Experimental Study on At-rest Lateral Earth Pressure Coefficient of Cemented Clay

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Abstract. The determination of lateral earth pressure is of practical importance and plays an important role in the design of retaining structures. Test results of at-rest lateral stress, coefficient of earth pressure at rest and its change law of an artificially cemented clay were presented in this paper. A K0 consolidometer was utilized to measure the at-rest lateral stress and vertical compression of the specimen. The test material was a Lianyungang marine clay and was mixed with a special kind of Portland cement that was designed for ocean engineering. The cement contents were 4, 6, 8, 10 and 12% by weight of dry soil particles and the curing time was 7, 14, 28, 60 and 90 days. The test results indicate that the at-rest lateral stress of cemented clay is different from that of uncemented clay. And at-rest lateral stress decreases rapidly with an increase in cement content and curing time. However, the lateral stress increases sharply when the applied load exceeds the vertical yield stress, which causes a corresponding change in K0.

1. Introduction

A good deal of water front structure construction has been carried out on natural soft ground in recent years. And stabilization and solidification of clay using cement agents has been used to increase bearing capacity of soft clay foundations[1-3]. In offshore sheet pile wharf engineering, the studies of the lateral stress and deformation behaviour of cement clay are important because they are the main factor determining the deformation and deflection of the bulkhead.

K0 was introduced by Donath in 1891 and represents a stress state under zero lateral strain. In general, the published K0 test methods can be divided into two categories, the in-situ methods[4-6] and the laboratory model methods[7-10]. In-situ evaluation methods provides some variation of K0 because of the many uncertainties that result from the disturbance during sensor installation. And most triaxial laboratory methods that have been used are too complex to be popularized. Modified oedometer devices with pressure cells have been used successfully by many researchers in the measurement of at-rest lateral earth pressure coefficient.

Much work has been done regarding K0[11], while almost all investigations are limited to uncemented soils and cemented sands. Information available on the at-rest lateral stress and the K0 characteristics for cemented clay are limited. The objective of this paper is to study the effects of
cement content and curing time on the magnitude of $K_0$ for cement-treated marine clay and to examine the test results in the light of these correlations.

2. Material and Methods

2.1 Soil sample

The clay used in this paper was taken from the Xuwei Harbor, which is located on the west coast of Haizhou Bay, the Yellow Sea, China. The site consists of about 12 m of soft clay overlying a deep silty sand layer which is underlain by sand. The soft clay below the sea floor is Holocene marine sediments, which are often distinguished by their high compressibility and high sensitivity. It is suggested that the marine clay is deposited after the last Ice Age and is usually considered to be younger than 11,700 years. Distinguished from Ariake clay in Japan, eastern Canadian clay and Bangkok clay in South Asia, the collected clay sample is characterized by its low liquid limit and different mineral composition.

To avoid impurities in the surface layer, the soil sample used in this study was collected from 2 m below the sea bed. According to laboratory particle analysis test results, this soft soil is a type of grey silty clay that is composed of 48.2% clay, 48.2% silt, and only 3.6% sand. The clay is in plastic state with natural water content that ranges from 55.8% - 68.2%. The bulk density and specific gravity $G_s$ are about 16.0 kN/m$^3$ and 2.72. The strength parameters that are predicted by an undrained shear test are $c_q = 9$ kPa and $\phi_q = \cdot$. The main physical properties of the tested soil are listed and described in Table 1.

Table 1. Main physical characteristics of soft marine clay.

| Properties             | Index value |
|------------------------|-------------|
| Liquid limit, LL (%)   | 78.5        |
| Plastic value, PL (%)  | 38.2        |
| Liquidity index, LI    | 0.62        |
| Clay particle (%)      | 48.2        |
| Silt particle (%)      | 48.2        |
| Sand particle (%)      | 3.6         |
| Unit weight, $\gamma_t$ (kN/m$^3$) | 16.32 |
| Water content, $w$ (%) | 55.8-68.2   |
| Initial void ratio, $e_0$ | 1.72     |
| Color                  | Gray        |
| Main mineral component | Illite-montmorillonite mixed-layer mineral |

2.2 Specimen preparation

The clay used in The homogeneity and uniformity of the cemented samples are influenced by water sulphate, soil grain-size distribution, chemistry and sampling method. To ensure the homogeneity of specimens, the adopted sampling procedure was as follows: First, the soil mass was air dried and sifted through a 1.0-mm sieve to remove impurities such as large particles and shells. In preparing the samples, a specified dry soil density of 1.0 g/cm$^3$, a water content of 63.2%, cement contents ($a_c$) of 4, 6, 8, 10, and 12%, and a curing time ($T$) of 7, 14, 28, 60 and 90 days were selected. The estimated amount of the base clay was thoroughly mixed with cement slurry by electrical mixer. Then the cement slurry was prepared with the required amount of cement with water. The mixing of the slurry and the clay was done until the mixture was uniformly mixed. At last, the mixed material was placed in a steel mold (90 mm in diameter, 60 mm in height) in three equal layers. During sampling, the specimen density was monitored carefully and maintained constant. The cement content is defined as the ratio of the dry weight of the cement to the dry weight of the soil particles in this paper.

The prepared sample was soaked in water in a 97% humidity room at 25 degree Celsius. It should be pointed out that the water used in this study is collected from the engineering site to make sure that
the chemistry of the water is similar to that of the pore water in its natural state. And the cemented used is a special kind of cement which was designed for ocean engineering. At the time of testing, the cemented clay sample was then trimmed to the dimensions required for the type of test to be conducted. One mixed molded sample was used to extract one sample specimen.

2.3 Testing methodology

In the laboratory, \( K_0 \) can be measured using modified thin-wall oedometer ring when the radial strain is less than a certain value\[12\]. And researchers have reported that the \( K_0 \) stress state can be assumed within the limit radial strain about \( 5 \times 10^{-5} \)[9].

![Figure 1. Schematic diagram of thin-wall \( K_0 \) consolidometer.](image)

The adopted modified oedometer ring is shown in Figure 1. The ring used in this study is made of aluminum with an internal diameter of 61.8 mm, an external diameter of 140 mm and a height of 40 mm. The thickness of the thin wall is 1 mm. A pair of high accuracy active strain gages was attached at the middle height of the wall and two other strain gauges were attached at the bottom of the ring to provide temperature compensation. These two pairs of gauges were joined together to compose a full-bridge circuit [13]. The lateral earth pressure was measured by two active strain gages during the test. And the vertical deformation was measured using an electrical dial gauge placed on the top of the loading cap. According to the calibration results, the lateral strain of the oedometer ring was less than the order of \( 10^{-5} \) within the radial pressure range and is significantly less than the value required for the lateral stress to drop to the active state.

3. Test Results

3.1 One-dimensional Stress-strain Response

Typical compression curves for cemented clay were shown below by the data obtained from tests carried out on a low liquid limit marine clay admixed with cement. The specimens were prepared by the sampling method described above to insure the uniformity of the sample. The compression behavior is shown in Figure 2 with regard to void ratio and logarithm of vertical effective stress.

As shown, the cemented clay specimens demonstrate concave-down compression curves and exhibit over-consolidation characteristics. It can be seen from these compression curves that almost all tested samples show little compression at a low vertical stress level, which indicates that, the specimens are initially much stiffer than the soil in its destruction state and become gradually softer as the vertical stress increases. It can be deduced from the compression behavior that some over-consolidation characteristics and a vertical yield stress has developed from mixing the marine clay with cement. The compression curves also show that the strength and resistance to compression increase with an increase in amount of cement added and the curing period maintained.
The vertical yield stress at which the soil starts to develop a large strain was determined from Figure 2 using the graphical procedure of Casagrande (1936) is shown in Figure 3. The key problem is to how to find the point with maximum curvature precisely, and the method adopted in this paper is as follows: first, obtain the mathematic function by curve fitting, then calculate the second derivative of each point on the curve, then we can find the points with maximum curvature. It can be seen from the figure that the yield stress increases as cement content and curing time increases. This indicates that a commensurate amount of bonding formed in the clay as the result of hydration products cementation. By analyzing the changing characteristic of vertical yield stress in Figure 3, we get the following conclusion: the vertical yield stress increases with cement content and curing time, but not in the same trend. The test data in Figure 3(a) state clearly that the vertical yield stress increases slowly at low cement content less than 8% and then grows rapidly with the increase of cement added. While the test data listed in Figure 3(b) indicate that the vertical yield stress increases rapidly at the first 14 days of curing although certain error exists in the test data. And the increasing trend becomes weak gradually with the increase of curing time.
3.2 One-dimensional Stress-strain Response

3.2.1 Cement Content

$K_0$ consolidation test on Lianyungang marine clay was carried out in order to study the effect of cement content on the at-rest lateral stress of cemented clay. Specimens were prepared by using 4, 6, 8, 10, and 12% cement by weight of dry soil particles. And the curing time was 7, 14, 28, 60, and 90 days. The relationship between the lateral stress and vertical stress during virgin loading is shown in Figure 4.

Figure 3(a). Variation of vertical yield stress at different cement content.

Figure 3(b). Variation of vertical yield stress at different curing time.

Figure 4. Relationships between at-rest lateral stress and vertical stress.
The common characteristic shown in Figure 4 is that the at-rest lateral stress increases nonlinearly during loading process. And this nonlinearity increasing trend is more marked for samples with high cement content. Taking the test data in Figure 4(a) as an example: the at-rest lateral stress increases almost linearly with the increase of vertical stress when cement content is less than or equal to 4%. And the nonlinearity becomes appreciable when the cement content is more than or equal to 6%. This is especially true in the samples with higher cement content of 8%, 10% and 12%.

The changing regularity of at-rest lateral earth pressure shown in Figure 4 was quite different from that of uncemented clay since the lateral stress increases linearly with vertical stress. And this was mainly due to the formation of cementitious products. Research has shown that hydration products were produced after mixing the clay with cement in saturation state. But the effect of cement content on at-rest lateral stress was not clear at low cement content because the cement amount was insignificant compared with soil mass. The hydration products increase with cement added, fill the pores among soil particles and enhance the interparticle bonding. And resulting the corresponding change of pore structure and microstructure characteristics finally. For more cement means better cementation, and the strength of stabilized soil is proportional to cement content. And the nonlinear increasing characteristic is more obvious as the result.

Figure 4 also indicates that the reduction in lateral stress with the increase of cement content is insignificant compared with cemented sand used by Zhu et al (1995). This means that cementation is more effective in sands than in clay. The difference is believed to be caused by the size distribution and angular shape of the sand particles. Sand samples have more grains to contact with each other and more effective interlocking. And the bonding strength is therefore stronger. Meanwhile, the clay particle has higher specific surface area and thus more cementitious agent is needed to bond the fine grains together. Under the influence of these factors mentioned above, the cementation is more effective in sand than in clay by comparison.

3.2.2 Vertical Stress
An important trait that the at-rest lateral stress of cemented marine clay demonstrated is its nonlinear relationship with vertical stress during loading as shown in Figure 4. This property is more pronounced in Figure 5 through the values of $K_0$ which were derived from the data in Figure 4, when taking specimens with a curing age of 90 days as an example.

![Figure 5. Relationships between $K_0$ and vertical stress at a 90-day curing age.](image)

It can be seen from Figure 5 that the $K_0$ of the cemented marine clay is influenced by the applied vertical stress, although some deviations exist in the graph. It can also be seen from Figure 5 that $K_0$ is relatively small at low vertical stress level, while its value increases substantially when the vertical stress exceeds a certain ambit.

For weakly cemented specimens with a cement content of 4% shown in Figure 5, $K_0$ increases when vertical stress exceeds 200 kPa firstly and then keeps constant in the range of stress applied. Specimens with a cement content of 6%, $K_0$ increases when the vertical stress exceeds 400 kPa. For
specimens with cement content of 8% or more, $K_0$ value is relatively small during the initial stage of loading. However, there is a sharp increase in $K_0$ when applied vertical stress is greater than 800 kPa.

![Figure 6. Compression curves at a curing time of 90 days.](image)

The stress dependence of $K_0$ for cemented clay can be illustrated by the compression behavior in Fig. 6. It can be seen from Figure 6 that the vertical deformation decreases significantly with an increase in cement content. For specimens with a cement content of 12%, the total vertical deformation is less than 8%, which is considered to be relatively small. For specimens with a cement content of 4%, the total compression is more than 20%. This indicates that a higher cement content results in a stronger soil skeleton. Vertical compression gives rise to a shear strain under $K_0$ conditions, and the shear strain leads to the progressive destruction of the cementation bonds. And $K_0$ increases in the process of loading as the result.

3.2.3 Curing Period
To study the effect of curing time on $K_0$, specimens that were cured at 7, 14, 28, 60, and 90 days were tested. Take the specimens with cement content of 4% as an example, the test results are shown in Figure 7.

![Figure 7. Effect of curing time on $K_0$ when $a_c = 4%$.](image)

An important characteristic demonstrated in Figure 7 is that the $K_0$ value is smaller with long curing time than that with short one. As can be seen from the figure, $K_0$ decreases sharply at the first 14 days of curing of the whole load range. And the decrease momentum of $K_0$ is moderated with the increase of curing time. When the vertical stress is lower than 200 kPa, the decreasing rate accelerated for specimens under 90 days of curing.

4. Discussion
The research results of this paper show out that the at-rest lateral stress in cemented clay is quite different from that of uncemented ones. And the lateral stress displays different identities within the scope of applied vertical stress. On the base of the experiment data listed in Figure 3 and Figure 4, it was discovered that the sharp increase of at-rest lateral stress of cemented clay appears when the applied load exceeds vertical yield stress. As a result, cemented clay shows different $K_0$ value when we take the line slope of two points, the origin of the coordinates and the lateral stress at different...
vertical stress level as the coefficient of $K_0$ before and after yield. The corresponding values of $K_0$ derived from Figure 3 at different cement content are shown in Figure 8 and Figure 9.

![Coefficient of $K_0$ before yield.](image1)

![Coefficient of $K_0$ after yield.](image2)

It could be seen from Figure 8 and Figure 9 that the coefficient of $K_0$ decreases with the increase of cement content, and this effect is proportionally more marked before yield. After yield, the trend, while still present, becomes less significant without taking into account the uncertainty in the accuracy of the test data. But, it made unambiguous that the stress-strain response of cemented clay has different properties. And the stress-strain response is influenced by the applied vertical stress according the laboratory study carried out in this study.

5. Conclusion
This paper presents results of the laboratory $K_0$ consolidation test for Lianyungang clay admixed with marine cement. The main objective is to research the coefficient of earth pressure at rest and its changing rule, and to process a reasonable expression to describe the coefficient of $K_0$ for marine clay with different cement content and curing times. Based on this research, the following conclusions can be made:

1. The at-rest lateral in artificially clay is different from that of uncemented clay. At-rest lateral earth pressure of cemented clay is related to cement content, curing time and vertical stress.

2. The cemented clay maintains different coefficient of earth pressure at rest before and after yield. A higher vertical stress yields a higher $K_0$ and this trend is more significant at a high cement content compared with that at a low content.

3. $K_0$ decreases with an increase in cement content and curing time, but the decreasing characteristics are not the same. The reduction in $K_0$ is proportionally more marked at low cement content and short curing time. At a high cement content and a long curing time, the trend becomes less significant.

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