior of untreated and grout-treated soft soil has been modeled using the nonlinear p-q model [15]. The p-q model has the following form:

$$\sigma = \left[ \frac{\varepsilon_c}{\varepsilon} \right] \left[ q + (p-q) \frac{\varepsilon_c + (p+q)}{\varepsilon_c} \right] * \sigma_c$$  (2)

Where: $\sigma$ = compressive stress, $\sigma_c$ = compressive strength with the corresponding strain, p and q = model parameters. The modeling for the variation of the stress-strain relationship for untreated and grout-treated soft soil has been shown in Figure 7. All the nonlinear p-q model parameters have been
summarized in Table 3. The used nonlinear p-q model has predicted the experimental data very well with $R^2$ range of 0.956 to 0.973. In general, both models can be used in other places in Iraq with a reasonable degree of agreement for void ratio-effective vertical stress and unconfined stress-strain relationships.

![Graphs](image)

**Figure 7.** Modeling the unconfined compression behavior of untreated and grouted soft soil (a) untreated soft soil, (b) treated with 1 grout, (c) treated with 3 grouts, and (d) treated with 5 grouts.

| Soil                | p    | q    | $\varepsilon_C$ | $\sigma_C$ | $R^2$ |
|--------------------|------|------|-----------------|------------|-------|
| Untreated soft soil| 10   | 1    | 0.371           | 10.133     | 0.956 |
| One grout treated soil | 0.6  | 2    | 0.609           | 31.441     | 0.973 |
| Three grouts treated soil | 0.55 | 1.8  | 0.504           | 30.401     | 0.967 |
| Five grouts treated soil | 0.12 | 0.7  | 1.102           | 20.008     | 0.968 |

### 6. Conclusions

The untreated and treated grout soft clay soil samples have been studied using both consolidation and unconfined compression stress laboratory tests where the soft soil samples have been treated with different schemes of cement grout and cured for two weeks. Based on the results of this study, the following conclusions can be drawn:

- The applied cement grout systems are low-cost and can be utilized in real-world field infrastructure ventures.
- Grout treatments have caused an alteration in the material behavior to the brittle condition prior to peak state with lower observed corresponding strain, especially for one and three grout treatment.
The void ratio has decreased by 30.6% as five grouts have been used for the soft soil treated with grout.

The unconfined compressive strength of the treated soft soil has increased by 210, 200, and 97% as one, three, and five grouts are used, respectively.

The maximum reordered strains for treated soft soil have increased by 64, 36, and 197% as one, three, and five grouts are applied, respectively.

Using the nonlinear polynomial model, the variations of the void ratio for both untreated and grout treated soft soil have been predicted very well with a maximum $R^2$ of 0.9991.

The unconfined compression behavior for untreated and grout-treated soft soils has been predicted very well using p-q model with a maximum $R^2$ of 0.973.

References

[1] Mollamahmutoglu, M. and Yilmaz, Y., 2011. Engineering properties of medium-to-fine sands injected with microfine cement grout. Marine Georesources and Geotechnology, 29(2), pp. 95-109.

[2] Pantazopoulos, I.A., Markou, I.N., Christodoulou, D.N., Drouidakis, A.I., Atmatzidis, D.K., Antiohos, S.K. and Chaniotakis, E., 2012. Development of microfine cement grouts by pulverizing ordinary cements. Cement and Concrete Composites, 34(5), pp.593-603.

[3] Markou, I.N. and Drouidakis, A.I., 2013. Factors affecting engineering properties of microfine cement grouted sands. Geotechnical and Geological Engineering, 31(4), pp.1041-1058.

[4] Schraid, F., Prietto, P.D. and Consoli, N.C., 2001. Characterization of cemented sand in triaxial compression. Journal of geotechnical and geoenvironmental engineering, 127(10), pp.857-868.

[5] Tan, Y. and Li, M., 2011. Measured performance of a 26 m deep top-down excavation in downtown Shanghai. Canadian Geotechnical Journal, 48(5), pp.704-719.

[6] Raheem, A.M., 2019. On the Behavior of Lateral Pipe-Soil Interaction in Ultra-Soft Clayey Soil Using Large Scale-Laboratory Tests. International Journal of Engineering and Technology Innovation, 9(2), p.119.

[7] Raheem, A.M., 2020. Controlling the permeability of sandy soil using different local waste materials. In Key Engineering Materials (Vol. 857, pp. 302-310). Trans Tech Publications Ltd.

[8] Poh, T.Y. and Wong, I.H., 2001. A field trial of jet-grouting in marine clay. Canadian Geotechnical Journal, 38(2), pp. 338-348.

[9] Raheem, A.M. and Vipulanandan, C., 2019. Characterization and finite element analysis of lime and polymer treated ultra-fine clay soils using the electrical resistivity and miniature penetrometer methods. Acta Geodinamica et Geomaterialia, 16(1), pp.71-84.

[10] Modoni, G., Croce, P. and Mongiovì, L., 2006. Theoretical modelling of jet grouting. Géotechnique, 56(5), pp. 335-347.

[11] Raheem, A.M. and Vipulanandan, C., 2019. Testing and modeling of filter cake formation using new seepage-consolidation concept. Engineering Science and Technology, an International Journal, 22(3), pp. 979-989.

[12] ASTM D422-63, 2007. Standard test method for particle-size analysis of soils. ASTM International, West Conshohoken, PA.

[13] ASTM D18, 2004. Standard test methods for one-dimensional consolidation properties of soils using incremental loading. ASTM International.

[14] ASTM D2166, 2006. Standard test method for unconfined compressive strength of cohesive soil. ASTM standard.

[15] Raheem, A.M. and Abdulkarem, M.A., 2016. Experimental testing and analytical modeling of strip footing in reinforced sandy soil with multi-geogrid layers under different loading conditions. American Journal of Civil Engineering, 4(1), pp.1-11.