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# ENHANCEMENT OF SOFT CLAY LOADING CHARACTERISTICS USING STABILIZED SAND COLUMNS WITH CEMENT DUST AND LIME – AN EXPERIMENTAL APPROACH

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**الملخص :**
يقيم البحث المقترح تأثير استخدام مزيج من غبار الأسمنت - الجير - الرمل (CLS) ، والمحاط بطبقة رقيقة من النسيج (Geotextile) على الخصائص الهندسية للطين اللين، بشكل أساسي ؛ قوة القص وخصائص الهبوط. تم تنفيذ برنامج اختبار النموذج التجريبي على أعمدة CLS بأقطار 3.5 و 4 و 5 سم بطول 60 ٪ و 80 ٪ و 100 ٪ من سمك الطين اللين المعالج. تم تحضير الطين اللين من الكاولينيت مع قوة قص غير مقيدة تبلغ 7 كيلو باسكال. أجريت سلسلة من 9 اختبارات باستخدام أعمدة CLS ، مع الأخذ في الاعتبار حالة الطين اللين بدون أعمدة CLS كمرجع. تم تحديد خصائص الإجهادات-الهبوط للحالات المختبرة لمعرفة مدى التحسن في الخواص الميكانيكية للطين اللين. لقد وجد أن؛ بالنسبة إلى أعمدة CLS غير كاملة الإختراق ، أدى زيادة قطر وطول العمود إلى تحسين إجهادات التحميل بنسبة مئوية بلغت 285٪ وخفض الهبوط بنسبة 91٪. يمنح عمود CLS المخترق لطبقة الطين اللين بنسبة 80٪ من سمكه الكلى تحسينًا أفضل في تحمل الإجهادات وتقليل الهبوط مع زيادة القطر ، مقارنةً بالوتيرة الناتجة عن استخدام الأعمدة بكامل سمك طبقة الطين اللين المعالجة.

**ABSTRACT:**
It is not easy to select the required suitable soil engineering properties to be foundation strata. The proposed research asses the influence of using the mixture of Cement dust – Lime– Sand (CLS), confined with a thin coat of geotextiles on soft clay engineering properties, mainly; shear strength and settlement characteristics. An experimental model testing program is carried out on confined CLS columns in diameters of 3.5, 4 and 5 cm with the length of 60%, 80% and 100% of the treated soft clay thickness. The soft clay is artificially prepared from Kaolinite with undrained shear strength of 7kPa. A series of 9 tests were conducted using the CLS columns, considering the case of soft clay without CLS columns as a reference. The stress-settlement characteristics are drawn for the tested cases to figure improvement in the soft clay mechanical properties. It was found that; for floating CLS columns, increasing the column diameter and length improved the bearing stress in a percentage reached 285% and reduced the settlement by 91%. The 80% penetration CLS column gives a better enhancement in bearing stresses and reduction in settlement with the increase in diameter, than that of fully penetrated one.

**Keywords: CLS columns; cement dust – lime; bearing capacity; settlement; ground modification; floating columns; soft clay; soil treatment; experimental model.**

## INTRODUCTION
The need to modify the engineering soil properties is highly required in such areas contain soft clays, peat and organic soils. These types of problematic soils will exhibit a very large deformation or settlement as a result of an increase in stresses due to building applied loads.

In highly organic soils; the binder used is mainly slag in combination with cement. Whole blocks of soil may be stabilized down to depths of typically three to five meters. In rare cases, such as in large offshore applications in Japan, deep mixing was performed down to depths of about seventy meters (Kitazume and Terashi, 2002). However, not only the type of soil and binder but also the mixing procedure (Larsson, 2003) and the curing conditions (e.g. stress conditions, moisture content and temperature) affect the strength of stabilized soil ( Babasaki et al., 1996; Ahnberg and Johansson, 2005).
A basic understanding of the types of chemical reactions that take place and the compounds formed when using different binders is essential in analyzing the rate and type of changes in properties that may develop. This also applies to the durability of stabilized soils. The chemical reactions involved in the hydration of different types of cement or lime were described and discussed thoroughly in many papers and textbooks (Taylor, 1997; Boynton, 1980). The various chemical processes involved in soil stabilization using a variety of binders were also described in the literature, ( Chew et al., 2004; Janz and Johansson, 2001; TRB, 1987; Saitoh et al., 1985; Ingles and Metcalf, 1972; Ruff and Ho, 1966),
The reactions generated when mixing various binders with soil vary by process, intensity and duration, but in general, exhibit many similar characteristics (Ahnberg and Johansson, 2005). Figure 1 represents a rough outline of the chemical processes taking place and the main reaction products formed when mixing common binders such as quicklime, cement, slag and fly ash into a soil. As the binder is mixed into the soil, hydration takes place, although slag may need an activator from another binder to start this process. Some reactions may involve cementation starting up directly, while others may lead to further reactions with the soil and its minerals.

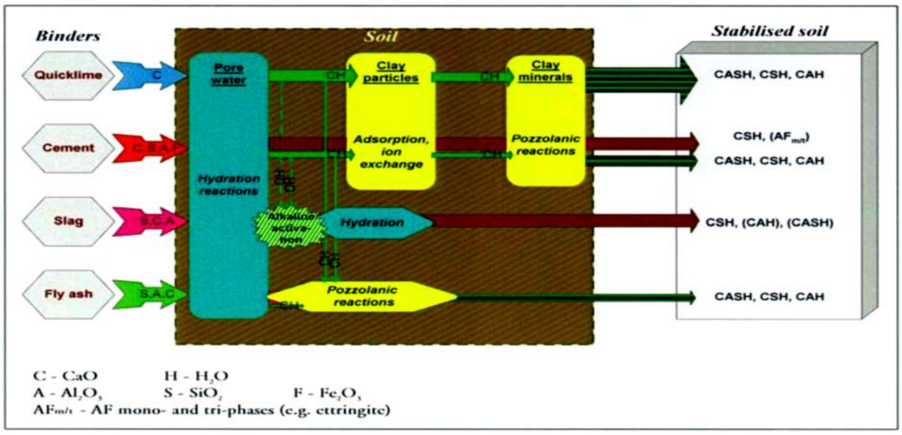


**Figure-1: Rough outline of the principal chemical reactions and reaction products formed by different types of binders in a soil. (Ahnberg and Johansson, 2005)**

Furthermore, the strength properties of stabilized soil may change considerably with time, mainly due to not only different chemical reactions taking place, but also external influences such as; the effect of an embankment or foundation loading, or changes in the surrounding soil and ground water conditions.
The research and development of current Deep Mixing Method (DMM) began in the late 1960s using lime as a stabilizing agent. DMM was put into practice in Japan and Nordic countries in the middle of the 1970s, and then spread to China and South East Asia. More than two decades of practice proved that; the equipment improved, stabilizing agents changed and the applications diversified (Kitazume and Terashi, 2002).

Deep mixing has different names such as “lime-cement column”, “deep improvement”, “dry jet mixing method” or “column improvement” (Larsson 2003). Improvement of soil using lime/cement column (LCC) is widely applicable in Sweden and Finland to improve the stability of a road and railway embankments constructed on soft soil (Kivelö and Broms 1999). This method is often more economical compared with other conventional methods such as excavation and replacement and embankment piles.

However, the deep mixing process is not simple concerning the chemical reactions between the binder and the soil. It is very complex and will contain different phases that influence the results and the properties of the improved soil (Larsson 2003). Due to the complexity of the mixing process and the variation of the soil properties, it is difficult to make a fairly uniform distribution of the binders. Hence this will result in variability in the strength as well as the settlement properties of the LCC (Bergman 2015).

The dry deep mixing method is widely used to improve a soft clay soil to increase the shear strength as well as to reduce the time for consolidation. It is a mechanical mixing process that makes parts of the soil stiffer than its original strength. It is mainly applicable to soft clay or peat soil. The experience of using lime columns; states that it is used for the improvement of soils for highway loads. The combined soil stabilization with vertical columns (CSV) soil stabilization system was developed in Germany in the last decade. The development began with the installation of short lime columns. The further development of the equipment made it possible to work with soil specific installation parameters. Today, slender CSV-columns longer than 10 m with a defined minimum diameter can be produced without difficulty.

Although several methods such as prefabricated vertical drains, geotextile reinforcing, cement and lime stabilization, were successfully implemented to treat such soils, there always remains the motivation for further improvement of the methods, especially in terms of efficiency and economics (Amer and Indra, 2007).

The purpose of the proposed research is to assess the effect of inserting cement dust-lime - sand (CLS) columns confined with a thin coat of geotextiles in the very soft clay formation, with different configurations for column length and diameter on the bearing capacity and settlement of the treated weak soil.

## MATERIALS

### Kaolinite (clay)

In the proposed experimental model testing program; the tested clay was artificially prepared from the Kaolinite, with the properties listed in Table 1. All properties were tested and measured according to the Egyptian code for soil mechanics and foundation design, part 2. Figures 2 and 3 display the output of the consolidation and hydrometer test on the artificially prepared very soft clay soil. The quartz content in Kaolinite is determined using XRD according to the standard ASTM C958-92(2014). This standard describes the procedure for the determination of the particle size distribution of alumina or quartz powders using X-ray monitoring of gravity sedimentation. This test procedure used an X-ray sedimentation apparatus, and ultrasonic probe or bath. An aqueous homogeneous dispersion of the specimen is permitted to settle in a cell. The decrease in particle concentration over a programmed settling distance is monitored by an X-ray beam passing through the sedimentation dispersion to a detector. The specimen concentration at any given sedimentation distance is inversely proportional to the X-ray flux and the equivalent diameter (spherical) is calculated from Stokes' law

**Table- 1 Kaolinite physical and engineering properties and X-ray diffraction**

| Test | Parameter | Value |
|---|---|---|
| Liquid limit (ASTM 423-66) & plastic limit test (ASTM 424-56) | Liquid limit | 27.6% |
| | Plastic limit | 15.9% |
| | **Plasticity index** | **11.7%** |
| Hydrometer test (ASTM 421-58) (ASTM 422-63) | % silt | 77 |
| | % clay | 23 |
| | Classification | CL |
| Direct shear test (ASTM 3080-72) | C(kPa) | 7.0 |
| | Φ(degree) | 0.0 |
| Compaction test(ASTM (698-70) (ASTM 1557-70) | $\gamma_{wet}$ | 2.17 |
| | $\gamma_{dry}$ | 1.93 |
| | O.M.C% | 12.43 |
| Consolidation test (ASTM 2435-70) | $G_s$ | 2.64 |
| | $C_c$ | 0.053 |
| | $C_r$ | 0.008 |
| XRD test (ASTM C 958-92) | Quartz | 38.6% |
| | Kaolinite | 61.4% |

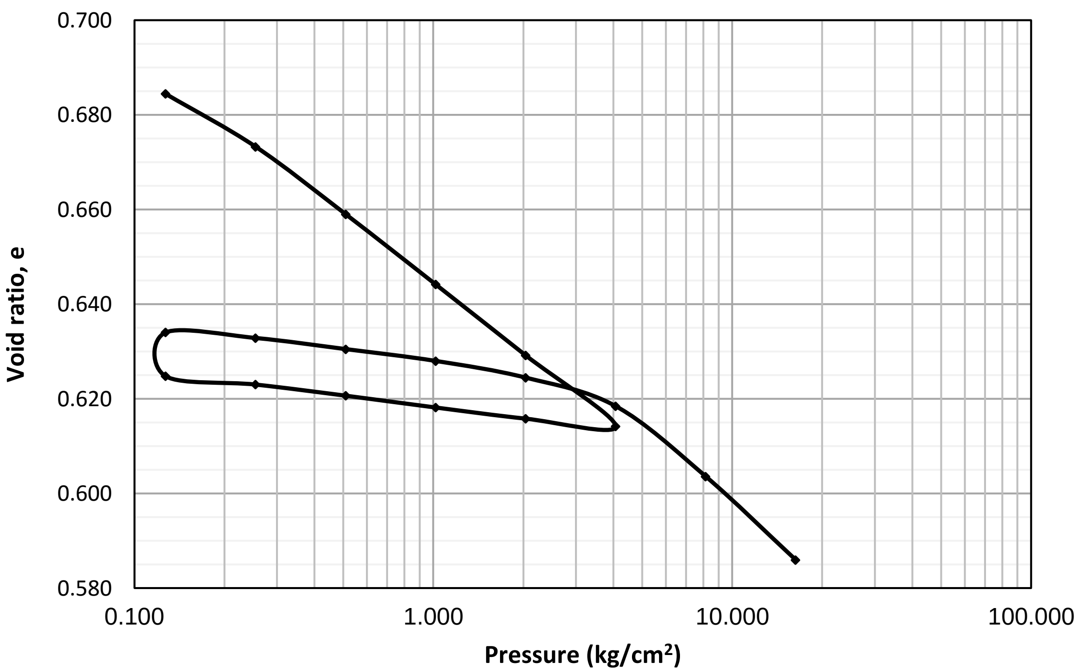


**Figure-2: Voids ratio - Log pressure relationship for the artificially prepared very soft clay.**

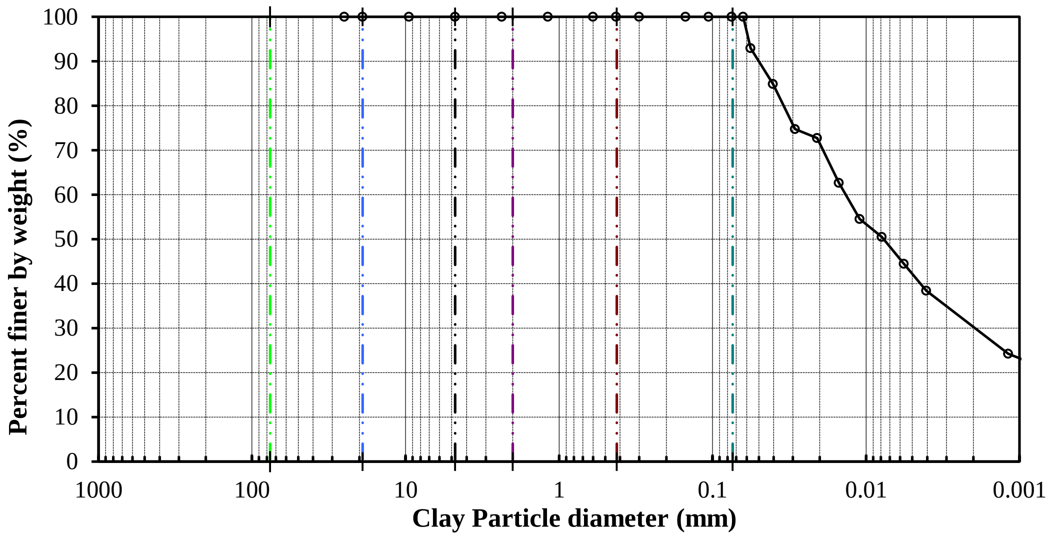


**Figure-3: Grain size analysis for the artificially prepared very soft clay.**

**Sand in CLS column mixture.**

The sand with the grading shown in Figure 4 was used in CLS column mixture as a filler material to control the fineness of the mixture. In addition to the grain size distribution analysis, the relative density and compaction tests were carried out to define the related physical properties of the used sand as presented in Table 2.

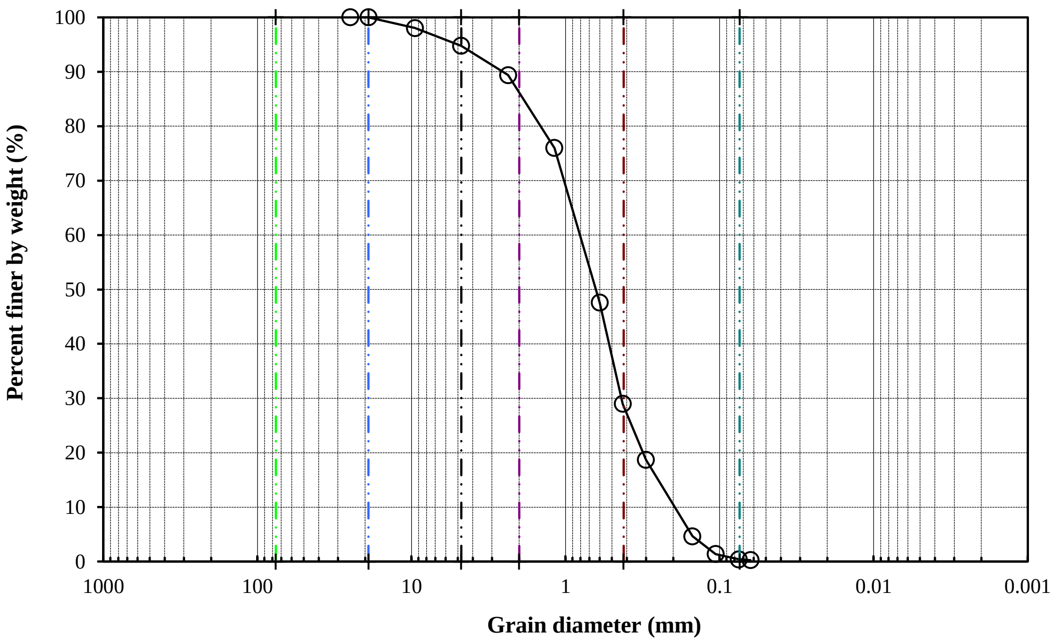


**Figure-4: Grain size analysis for the sand used in the CLS column**

**Table-2 Physical properties of the sand used in CLS column mixture**

| Test type | Property | Value |
|---|---|---|
| **Relative density** (ASTM D 2049-69) | **Maximum voids ratio** | 0.69 |
| | **Minimum voids ratio** | 0.47 |
| | **Minimum density (gm/cm$^3$)** | 1.57 |
| | **Maximum density (gm/cm$^3$)** | 1.80 |
| **Grain size Analysis** (ASTM D 421-85) (ASTM D 422-63) | **Effective Diameter ($D_{10}$)** | 0.196 mm |
| | **$D_{30}$ (mm)** | 0.433mm |
| | **$D_{60}$ (mm)** | 0.806mm |
| | **Uniformity coefficient ($C_u$)** | 4.122 |
| | **Coefficient of curvature($C_c$)** | 1.19 |
| | **Description** : fine to coarse sand , trace of gravel ,trace of silt | |
| **Compaction** (ASTM D 2435-70) | **Maximum dry density(kN/m$^3$)** | 18.02 |
| | **Optimum moisture content (%)** | 9.87 |

## Lime and cement dust

The improvements in engineering properties of unsatisfactory soil formations can be enhanced by lime which is attributed to two basic reactions; immediate reduction in plasticity and changes in the workability and swell properties and the second is a time-dependent gain in strength through inter-particle cementation through pozzolanic reaction between the lime and reactive alumina or silica in the soil.

Cement Dust has two important effects on soil behavior; it greatly reduces the moisture susceptibility of some soils, giving enhanced volume and strength stability under variable moisture conditions and it can cause the development of inter-particle bonds in granular materials, producing the stabilized material with tensile strength and high elastic modulus. Strength gain in soils using cement dust/cement stabilization occurs through the same type of pozzolanic reactions found using lime stabilization. Both lime and cement contain the calcium required for the pozzolanic reactions to occur. With lime stabilization; silica is provided when the clay particle is broken down. However, with cement stabilization; the cement already contains the silica without needing to break down the clay mineral. Thus, unlike lime stabilization, cement stabilization is fairly independent on the soil properties; the only requirement is that the soil contains some water for the hydration process to begin.

The chemical composition of both cement dust and lime used in the proposed mixture of CLS column are chemically analyzed according to the standards ASTM C 1365-06(2011) and ASTM C 25-99 respectively with the results demonstrated in Table 3.

**Table- 3 Cement dust and lime chemical analysis**

| Component | Cement Dust Composition (%) | Lime Composition (%) |
|---|---|---|
| **$SiO_2$** | 0.97 | 12.89 |
| **$Al_2O_3$** | 2.4 | 1.62 |
| **$Fe_2O_3$** | 0.8 | 0.07 |
| **$F^-$** | N.D | 0.15 |
| **CaO** | 0.35 | 55.45 |
| **$K_2O$** | 15 | - |
| **$Na_2O$** | 6 | 0.16 |
| **MgO** | 1.7 | 0.12 |
| **$Cl^-$** | 19 | 0.24 |
| **$SO_3$** | 7.1 | 3.45 |
| **L.O.I** | 12 | 25.13 |
| Natural moisture in sample | 0.03 | 0.34 |

### Column encasement (Geotextile)

This needle-punched nonwoven geotextile is constructed of 100% polypropylene staple fibers, which have a random, three dimensional pore structure and are therefore highly water permeable and high strength, dimensionally stable fabric. The fabric resists ultraviolet deterioration, rotting, biological degradation and resists naturally encountered bases and acids.

Polypropylene is stable within a pH range of 2 to 13. Designed and manufactured primarily for construction applications, these fabrics are used in a variety of civil and environmental applications to separate aggregates, filter materials and provide a reliable foundation under specific areas

The technical characteristics obtained from the fabric weight test, tensile strength test, thickness test and puncture force test as shown in Table 4 and the used testing apparatus in Figures 5 and 6. The function of the geotextile is to enhance the soft clay - CLS columns interface engineering properties and to confine the CLS column mixture till its hardening by the moisture extracted from the all-around wet soft clay formation.

**Table- 4 Technical characteristics of non-woven geotextile**

| Test | Standard | Value | Unit |
|---|---|---|---|
| **Fabric weight** | ASTM D-5261 | 438.51 | $g/m^2$ |
| **Tensile strength** | ASTM D-4595 | 5.86 | kN/m |
| **Thickness** | ASTM D-5199 | 2.44 | mm |
| **Puncture force** | ASTM D-4833 | 260.24 | N |

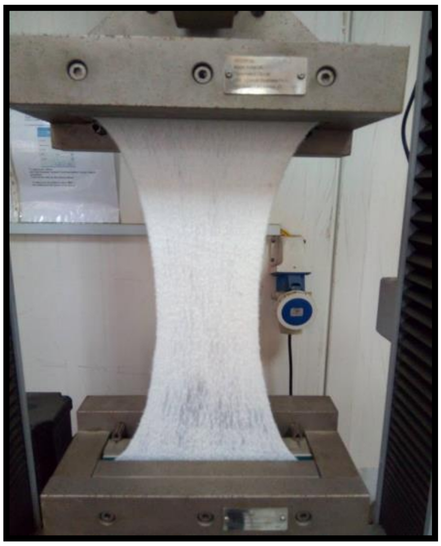

**Figure-5: Non-woven geotextile tensile strength test**

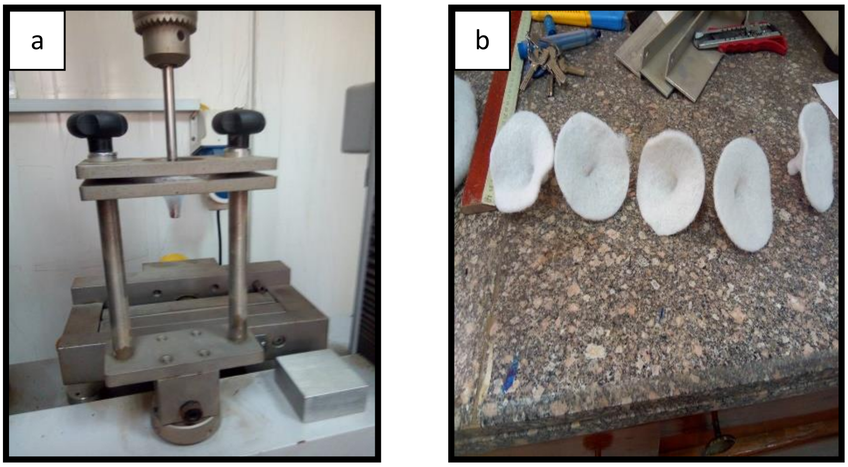


**Figure-6: Non-woven geotextile punching force test; a) Apparatus and b) The sample after test**

## EXPERIMENTAL MODEL SETUP

Series of laboratory tests were made on the artificially prepared soft clay treated with CLS columns confined with geotextile along the whole perimeter of the CLS columns, targeting the configuration and assessment of the soft clay / CLS columns system and to compare and analyze the results for both cases; the soft clay with and without CLS columns

### Model tank

The experimental model mainly consisted of a steel tank and a steel loading frame with horizontal overhead reaction beams. The tank has inner plan dimensions of 1400 mm x 1600 mm with depth of 700 mm as shown in Figure 7. The tank proportions were designed to guarantee a sufficient rigidity to maintain plane strain conditions, by minimizing the out of plane displacement.

**Figure-7: Experimental model tank**

A Drainage system was laid at the tank bottom, which consisted of pipe network imbedded in sand cushion to increase the rate of clay consolidation by facilitating easy paths for the soft clay water as shown in the Figure 8.

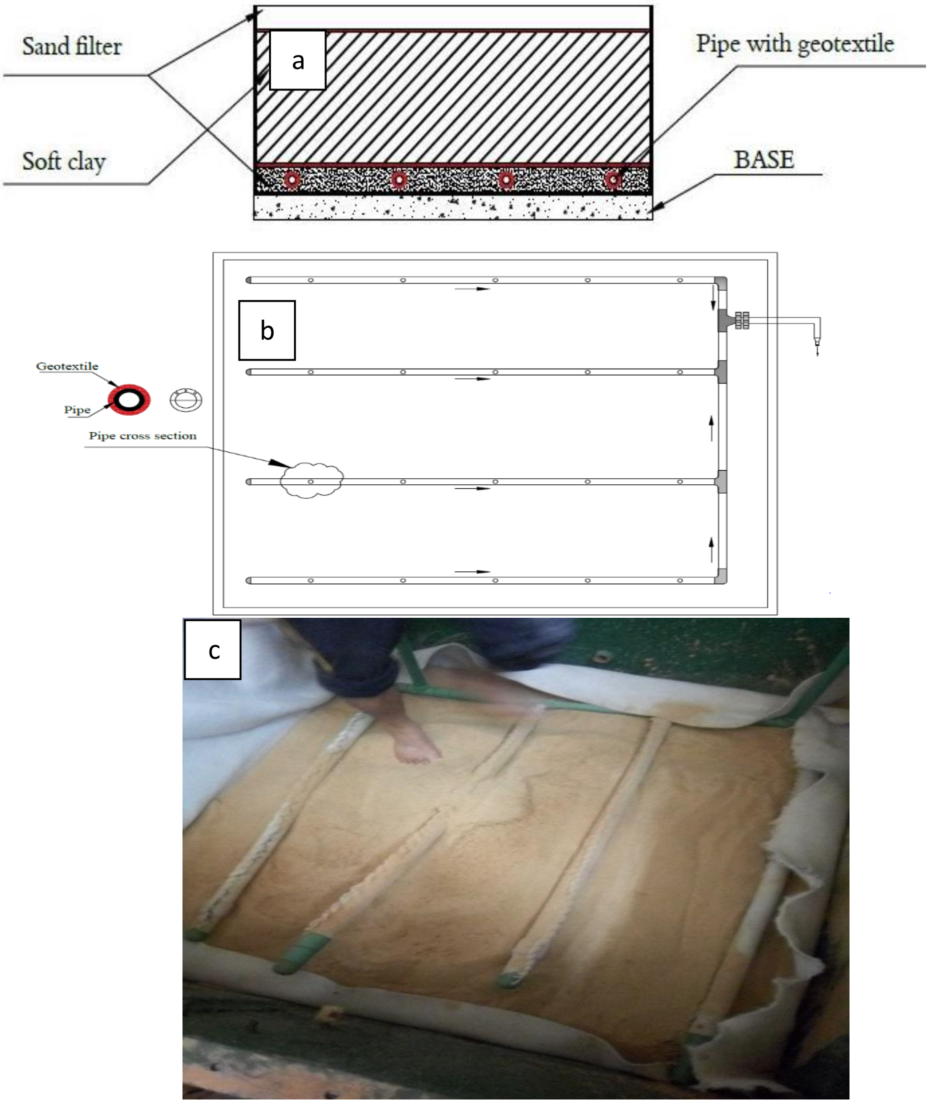


**Figure-8: Drainage pipe network at the tank bottom;a) Sectional elevation view, b) Plan view and c) Photo**

**Loading system and measuring instruments**

The loading system consisted of the traditional odometer that is used in laboratory consolidation test, fixed upon a steel frame and modified in a way to apply the load on the center of the footing model instead of the consolidation cell, as shown in Figure 9. A calibrated linear vertical displacement transducer (LVDT) connected to an electronic data acquisition unit was used for recording the entire footing displacements under the effect of the testing load.


**Figure-9: The loading system with measuring instruments for the experimental model.**

**Experimental model materials**

**Cement dust – Lime – Sand (CLS) trial mixtures**

Different percentages of cement dust, lime and sand were examined to determine the optimum percentage of each individual in the mix. The unconfined compressive strength was determined for the geotextile-encased samples after being submerged in water for 7 days as presented in Figure. 10. Table 5 demonstrates the tested percentages

**Table- 5 The sample component percentages**

| Sample no | lime % | Cement dust % |
|---|---|---|
| **1** | 4 | 20 |
| **2** | 4 | 25 |
| **3** | 4 | 30 |
| **4** | 4 | 35 |
| **5** | 10 | 30 |
| **6** | 8 | 30 |
| **7** | 6 | 30 |
| **8** | 2 | 30 |

The testing program results indicated that the optimum percentage of lime was between 3.5% and 5.5% and the optimum percentage of cement dust was from 25% to 30 % as shown in Figure 10. According to these results, the cement dust, lime and sand percentages used were 28%, 5% and 67 %, respectively.

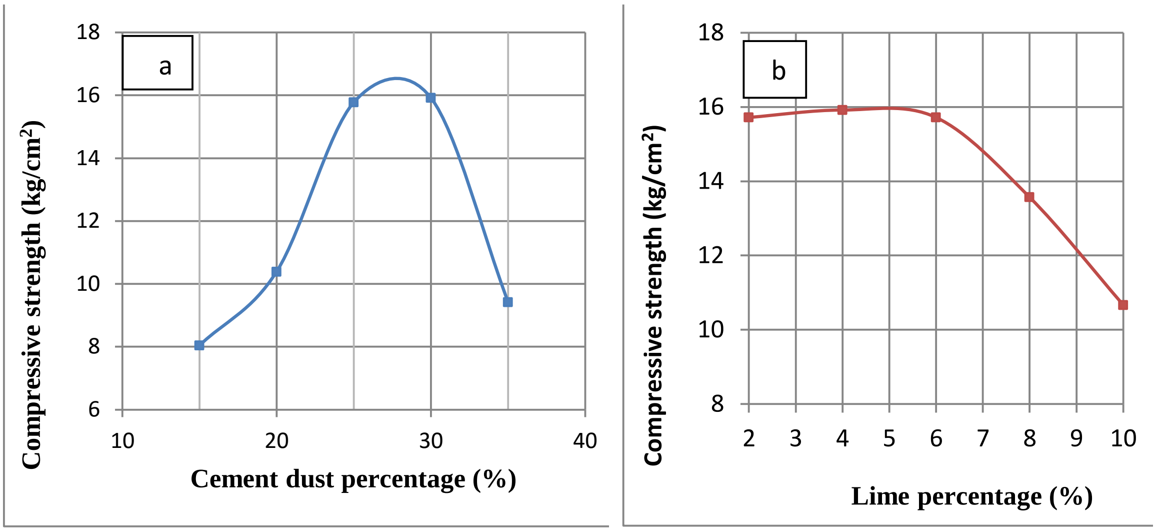


**Figure-10: Optimum percentage of CLS column constituents: a) Cement dust and b) Lime**

**Artificially prepared soft clay from Kaolinite**

The clay was prepared from kaolinite by adding water content in the percentage of 150 % from kaolinite liquid limit and well mixed for 15 min, then poured in the tank in a thickness of 50 cm as shown in Figure. 11. The placed kaolinite has nearly no strength, so the consolidation was proceeded by applying loads using the weight of the overlaid concrete slab that was insufficient to satisfy the required degree of consolidation and the aimed clay strength. The target clay strength is midway the very soft clay formation ( less than 12kpa). So the fiber balloon pressure system with dimension equal to the inner model tank is used to reach a maximum shear strength value of 7 kPa as shown in Figures 12 a and b. The final thickness of the clay after reaching the required shear strength was 35 cm.

**Figure-11: Very soft clay artificially prepared using Kaolinite.**


**Figure-12: Consolidation process using a) Concrete slab and b) Balloon**

**Column formation and installation**

The geotextile was prepared to form the outer columns perimeter with the required diameters (3.5 cm, 4.0 cm and 5.0 cm). The geotextile was wrapped around the pipe with the required diameter and sewed with an overlap of 2 cm as displayed in Figure 13.

**Figure-13: Encasement geotextile after preparation**

Then, the columns are installed using the displacement method in a triangular pattern in the consolidated artificially prepared clay layer. In the displacement method, a steel pipe with closed tip is driven down into the clay till reaching the required depth as shown in figure 14. The geotextile is put into the steel pipe and the column material can be filled up. Then the pipe is pulled up under vibration to compact the column material as shown in Figure. Practically, the CLS column installed by displacement method have diameter approximately 0.8 m and the geotextile diameter is approximately similar to the internal diameter of the steel pipe (Alexiew et al. 2005).

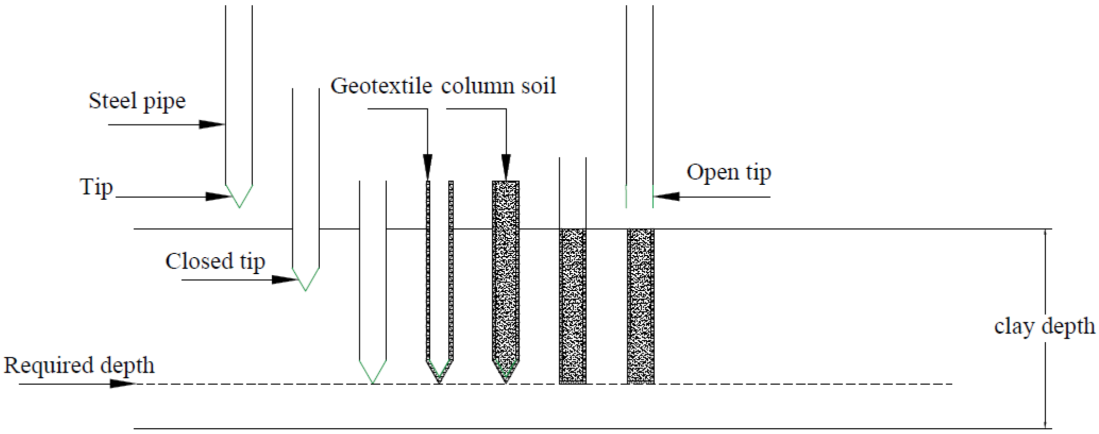


**Figure-14: Displacement method sequence for Cement-Lime columns installation in soft clay formations. (Alexiew et al. 2005).**

## EXPERIMENTAL MODEL TESTING PROGRAM

Figure 15 represents the two studied parameters; the CLS column embedment depth and diameter. The untreated soft clay formation is considered as a reference to evaluate the influence of the studied parameters in the proposed testing program

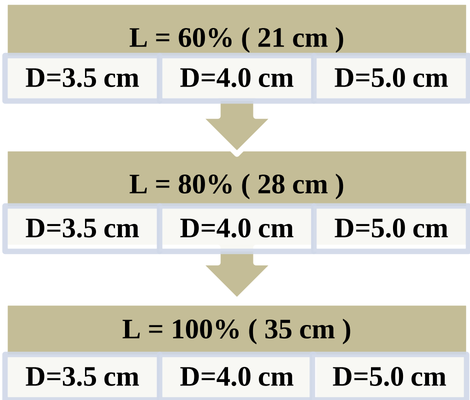


**Figure-15: Experimental model testing matrix**

## RESULTS AND DISCUSSIONS

### Effect of floating Cement dust - Lime – Sand (CLS) Columns

The experimental model tests output for the floating columns indicated an appreciable increase in treated very soft clay bearing capacity and settlement reduction in values as tabulated in Table. 6 and presented in Figure 16 a and b, respectively, for the cases of 60% and 80% penetration of the soft clay layer. The results generally showed that the CLS columns improved the soft clay engineering properties as it extracted the soft clay moisture that facilitate the consolidation process of the proposed soft clay formation and led to increase in bearing capacity and reduction in settlement.

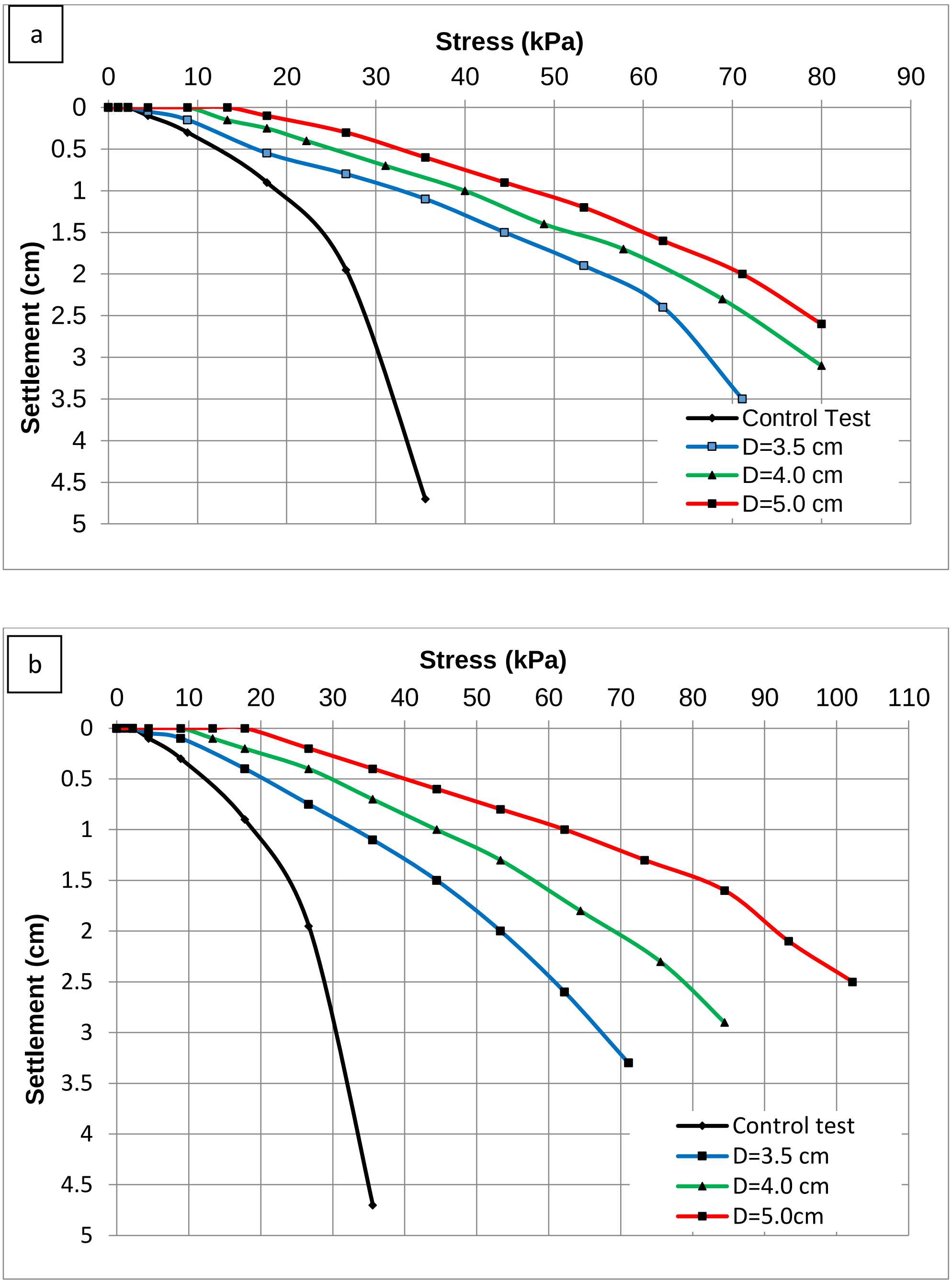


**Figure-16: Stress- settlement relationship for CLS column in very soft clay; a) partial penetration (60%) and b) partial penetrated (80%)**

Figure 17 represents the diameter influence of Cement dust - Lime – Sand column on the very soft clay – CLS composite bearing capacity for partial penetration percentages of 60% and 80% and fully penetrated columns. It could be noticed that the rate of increase in bearing capacity was higher for 80% penetration than that of 60% and full penetration cases. At the smaller CLS diameter (3.5 cm), both percentages of partially penetrated CLS columns were similar with higher gain in case of fully penetrated CLS columns.

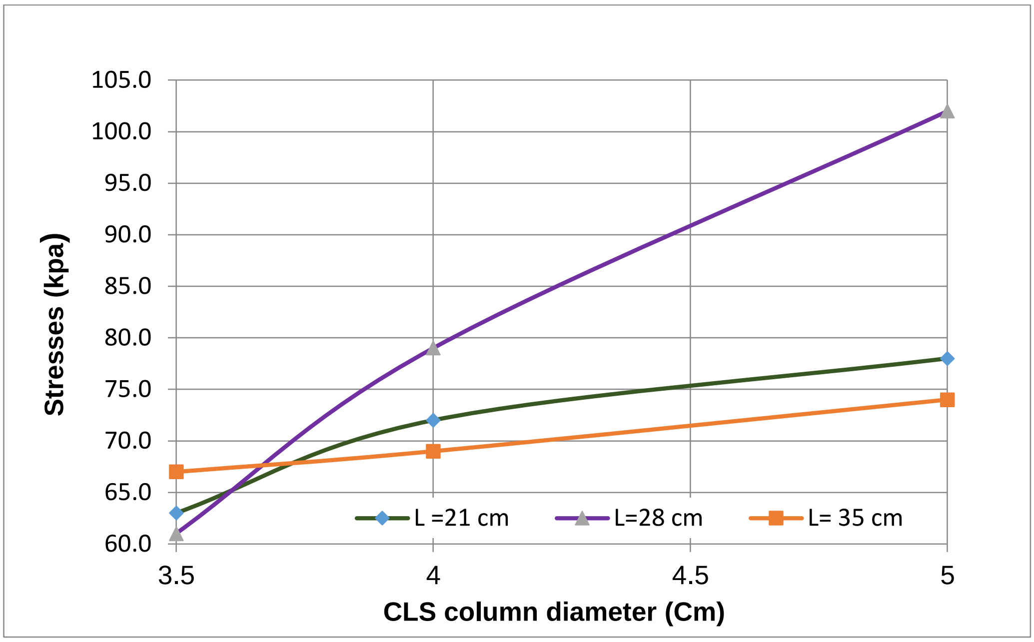


**Figure-17: Effect of CLS diameter on the treated soft clay stresses for 60 % (21cm), 80 % (28cm) and full penetration 35cm) .**

**Effect of fully penetrating Cement Dust – Lime – Sand Columns**

The results proved that the floating CLS columns (Partial penetration 60% and 80%) gave better improvement in the bearing capacity of the treated very soft clay layer, than fully penetrating CLS columns. This may be due to low compressive strength of the CLS to act as a bearing element., so the column was bulged towards the very soft clay formation. Figure 18 displays the results of fully penetrated CLS columns. It could be observed that there was no appreciable effect in settlement reduction for these columns.

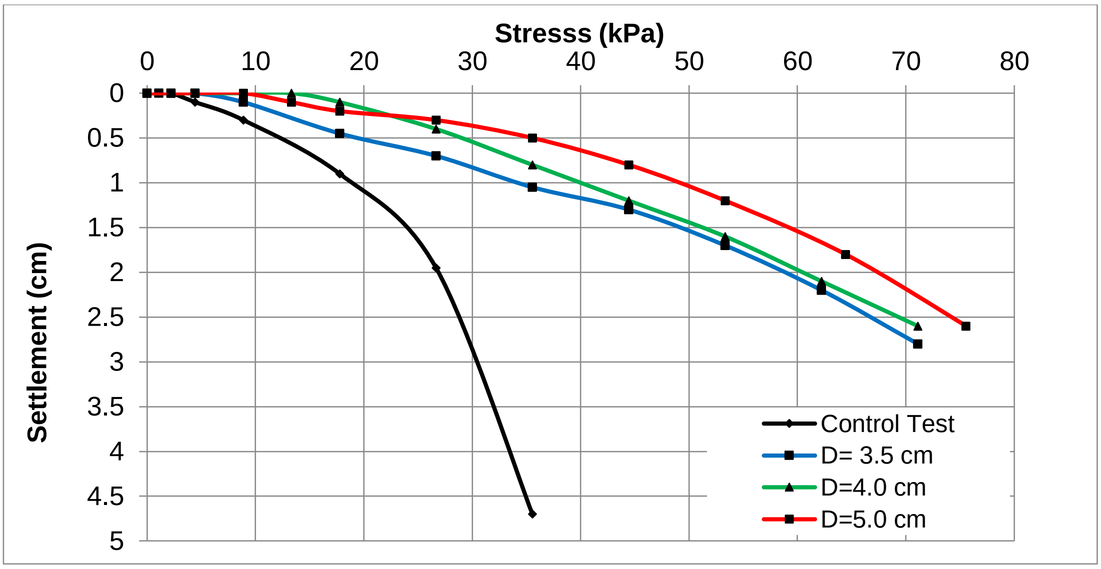


**Figure-18: Stress - settlement relationship for fully penetrating CLS column in very soft clay**

The testing program results revealed that increasing the partially penetrated CLS column length and diameter could highly improve the bearing capacity of the treated clay formation as presented in Figure 19. This is due to the increase in the column perimeter area that permitted more water extraction and hydration of the cement dust and activated the chemical reactions required for the lime to create bond with the sand as a filler material. The increase in bearing capacity of the treated clayey soils is more efficient in case of partially penetrating CLS columns. This may be attributed to that the fully penetrating CLS columns behave as an end bearing elements with insufficient shear strength for the column material. Table 6 represents the improvement percentages in bearing stresses at settlement of 1.5 cm for the tested configurations.

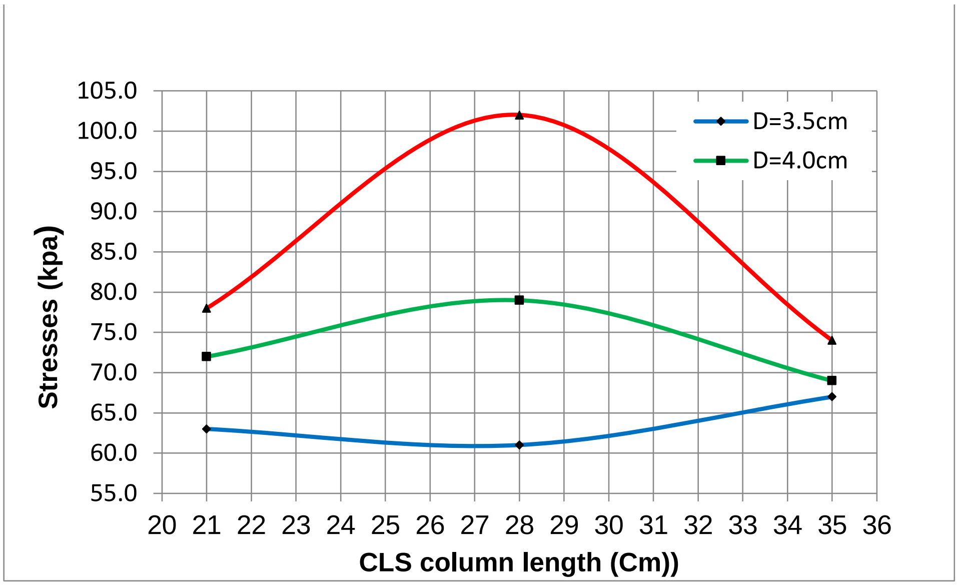


**Figure-19: Effect of increasing CLS column length on CLS –very soft clay bearing capacity for CLS diameters 3.5, 4 and 5 cm**

**Table- 6 The bearing capacity improvement percentages at settlement of 1.5 cm**

<table>
<tr><th rowspan="2">Case</th><th rowspan="2">Diameter (cm)</th><th rowspan="2">Length(cm)</th><th colspan="2">Bearing capacity (kPa)</th><th rowspan="2">Improvement (%)</th></tr>
<tr><th>Untreated</th><th>treated</th></tr>
<tr><td>No column</td><td>----</td><td>----</td><td rowspan="10">22.89</td><td>----</td><td>----</td></tr>
<tr><td rowspan="9">With CLS columns</td><td rowspan="3">3.5</td><td>21</td><td>44.4</td><td>194%</td></tr>
<tr><td>28</td><td>44.4</td><td>194%</td></tr>
<tr><td>35</td><td>48.85</td><td>213%</td></tr>
<tr><td rowspan="3">4.0</td><td>21</td><td>51.9</td><td>227%</td></tr>
<tr><td>28</td><td>57.74</td><td>252%</td></tr>
<tr><td>35</td><td>51.075</td><td>223%</td></tr>
<tr><td rowspan="3">5.0</td><td>21</td><td>59.98</td><td>262%</td></tr>
<tr><td>28</td><td>80.7</td><td>353%</td></tr>
<tr><td>35</td><td>58.85</td><td>257%</td></tr>
</table>

## Settlement characteristics

The effect of diameter of the CLS columns on the CLS-Clay composite settlement under different bearing stress levels for both partially and fully penetrated CLS are presented in Figure 20 a, b and c.

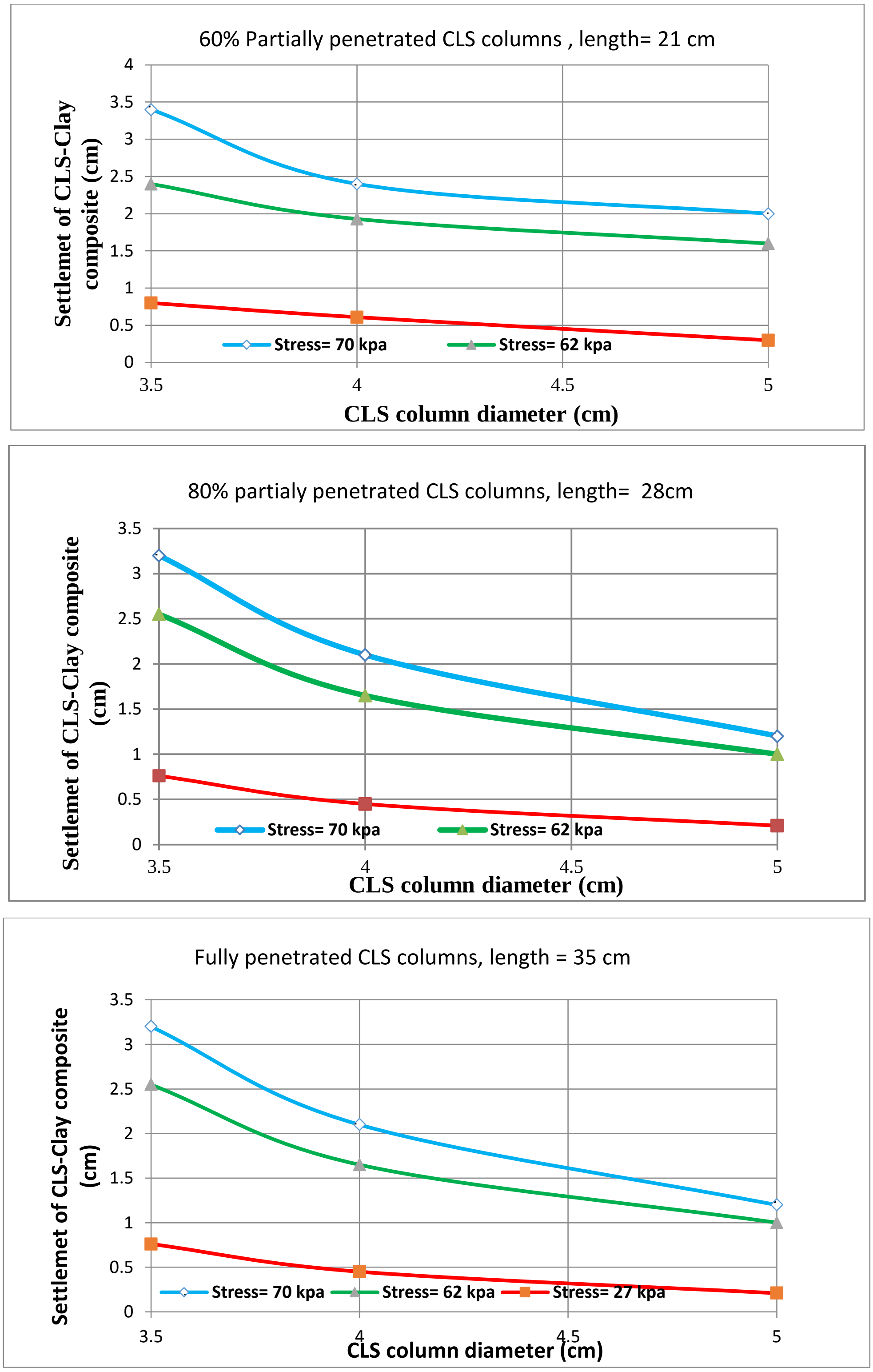


**Figure-20: Effect of CLS column diameter on the settlement of CLS-soft Clay composite: a) L = 21 cm, b) L = 28 cm and c) L = 35 cm**

Generally, it could be noticed that the settlement of CLS-soft clay composite decreased in different rates for both; partially and fully penetrating CLS columns, as the CLS column diameter increased for all the tested bearing stresses. The enhancement in settlement characteristics is better in case of partially penetrating CLS columns. This insufficiency in settlement reduction for the fully penetrating CLS column may be referred to that the column acted as a bearing stress transmission element with poor material properties regarding the strength. As the CLS columns are used to improve the loading characteristics of the composite and not used as load transmitting elements.

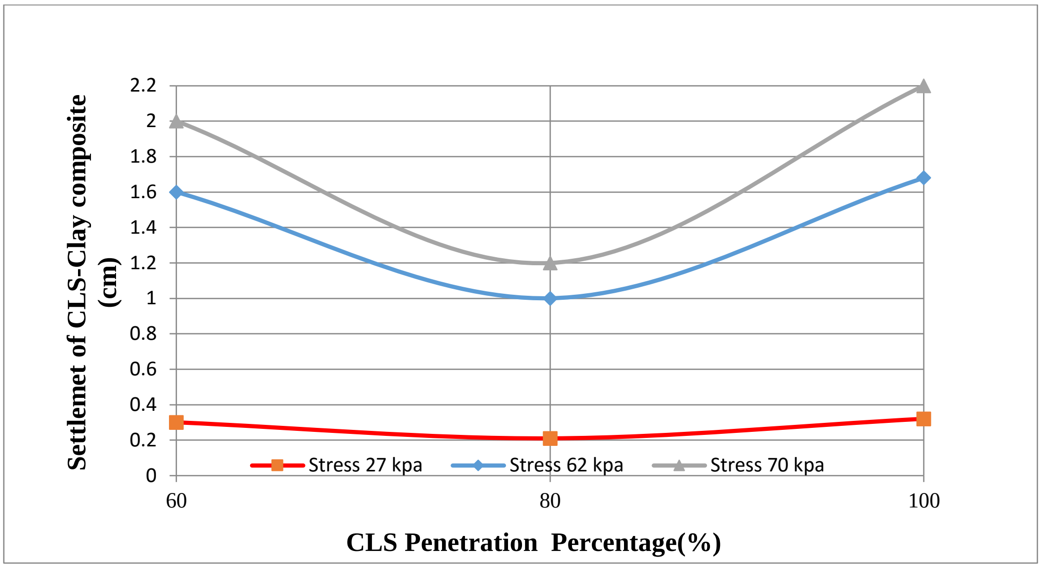


**Figure-21: Effect of CLS penetration percentage on the settlement of CLS-Clay composite**

## CONCLUSIONS

An experimental model testing program was carried out to assess the effect of the penetration percentage of geotextile encased- CLS columns on bearing capacity and settlement of treated very soft clay formation. All the stated percentages are relative to the untreated case (no CLS columns). Based on findings from this research with its testing conditions, these conclusions can be drawn:

### Bearing Capacity

1- The partially penetrated CLS columns have a better enhancement in composite bearing capacity compared with that of the fully penetrated CLS columns.
2- The increase in the CLS penetration percentage from 60% to 80%, highly affects the gain in bearing capacity for all tested CLS diameters.
3- For floating CLS columns as the penetration percentages raised from 60% to 80%, the rate of bearing capacity enhancement is much higher with the CLS diameter increase.
4- The improvement rate in bearing stress is the same for 60% CLS penetration and fully penetrated columns for larger CLS diameters.
5- The improvement in the ultimate bearing stresses for the experimentally tested 5 cm diameter, are 220%, 285%, and 210% for 60%, 80%, and fully penetrated CLS columns respectively.

### Settlement

1- Settlements are reduced with the increase of CLS column diameter, for both of the floating and fully penetrated cases for all stress levels.
2- Rate of settlement reduction is higher in floating CLS columns than that of the fully penetrated one, at high stress levels

3- The least reduction in settlement is for the case of fully penetrated CLS columns at high stress levels.
4- The settlement reduction percentages for the experimentally tested 5 cm diameter are 87%, 91%, and 89% for the penetration percentages of 60%, 80%, and fully penetrated CLS columns at low stress level(36kpa).

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