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A Laboratory Test on The Strength and Load-Settlement Characteristic of Improved Soft Soil Using Lime-Column

Uji Model Kuat Dukung dan Karakteristik Beban-Penurunan Tanah Lunak Dengan Perkuatan Kolom Kapur di Laboratorium

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ABSTRACT
This paper presents the application of lime-column technique on soft clay soil. The research studied the strength distribution surround the installed lime-column and the load-settlement characteristic in laboratory. The lime-column was designed as single column with 50 mm in diameter (D), and the depth was 200 mm. The laboratory tests carried out were unconfined compression strength test, cone penetration test, and small plate loading test. The soil and lime-column was prepared in a steel box sized of 1.2 m width x 1.2 m length x 1 m height. The test results show that the lime-column contributes to enhance the soil strength in radial and vertical direction up to 3xD from the center of lime-column. It was also observed that soil strength tends to increase with time. The bearing capacity of the soft soil increased from 0.23 kN to 5.2 kN after the lime-column was installed. For designing the lime-column grid, it was recommended that the spacing between lime-column was 4 times the column diameter.

Keywords: strength, settlement, soft soil, lime-column, expansive clay

INTRODUCTION

The Deep Mixing Method (DMM) is a common technique for an in situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. These materials are widely referred to as “binders” and can be introduced in dry or slurry form. They are injected through hollow, rotated mixing shafts tipped with some type of cutting tool (Terashi, 1997). Other variant of the DMM was lime-column method (LC). The lime-column method was formed by injecting the dry or wet lime under preferable pressure into soil in-situ (Rogers and Glendinning, 1997). This lime-column technique has been applied successfully in recent years to improve the physical and mechanical properties of the soils. This technique would increase soil bearing capacity and reduces soil settlement owing to improving of soil strength and stiffness. Hence, this technique was preferable for soft soil improvement (Broms and Boman, 1975). A study carried by Baker (2000) on full-scale model showed that the stiffness of the improved soil using lime-column increased more significantly than that of lime-cement column. Several researchers (e.g. Shen et al., 2003; Tomoz et al., 2003; Budi, 2003) studied separately the strength of the soil surrounding the lime-column. They reported that the soil strength increased near the column to a distance up to 2 to 3 times of the column diameter in radial direction. But, the effect of strength change beneath the bottom of lime-column was not studied.

It is reasonable to assume that the lime will flow easily downward into soil in vertical direction and the soil strength may also increase with the availability of lime. This research studied the strength distribution surrounding the installed lime-column in both radial and vertical direction from the center of the lime-column. The research also investigated the settlement characteristics of the soil before and after the lime-column was installed.

EXPERIMENTAL DESIGN

Soils
The disturbed soil and undisturbed samples were taken from the field in Kasihan, Bantul. The specific gravity of the soil was about 2.64. The particle size distribution of the soil sample is shown in Figure 1a. The soil consisted of about ten percent coarse and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles. The fine particle was dominantly silt and 90% fine particles.
Laboratory Test

Lime columns of 50 mm in diameter and 200 mm in length were installed in the container of 120 x 120 x 100 cm in dimension (Figure 2). The clay prepared in the tank was saturated by controlling the water level at the ground surface for 1 – 2 months. Preloading was also performed to obtain a uniform thickness. The preloading was equivalent with surcharge pressure about 3.26 kPa. It results in a degree of saturation about 90%-98%. Soil sample was taken from the container for consolidation testing. The test results confirmed that the OCR value was about 1.85. Hence, the soil is overconsolidated clay. The compressibility coefficient (Cc) and swelling index (Cs) are about 0.5 to 0.6 and 0.07 to 0.085 respectively.

In the field application, a hollow tube is pushed into the soil to the required depth and quicklime powder is then forced into the pile or column by air pressure as the tube is withdrawn. In the laboratory, the field application was simulated by filling the column hole with the quicklime powder in four successive layers, each layer was compacted gently to form lime-column.

Laboratory tests conducted were unconfined compressive strength test (UCS) and cone penetration test (CPT). The UCS test procedure was according to the ASTM D2165. The UCS test was performed at varying distance from the installed LC that are 50 mm, 100 mm, 150 mm and 200 mm in radial direction (Figure 2c). To avoid much disturbance and sampling difficulties, the UCS samples were taken at depth of 100 mm (one-half of lime-column length) by using PVC tubes. The CPT was performed also at radial direction. The test method refers to ASTM D3441 for mechanical CPT. The cone resistance (qc) was recorded every 200 mm of depth. So, in this study, the CPT will result cone resistance value at radial and vertical direction. Loading test was performed in this study to investigate settlement characteristic. A steel plate with 25 mm thickness and 150 mm in diameter was placed on the soil surface. This foundation was then loaded until failure. The loading rate was arranged about 1 mm/minute. The settlement and load was recorded from the dial gauge on the foundation and in proving ring respectively (Figure 3).

RESULTS AND DISCUSSION

Unconfined Compression Test

Figure 4 and 5 show the development of unconfined compressive strength of soil surrounding the lime-column at different ages after installation. The effect of lime on the strength of soil depends on numerous factors such as type of soil and lime, curing period, moisture content, temperature, etc (Sakr et al., 2009). In this study, the unconfined compressive strength of the soil treated with the lime column has also been determined in order to compare the variation in unconfined compressive strength with the distance from the lime column. Figure 4 shows changes in unconfined compressive strength with aging time.
The figure illustrates that the strength of the soil surrounding the lime-column does not increase very much after seven days of installation. After three days of installation, the soil strength near 1xD distance from the lime-column increase about 94%, and 57%, 35%, 7% respectively at 2xD, 3xD, 4xD from lime-column. Rao and Rajasekaran (1996) wrote that the lime migration takes place in seven to 15 days after installation to penetrate into soil up to 5xD in radial direction. Based on the result, it can be said that the effective time for lime-column installation is three days. Thus, after the period, the other construction activity may be allowed to be performed. This characteristic explained that after lime-column has been installed, the lime or calcium ions migrate into soil surrounding the lime-column. The soil properties around lime-column will change due to consolidation, densification, and hardening resulted by the chemical reaction between lime and soil. In chemical reaction, calcium and hydroxyl ions migrated through the clay. The hydroxyl ions cause highly alkalinic conditions in clay soil. This condition give rise to the slow solution of alumino-silicates which are then precipitated as hydrated cementitious reaction products. These reaction products contribute to flocculation by bonding adjacent soil particles together and when curing is allowed the clay soil is strengthened.
The soil strength around the lime-column varies with the dis-
properties and the strength developed gradually over a long peri-
time dependent, then the soil strength would increased with time.

After that, the soil undergoes a permanent change in mechanical
on in soil strength (Figure 4). Since the pozzolanic reactions are
days after installation of the lime-column and resulted modificati-
mechanism by Bell (1996) and Sivapullaiah et al. (2000).

This characteristic was in agreement with reaction mechanism by Bell (1996) and Sivapullaiah et al. (2000).

During migration, the lime reacts with the surrounding soil. As an exothermic reaction, this reaction consumes some amount of water and produces reaction product as cementation compound materials. A similar characteristic was also mentioned in Horpi-bulsuk et al. (2003) which studied cement admixture in high wa-
ter content clay. In the case of soft clays, water is already present (or increases owing to the admixture): it is not free, but it is able to interact with the clay and develop strength cement admixed soft clays. As hydration process, the water content would decrea-
s due to the lime reaction with water especially in the influenc-
ed zone (Figure 6). As a result, the soil strength nearby the lime-
column increases with decreasing of water content.

It was interesting to understand the stress-strain behaviour after installation of the lime-column. As shown in Figure 7, no clear peak is observed at the stress-strain curves for the untreated samples. In comparison, the stress–strain curves of the lime-treat-
ed samples shown in Figure 7 have slight peaks due to cementa-
tion of soil particles resulted by the pozzolanic compounds from lime reactions. It indicates that soil becomes stiffer and behaves in a slightly brittle manner after lime treatment.

**Static Cone Penetration Test (CPT)**

Cone penetration test is commonly used to determine the soil strength. The cone-tip resistance ($q_c$) vary with soil layer and soil properties. Figure 8 shows variation of the CPT results after installation of lime-column. It is shown that the lime column not only improves the soil strength in radial direction but also in ver-
tical direction beneath the column. This characteristic was con-
sistent with the UCS results. The CPT results confirm that the $q_c$
reaches higher value near the lime-column and decreases with distance from column.

In vertical direction, higher $q_c$ value is obtained near the base of column and decreases gradually to a depth of 40 cm to 60
distance from the center of the lime-column both in radial and verti-
cal direction. It was observed that the soil strength was likely to the same with untreated soil if the distance from lime-column is greater than 200 mm or 4xD. The soil strength will increase if the distance is closed to lime-column. Most of the strength increase concentrates at the soil adjacent side surface of the lime-column, up to 50 mm or 1xD in radial direction from the column. The ma-
imum soil strength increase about 2 times from 5.8 kPa to 11.9 kPa at 1xD radial direction. The soil strength in the distance of twice of the diameter (2xD) does not decrease very much (between five to seven percent, Figure 5). This influenced distan-
ce may be noted as main influenced zone. However it is noted that the lime migrates effectively to a radial distance of 3 times of the column diameter (3 x D), which is indicated by the higher soil strength than that before improvement. This zone may be called as effective influence zone within which the strength decreased in the range of 24%-28%. After a distance of 4xD (200 mm), the soil strength is approximately same as the soil strength before lime-column improvement. The migration distances are small in clayey soils because the soil has low to very low permeability. The coefficient of hydraulic conductivity of the clay soil used in this study ranges in between $2.6 \times 10^{-8}$ to $8 \times 10^{-10}$ m/sec.

In the field, lime-column was usually installed in a group of column instead of single column. Spacing between columns can be designed based on reduction of the soil strength associated with distance from lime-column. This study proposed that the spacing between lime-column was 4 times the diameter of lime-
column to yield considerable improvement. The proposed spacing reflects to the main influence zone of the UCS surrounding lime-column (Figure 5). Bergado et al. (1994) noted that to redu-
cenental settlement between column and soil surrounding lime-
column, then, the column spacing can be designed 3 to 4 times the diameter.

During migration, the lime reacts with the surrounding soil. As an exothermic reaction, this reaction consumes some amount of water and produces reaction product as cementation compound materials. A similar characteristic was also mentioned in Horpi-bulsuk et al. (2003) which studied cement admixture in high wa-
ter content clay. In the case of soft clays, water is already present (or increases owing to the admixture): it is not free, but it is able to interact with the clay and develop strength cement admixed soft clays. As hydration process, the water content would decrea-
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In vertical direction, higher $q_c$ value is obtained near the base of column and decreases gradually to a depth of 40 cm to 60
cm underneath column. In other words, the lime can penetrate into soil about 8 to 12 times of column diameter beneath the column. It indicates that the length of the lime-column need not be installed fully in soft soil thickness. The influenced zone in vertical direction is wider than in radial direction. The lime migration in vertical direction was possible driven by the gravity force and due to the compaction during the installation to be able to migrate more rapidly and wider. It was found in this investigation that the main migration zone can reach up to 4 times of column diameter beneath the column tip (Figure 8). However, it should be noted that due to the variability of in-situ soil is relative high in vertical direction; the range of lime migration in the field may be different from the laboratory results.

Settlement Characteristic

Figure 9 shows the load–settlement curves for the constant rate loading test carried out using 150 mm circular plates directly on soft soil surface. When loading is applied, it is assumed that the column and soil nearby the column deform as a unit. Hence, the settlement will depend on the ratio between area of lime-column and the loaded or influencing area. The ratio is known as area replacement ratio (Bergado et al., 1994; Kempfert, 2003). The area replacement ratio ($a_c$) of the soil-column was 0.33 that is a ratio between diameter of lime-column (50 mm) and foundation (150 mm). Comparing the load–settlement curves, it was clearly observed that installation of the lime-column improved the bearing capacity of the soft soil. This behavior is consistent with the UCS test and CPT results as described in previous section.
Before installation of the lime-column, based on the load-settlement curve, the mode of failure was likely defined as general shear failure (Craig, 2004). The soil experienced failure at 0.23 kN loading. Coincidently, the plate undergoes larger settlement up to 37 mm (Figure 9a). On contrary for the lime-column improved soft soil, the strength of improved soft soil increased continuously even at large deformations (Figure 9b). Failure would be attained after reaching 60 mm vertical deformation. The ultimate load was approaching 5.2 kN. It means that the bearing capacity increases 23 times from the load was measured at 37 mm vertical deformation, the bearing capacity increases 13 times from 0.23 kN to 3 kN.

Kempfert (2003) mentioned that the effect of a soil improvement is usually expressed by an improvement factor \( \beta \):

\[
\beta = \frac{\text{Settlement of the unimproved soil}}{\text{Settlement of the improved soil}}
\]

Larger improvement factor indicates larger reduction in soil settlement. Comparing the settlement at \( P_{\text{limb}} = 0.23 \) kN, the settlement of the unimproved soil is about 37 mm while settlement of the improved soil is about 2 mm. Hence, the improvement factor \( \beta \) is 18.5.

**CONCLUSIONS**

The following conclusions can be drawn from the above research findings.

1. The installation of lime-column in the soil can improve the strength of the soil surrounding the column in both vertical and radial directions. Higher strength attained near the column and decreased gradually with the distance from the column.
2. The increased soil strength is a result of the lime migration into and reaction with soil. The lime can penetrate into soil up to 3xD in radial direction and 8xD in vertical direction. But, the main influenced zone is within 2x in radial direction and 4xD beneath column in vertical direction. For designing the lime-column grid, it was recommended that the spacing between lime-column is 4 times the column diameter.
3. The water content of surrounding soil decrease after installation of the lime-column owing to the imbibing of water for chemical reaction between lime and soil. The amount of water content decrease reduces with the distance from the column edge.
4. The effective aging time of the lime-column is three days after installation.
5. The bearing capacity of the soft soil increased 23 times from 0.23 kN to 5.2 kN after the lime-column was installed. The improvement factor \( \beta \), for are replacement ratio \( a_c = 0.33 \), was about 18.5.

**ACKNOWLEDGEMENT**


**REFERENCES**


