ESTIMATION OF COEFFICIENT OF EARTH PRESSURE AT REST USING MODIFIED OEDOMETER TEST

NIPON TEERACHAIKULPANICH(i), SATOSHI OKUMURA(ii), KAZUAKI MATSUNAGA(iii) and HIDEKI OHTA(iv)

ABSTRACT

A series of experimental trial for estimating the coefficient of earth pressure at rest, $K_0$, is presented. The developed apparatus is a modified Oedometer covered with pressurized chamber specially designed for $K_0$ determination based on the principle of effective stress originally proposed by Ohta et al. (1979). $K_0$ is estimated from the developed apparatus primarily by means of load cell and auxiliary by means of pore pressure transducer aiming at confirming the test results. $K_0$ triaxial consolidation is carried out to verify the result of purposed method. $K_0$ values are obtained using Oedometer tests on two samples one of which is taken horizontally and the other is taken vertically from a block and $K_0$ values from empirical equation are also estimated for comparison. It was found that the proposed method gives a comparable $K_0$ of kaolin to $K_0$ triaxial consolidation method but somewhat higher than those from empirical equations and lower than $K_0$ obtained using Oedometer.

Key words: coefficient of earth pressure at rest, consolidation, effective stress, friction, kaolin (IGC: D5)

INTRODUCTION

In many geotechnical problems, the initial state of stress existing in the ground is an important parameter that must be known for designs and analysis. The in-situ vertical effective stress, $\sigma_v^e$ at any depth can be simply estimated from the profiles of overburden pressure and pore water pressure. On the contrary, the in-situ horizontal effective stress, $\sigma_h^e$, is difficult to directly measure and also difficult to estimate empirically because it depends not only on the soil properties but also on the geological history of soil deposits and is most often approximated.

The relationship between the vertical effective stress and the horizontal effective stress under conditions of zero lateral deformation is usually expressed by coefficient of earth pressure at rest $K_0=\sigma_v^e/\sigma_h^e$.

The coefficient of earth pressure at rest, $K_0$, has been studied by geotechnical engineers for many years for its being an essential parameter in designs and analysis of many geotechnical problems such as earth retaining structures, piles, and slope stabilities. Moreover, in the last few decades, $K_0$ represents an essential step in any numerical analysis of soil/water coupled geotechnical boundary value problems involving constitutive stress-strain-time formulations.

The information of $K_0$ in soft soils is limited by the difficulty of sample handlings and measurements under the strictly defined condition of no lateral displacement.

Nevertheless, there are published research measurements of $K_0$ with methods chosen to provide the condition that the lateral strain is zero. These methods can be classified in two categories: (1) in-situ methods; (2) laboratory methods.

In-situ Methods

The in-situ tests to evaluate $K_0$ have been proposed by many researchers that can be grouped into three categories. The direct tests involve very small disturbance in the soils caused by the insertion of test devices such as Self-boring Pressure meter (Baguelin et al., 1972; Jezquel, 1972; Wroth and Hughes, 1973; Hamouche et al., 1995). The semi-direct tests involve inserting probes in the ground without any precaution for avoiding disturbance such as, A large pile instrumented with total pressure cell (Kenney, 1967), Hydraulic Fracturing (Bjerrum and Andersen, 1972; Bozozuk, 1974; Lefebvre et al., 1991; Hamouche et al., 1995), Total Pressure Cells (Massarsch, 1975; Massarsch and Broms, 1976; Tavenas, 1975), Dilatometers (Marchetti, 1980; Hamouche et al., 1995), $K_0$ Stepped Blade (Handy et al., 1982; Handy and et al., 1990), and Cone penetration test (Masood et al., 1993). The non destructive method involves measuring shear wave velocity of cohesionless soils (Fioravante et al., 1998; Hatanaka et al., 1999).

However, the different methods of in-situ evaluation of $K_0$ gave some variations on $K_0$ due to many uncertainties...

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Fig. 1. COWK triaxial apparatus

(a) COWK triaxial chamber

(b) Typical COWK triaxial test set-up
related to sensitivity of derived $K_0$ to the small disturbance caused by inserting the probe into the ground.

**Laboratory Methods**

The laboratory methods fall into two distinct classes. The first uses a rigid lateral boundary; consolidometer type, which provides the required “zero lateral strain” condition but also allows undefined friction between the wall and the soil such as Semi rigid Confining Ring (Newlin, 1965), Null Type Confining Ring (Brooker and Ireland, 1965; Singh et al., 1973), COWK (Ohta et al., 1979), Semi-rigid Consolidometer (Abdelhamid and Krizek, 1976; Edil and Dhowain, 1981; Mesri and Hayat, 1993; Ting et al., 1994). The second uses a flexible lateral boundary with a feedback system to maintain the position of boundary; triaxial types such as Rigid Cell (Davis and Poulos, 1963), Controlled Volume Triaxial (Lewin, 1970), Null Type Triaxial Test (Bishop, 1958; Moore and Spencer, 1972) Automatically simulating $K_0$ consolidation and $K_0$ swelling in triaxial cell (Menzies et al., 1977), A Simple $K_0$ Triaxial Cell (Campanella and Vaid, 1972), Double cell $K_0$ triaxial apparatus (Okochi and Tatsuoka, 1984), $K_0$ consolidation test in triaxial apparatus (Fukagawa and Ohta, 1988), Triaxial strain path testing (Lo and Chu, 1991), Automated $K_0$-consolidation apparatus in triaxial cell (Tsuchida and Kikuchi, 1991; Watabe et al., 2003). The advantage of using a flexible lateral boundary is the absence side friction but the disadvantage is how to control the soil specimen to be flexible lateral boundary. The advantages are that soil can be consolidated under conditions of perfect-condition but also allows undefined friction between the wall and the soil such as Semi rigid Confining Ring (Newlin, 1965), Null Type Confining Ring (Brooker and Ireland, 1965; Singh et al., 1973), COWK (Ohta et al., 1979), Semi-rigid Consolidometer (Abdelhamid and Krizek, 1976; Edil and Dhowain, 1981; Mesri and Hayat, 1993; Ting et al., 1994).

**TESTING APPARATUS**

**Concept**

The concept of modified Oedometer with a pressurized chamber mounted on a consolidation machine was invented and developed by Ohta et al. (1979). The acronym “COWK (Cambridge-Ohta-Wroth-Kyoto) triaxial apparatus” was coined to call the developed apparatus as shown in Figs. 1(a) and (b). The soil specimen (1) is placed in the container ring (2). The outside of container ring is covered with a rubber membrane (3). Two of rubber o-rings (4) and (5) are fitted over the membrane and the other o-ring (6) is in the groove of the pedestal (7) to provide the seals. Additionally, the vertical drainage is provided by a cast-in-place high air-entry ceramic disk (8) sealed in the top portion of the pedestal. The soil specimen is consolidated in the container ring; $K_0$ consolidation, supplying with cell pressure (CP) and back pressure (BP) in order to effectively dissolve any small volume of entrapped air in the specimen.

After completion of primary consolidation, the drainage valve is closed and the container ring is to be eliminated by withdrawing downwards. During this process, the constant effective stresses are needed to be kept unchanged under undrained condition by means of having no additional deformation. Thus, the specimen volume and vertical displacement are kept constant after closing the drainage valve and by means of fixing the movement of yoke (9) shown in Fig. 1(b).

No volume change and no vertical displacement provide no lateral displacement resulting in no deformation at all. This ensures that no change in effective stress state takes place during the process of container ring withdrawal.

After withdrawal of container ring, the specimen is exposed to the rubber membrane being pressurized by cell pressure (CP). The total horizontal stress becomes equal to the effective stress plus the back pressure after the completion of primary consolidation as shown in Fig. 2

$$\sigma_{h0} = \sigma'_{h0} + u_0$$

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in which $u_0 = \text{BP}$ (back pressure).

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No volume change and no vertical displacement provide no lateral displacement resulting in no deformation at all. This ensures that no change in effective stress state takes place during the process of container ring withdrawal.

After withdrawal of container ring, the specimen is exposed to the rubber membrane being pressurized by cell pressure (CP). The total horizontal stress becomes equal to the effective stress and the pore water pressure changes to $u_1$ while the effective stresses remain constant as shown in Eqs. (3) and (4):

$$\sigma_{v1} = \sigma'_{v0} + u_1$$

$$\sigma_{h1} = \sigma_{h0} + u_1$$

Substitution of $\sigma_{h1} = \text{CP}$ into Eq. (4) yields:

$$\sigma_{h0} = \text{CP} - u_1$$

in which $u_1$ is pore water pressure measured by pressure transducer (10) after the withdrawal of the container ring.
Consequently, $K_0$ is determined by Eq. (6):

$$K_0 = \frac{\sigma_{10}^0}{\sigma_{00}^0} = \frac{\text{CP} - u_i}{\sigma_{00}^0}$$

(6)

since $\sigma_{00}^0$ is already known as the consolidation pressure during the preceding consolidation process.

Moreover, substitution of $u_i$ from Eq. (5) into Eq. (3) yields:

$$\sigma_{11} = \sigma_{00}^0 + \text{CP} - \sigma_{10}^0$$

(7)

Then, Eq. (7) minus Eq. (1) yields:

$$\sigma_{11} - \sigma_{00}^0 = (\sigma_{00}^0 + \text{CP} - \sigma_{10}^0) - (\sigma_{00}^0 + u_0)$$

(8)

Thus, $K_0$ is also determined by Eq. (9):

$$K_0 = \frac{\sigma_{10}^0}{\sigma_{00}^0} = \frac{\text{CP} - u_0 + (\sigma_{00}^0 - \sigma_{11})}{\sigma_{00}^0}$$

(9)

The difference of vertical total stresses ($\sigma_{00} - \sigma_{11}$) is measured by means of load cell (11) attached on the top cap (12) as well as by the load cell (13) which detects the change of reaction to the yolk. Both of pressure transducer (9) and load cell instrumentation (11) and (13) are used to confirm the estimation of $K_0$ value.

**Friction**

**Side Friction Cut**

In reality, the side friction between the container ring and the consolidating soil exists along the container ring. The side friction directly affects the estimation of coefficient of earth pressure at rest due to the reduction of vertical effective stress. In order to transfer most of the vertical load to the specimen, change of direction of the friction from upward to a little bit of downward is required. Downward pre-withdrawal of container ring after the completion of the primary consolidation is the technique to change the friction direction. Several steps of pre-withdrawal of container ring are performed in order to make the vertical effective stress as equal as the applied load.

**Excess Pore Water Pressure due to Side Friction**

During withdrawal of container ring under undrained conditions, some excess pore water pressure is also generated. It is believed that this pore water pressure $u_i$ is caused by side friction. This excess pore water pressure causes the decrease in effective stresses. Therefore, it is unavoidable to obtain a $K_0$ value of slightly over consolidation in which slightly higher than $K_0$ of normal consolidation. The change of pore water pressure due to the specimen exposure to the cell pressure defined as $u^p$ is measured as the summation $u_i + u_e$. In order to obtain $u_i$ for Eq. (6), $u_i$ has to be estimated by measuring the pore water pressure during pre-withdrawal of container ring. It should be noted that the pore water pressure due to friction $u_i$ gives no effect on Eq. (9).

**Top Cap Interlocking**

The main objective of the newly designed apparatus is to build the simple apparatus for $K_0$ measurement. The simple design of the loading system of COWK triaxial apparatus is shown in Fig. 1(a). This kind of loading system performs properly when the load is increasing. However, the withdrawal of the container ring causes slight inclination of the top cap. This is due to a slight inhomogeneity of the consolidated specimen which then produces some interlocking between the top cap and the hole in the upper plate through which the top cap comes out of the triaxial chamber. Therefore, the change in vertical total stresses, $\sigma_{00} - \sigma_{11}$, in Eq. (9) is very often reduced by the interlocking. The method for estimating the actual change in $\sigma_{00} - \sigma_{11}$ by eliminating the effect of interlocking will be described later.

**Description of Main Components**

Figure 1(a) shows the apparatus with all essential details. The apparatus is made from a precision-machined rigid stainless steel consisting of Perspex cylindrical chamber (14), (200 mm in diameter, 200 mm in height, and 20 mm in thickness), upper and lower end plates (15) and (16) which are connected by three of riser legs (17), shown in Fig. 1(b), located inside the chamber. The chamber is sealed by means of rubber o-rings (18), (19) and silicone grease sealant. The cell is supported by the base plate (20) connected by three of riser legs (21).

The pedestal (7) is screwed in the lower end plate (16). Rubber o-rings are used to provide the seals; one (6) located in the groove at 25 mm from the top of pedestal and the other one (19) in the bottom of pedestal. A ceramic disk (8) (air entry value = 300 kPa) is installed at the top portion of the pedestal to provide the vertical drainage.

The dimension of container ring (2) is 60 mm in internal diameter, 90 mm in height, and 6 mm in thickness. The inside surface of the container ring is coated with chromium in order to reduce the friction. With this diameter size, undisturbed sample taken by thin-walled tube, diameter 75 mm, is also applicable. Furthermore, the thickness of container ring is thick enough for preventing any lateral stain during $K_0$ consolidation. The top cap (12) dimensions are 60 mm in diameter and 90 mm in height. Weight of top cap is 1.972 kg causing the addition of axial vertical pressure of about 7 kPa once it is placed on top of the specimen.

$K_0$ value must be measured under conditions of no volume change and no deformation with the purpose of keeping the effective stresses unchanged. In order to satisfy these conditions, the rubber membrane (3), 0.025 mm thick, is wrapped on the container ring and top cap. Three of rubber o-rings are used to provide the seals; the first one (4) is located on the container ring and fixed its vertical movement by o-ring holders (22), the second o-ring (5) is on the top cap, and the last o-ring (6) is located in the groove on the pedestal.

The withdrawal of container ring is performed by screwing three of the jacking bars (23) against the
container ring by means of wrenches.

**Control System**

Figure 1(b) illustrates the typical COWK triaxial apparatus test set-up. The apparatus is mounted on the consolidation machine. The cell pressure and back pressure tube are connected to the outlets located at the lower end plate and the pedestal outlet respectively by means of 1/8 inch (3.2 mm) copper tube and fitting. Pressure transducers (10), (24) (TEAC 1 MPA model TP-BR1MP) are attached to the BP and CP drainage paths. The cell pressure and back pressure are controlled by the precision regulator (25) and air supply compressor (26).

The axial vertical loading is applied by means of dead weight (27) on loading system of consolidation frame. A load cell (11) (TEAC model TT-FR 10 kN) is connected to the top cap (12) and attached to the yolk (9) for vertical stress measurement. The specimen deformation is measured by the axial dial gauge transducer attached to the stand bar (28) and its tip is sitting on the top of yolk.

The movement fixing of the loading ram is set by supporting the loading plate (29) with a load cell (13) (Kyowa model LC-20KA) mounted on the screwed jack (30) in order to resist and prevent the downward movement of the loading plate shown in Fig. 1(b). For the upward movement prevention, an additional dead weight is placed on the loading plate. The withdrawal distance is monitored by the axial dial gauge transducer (31) placed on top of the jacking bar.

All data are measured by electronic load cell, electronic pressure transducers, and axial dial gauge transducers. The signals from these measuring devices are set to collect at every one second and then are saved to data logger (32) (Kyowa EDX-1500A Digital Memory Recorder/Analyzer) in which data are acquired and stored.

**EXPERIMENT PROGRAM**

**Clay Investigated**

In this study, kaolin is used as the specimen to verify the proposed methods because of many research evidences, convenient in a preparation, homogeneity when purchased commercially, and generally low degree of creep. The type of kaolin used in this study is a white powder marketed ASP100. The liquid limit, plastic limit and specific gravity are 77%, 28% and 2.61, respectively. The slurry kaolin is prepared by mixing kaolin powder with the distilled water at water content of 120–130% by weight. The mixture is then thoroughly stirred by means of a motor-driven rotary mixer at atmospheric pressure for one hour and de-aired under vacuum for another one hour.

**Specimen Preparation**

The slurry kaolin is poured into the container ring and pre-consolidated at 39.2 kPa for one day. The specimen is trimmed into 20 mm in height. The excess soil is extruded out and taken for three samples to determine the water content. The top cap is placed on top of the specimen separated by a filter paper. The container ring is slide up about 12 mm with the aim of providing the distance for pre-withdrawal. The silicone oil is used for lubricating the surfaces between container ring, top cap and rubber membrane. An entrapped air is taken out as much as possible after placing the membrane. Two of the rubber o-rings are placed on the container ring and top cap. The cream silicone grease is painted on the outside of membrane in order to minimize intrusion of the air through the membrane into the specimen during the test. The o-ring holders and riser rods are placed in order to prevent the movement of o-ring at the middle of container ring during withdrawal of container ring.

For the cell assembler, the double o-rings are first placed in the groove of the upper and lower end plate lubricated and sealed by the silicone grease sealant. Three poles of riser rods are screwed on the lower end plate. The Perspex cylindrical chamber is placed on the lower end plate and then the upper plate is placed on the top by orienting the direction of holes right to the riser rods and top cap. All bolts are screwed into the riser rods to assemble all parts together. Next, the load cell is attached on the top cap. The COWK triaxial apparatus is then mounted on the consolidation machine. The center of loading ram is adjusted right to the center of yolk. The jacking bars are placed and fixed on the upper plate. The cell pressure and back pressure lines are connected to the water pressure supply system. At this stage, the pressure transducer and load cell are set the reading to zero relative to atmospheric pressure. The yolk is lowered down to sit on the load cell and connected together. The water is filled into the chamber via the air-bleed valve. Finally, the chamber is fully filled by silicone oil (Shinetsu KF-96-3000CS) in order to retard the cell water to leak out through the small gap between the top cap hole on the upper plate.

**Consolidation**

Consolidation is performed by step-wised incremental loading. The specimen is loaded by the dead weight. Since the specimen is preconsolidated at 39.2 kPa, the total vertical stresses of 100, 200, and 300 kPa are selected to consolidate the specimens before withdrawal of container ring to measure $K_o$.

The loading preparation is suggested by following procedures. Firstly, for example of consolidation at vertical effective stress of 100 kPa, gradually increase the cell pressure to 300 kPa while the drainage valve is closed. Secondly, the vertical loading of 200 kPa is applied to the specimen by means of dead weight. Thirdly, gradually increase the back pressure to 200 kPa and then open the drainage valve. The specimen is under the equilibrium condition because the previous vertical loading is canceled by the back pressure. Finally, the additional vertical loading of 100 kPa is applied to consolidate the specimen.

The measurement of pore water pressure in undrained condition allows calculating the pore pressure coefficient.
Withdrawal of Container Ring

The withdrawal of container ring as stated in previous section will be explained here in detail. The pre-withdrawal procedure is needed to perform in order to make the specimen fully consolidated under the applied (intended) vertical load and to estimate the pore water pressure generated by the cut of side friction. After the primary consolidation is completed, the drainage valve is closed to provide the undrained condition. Then, the jacking bars are gradually screwed downward against the container ring. The withdrawal distance is monitored by a dial gauge transducer attached on the top of jacking bar. The change in pore water pressure $u_1$ is recorded during the pre-withdrawal of container ring. After finishing the pre-withdrawal at each step, the drainage valve is opened to allow the specimen to further consolidate. Total length of pre-withdrawal is determined by the set up level of container ring plus the specimen deformation after consolidation $(12 + \Delta d)$ mm. Two times of pre-withdrawal of averagely 5 mm are performed at each step.

Finally, the last step is the full withdrawal of container ring to expose the specimen to the cell pressure directly applied to the specimen through the rubber membrane. The drainage valve is closed out of back pressure. The movement of loading ram is fixed as described earlier. At this stage, there is a small change in pore water pressure possibly due to a slight disturbance in the mechanical loading system of the consolidation machine. Therefore, the new record of pore water pressure and vertical load are updated to use in the calculation.

Pore Pressure Measurement

The response of pore pressure induced by change in total stress under undrained condition is usually expressed by Skempton’s pore pressure coefficient $A$ and $B$ (Skempton, 1954):

$$\Delta u = B[\Delta \sigma_1 + A(\Delta \sigma_1 - \Delta \sigma_3)]$$

In partially saturated soils, the compressibility of the pore fluid is appreciable due to the presence of pore air resulting in a pore pressure parameter lower than 1.00. The value higher than 0.95 is generally accepted as satisfiable enough for any practical test. However, the change in $u_1$ is somewhat influential to $K_0$ value in Eq. (6) when the vertical effective stress is low. To obtain more reliable $K_0$ from Eq. (6), the correction of pore pressure measurement is needed to apply.

For the fully saturated and partially saturated specimen, the response of pore water pressure is illustrated in Fig. 3. In this study, the pore pressure parameter is measured while specimen is covered by the container ring. Thus, Eq. (10) is reduced to $\Delta u = B \Delta \sigma_1$. The incremental dead weight of 10 kPa is used to apply the vertical loading to the specimen under undrained condition and then the response of the pore water pressure is measured. The response curve for not fully saturated specimen could be obtained from these data. This response curve will be used for $u_1$ correction later.

Estimation of Top Cap Interlocking

As stated earlier, due to a slight inclination of the top cap caused by inhomogeneity of the consolidated specimen, some interlocking results around the top cap and its hole in the upper plate after withdrawal of container. This amount of interlocking can be checked after withdrawal of the container ring by applying the vertical load to the specimen. This additional application of the vertical load brings the specimen into a state of undrained compression. The relationship of principal stress difference $\Delta q$ and the axial stain during this undrained compression process is used to estimate the total stress change, $\sigma_{00} - \sigma_{11}$ in Eq. (9), because the axial strain starts to increase only after the vertical compressive load becomes large enough to overcome the interlocking between the top cap and the hole in the upper plate of the cell through which the load is transmitted to the top cap as shown in Fig. 4.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Some of the results obtained by the new apparatus are
described in this section. Since the measured quantities show the similar characteristic, only the result for the case of $\sigma'_v = 105$ kPa is described in detail here.

**Estimation of $u_f$**

Figure 5 shows the pore water pressure induced by pre-withdrawal under undrained condition. Also, the other tests show the similar characteristics. It can be seen that pore water pressure increases after each of pre-withdrawal of container ring. The first step of pre-withdrawal gives the peak and subsequently increasing residual values of the pore water pressure generation. After opening the drained valve to release the excess pore water pressure, the specimen further consolidates as shown in Fig. 5 for the vertical displacement of specimen and time relation. This further displacement is large in the first step and smaller in the next step indicating the success of the side friction cut.

**Full Withdrawal of Container Ring**

Figure 6 shows the measurement of load cell and pore pressure transducer for the full withdrawal of container ring. The pore water pressure and load cell increase while the container ring is being withdrawn. Very small amount of vertical displacement in the extension side is observed after completion of withdrawal. It is inevitable to have this type of displacement because a change of force makes the diaphragm inside the load cell to deform.

**$K_0$ Determination**

**By Pore Pressure Transducer**

From Figs. 5 and 6, $u_i$ is about 32 kPa and $u^*$ is about 254 kPa. Thus, $u_i$ obtained by $u = u^* - u_i$ is 222 kPa. Nevertheless, it is necessary to correct the value of $u_i$ by considering the saturation of specimen. After the completion of primary consolidation but before performing pre-withdrawal of container ring, the pore pressure parameter was measured by applying five incremental vertical loadings of 10 kPa (total $\Delta \sigma_1 = 50$ kPa) on specimen under undrained condition by means of dead weights in order to estimate $B$ value as described earlier. The data points were used for constructing a fitting curve based on linear relationship as shown in Fig. 7. Substitution of $u_l$ in the curve fitting equation yields the corrected $u_i$ equal to $223$ kPa. Then, substitution of corrected $u_i$ in Eq. (6) yields $K_0$ by means of pressure transducer equal to 0.72.

**By Load Cell**

The correction of $K_0$ values by means of load cell is performed after pore water pressure change due to full withdrawal of container ring becomes constant. Figure 8 shows the increment of principal stress difference $\Delta q$.
against axial strain in triaxial compression after measuring $K_0$ based on the pore pressure transducer. It can be clearly seen that principal stress difference is increasing while the axial strain is zero. However, the principal stress difference calculated by using the average cross sectional area; $A = A_0(1 - e_v)/(1 - e_a)$ shows a band as shown Fig. 8(a) due to resolution of the dial gauge transducer within the range of about 0.008 mm (in Fig. 8(b)). The position that the specimen started to deform is not obviously noticeable from Fig. 8(b) but shows the transitional trend instead. Thus, the lower (14 kPa) and upper (32 kPa) possible values were considered as interlocking ($s_{v0} - s_{v1}$). Additionally, the authors also chose the mostly likely value of ($s_{v0} - s_{v1}$) as 24 kPa. $K_0$ values by means of load cell obtained by substitution into Eq. (9) were 0.77, 0.60, and 0.68 for lower, upper and most likely values of respectively.

Table 1 shows the summary of test results both normal and overconsolidated kaolin specimen. The initial water contents are comparable except for Test 1 which is a little bit lower than the others. The $B$ value tends to low as the vertical effective stress and overconsolidation ratio increase. $K_0$ values of normally consolidation are falling in the range of 0.71–0.75 for Eq. (6) and 0.68–0.76 (most likely value) for Eq. (9) both pore pressure transducer and load cell measurements. Also, $K_0$ values of overconsolidated specimens are higher as expected from the past studies (Brooker and Ireland, 1965; Wroth, 1972; Abdelhamid and Krizek, 1976; Edil and Dhowian, 1981; Mayne and Kulhawy, 1982; Garga and Khan, 1991; Mesri and Hayat; 1993; Ting et al., 1994).

**Table 1. COWK triaxial test summary**

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<tr>
<th>Test</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>Initial water content, $w_i$%</td>
<td>71.85</td>
<td>77.71</td>
<td>78.44</td>
<td>79.77</td>
<td>78.59</td>
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<tr>
<td>Initial void ratio, $e_0$</td>
<td>1.88</td>
<td>2.03</td>
<td>2.05</td>
<td>2.08</td>
<td>2.05</td>
</tr>
<tr>
<td>Void ratio at $\sigma_v$, $e_{v'}$</td>
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<td>1.49</td>
<td>1.41</td>
<td>1.55</td>
<td>1.41</td>
</tr>
<tr>
<td>$B$ value</td>
<td>0.96</td>
<td>0.90</td>
<td>0.84</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td>$\sigma_v'$ (kPa)</td>
<td>105</td>
<td>203</td>
<td>301</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>OCR</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

$K_0$ by means of pore pressure transducer

| $u_1$ (kPa) | 32  | 24  | 29  | 13  | 21  |
| $u^*$ (kPa) | 256 | 264 | 263 | 300 | 291 |
| Corrected $u_1$ (kPa) | 224 | 246 | 277 | 304 | 299 |
| CP (kPa) | 300 | 399 | 499 | 399 | 399 |
| $K_0$ from Eq. (6) | 0.71 | 0.75 | 0.74 | 0.90 | 0.95 |

$K_0$ by means of load cell

| Corrected $\sigma_{v0} - \sigma_{v1}$ (kPa) | Lower | 14 | 33 | 55 | 91 | 84 |
| Most likely | 24 | 41 | 74 | 94 | 90 |
| Upper | 32 | 49 | 85 | 100 | 94 |
| CP-BP | 95 | 196 | 291 | 193 | 193 |

| $K_0$ from Eq. (9) | Lower | 0.77 | 0.80 | 0.78 | 0.97 | 1.04 |
| Most likely | 0.68 | 0.76 | 0.72 | 0.94 | 0.98 |
| Upper | 0.60 | 0.72 | 0.68 | 0.89 | 0.94 |

**COMPARISON**

**Verification of $K_0$ by means of $K_0$ Triaxial Consolidation Test**

In order to verify the test results of COWK triaxial apparatus, the estimation of $K_0$ value, based on the concept that the ratio of the volume of water dissipated from the specimen to cross sectional area of specimen equals to the specimen vertical displacement, is carried out; $\Delta h = \Delta V/A$, where $\Delta h$ = specimen height change, $\Delta V$ = volume of dissipated water measured by burette, and $A$ = specimen cross sectional area.

$K_0$ triaxial consolidation test is performed on the specimen after COWK triaxial test without experiencing
undrained compression described in the previous section. The result is shown in Fig. 9. The specimen prior to the $K_0$ triaxial consolidation is in $K_0$ condition after completion of the withdrawal of the consolidation ring. The process is as follows. The increment of cell pressure laterally consolidates the specimen. In order to make the specimen return to $K_0$ condition, the vertical loadings are applied to the specimen until the vertical displacement becomes equal to the ratio of the volume of dissipated water to specimen cross sectional area after primary consolidation completed. Consequently, the specimen is returned to $K_0$ condition again at higher stress level. Three steps are performed at the cell pressure of 300, 350 and 400 kPa.

It is found that $K_0$ values are falling in the range of 0.72–0.74, agreeing well with the previous method using COWK apparatus.

Considering the time consumption and cost of operation, $K_0$ triaxial consolidation test requires longer time for consolidating the specimen returning to $K_0$ condition per one step; more than ten times as shown in Fig. 9 as the data points on the path, while the proposed method required only few steps of consolidation; for estimating $K_0$ value. Moreover, for those complicated apparatuses for $K_0$ triaxial consolidation, listed in laboratory methods in INTRODUCTION, it should be more expensive than the simple apparatus used in this study.

**Compare to $K_0$ Estimated from Conventional Oedometer Tests**

Tavenas et al. (1975) suggested that the value of the ratio of horizontal to vertical preconsolidation pressures is a practical solution to the problem of $K_0$ determination.

The same slurry kaolin is preconsolidated in a consolidometer, 200 mm in diameter, at a pressure of about 145 kPa. Then, the specimen is half divided with 100 mm in height and filmed with paraffin before use. The samples are trimmed in horizontal and vertical planes and tested in the Oedometer. Figure 10 shows the test results of three specimens. The vertical line, appeared in $e - \log \sigma'$ between 100–200 kPa, (10 kPa of interval) can be used as a guide line for reading preconsolidation pressure. The test O-1 and O-2 are tested under the same loading condition. It can be seen that the preconsolidation pressure on the vertical and horizontal planes are in the range of effective stresses 100–160 kPa. Thus, the special sub loading steps are paid in Test O-3 by applying incremental loading of 10, 20, 20, 20 kPa to the specimen in the range of the vertical stress of 80 to 160 kPa. The interpretations of preconsolidation pressure shown.
Table 3. Indirect determination of \( K_0 \) for normally consolidated soils

<table>
<thead>
<tr>
<th>( K_0 ) equation</th>
<th>Reference</th>
<th>( K_0 ) for Kaolin ( \phi' = 25^\circ, I_p = 49 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_0 = 1 - \sin \phi' )</td>
<td>Jaky (1948)</td>
<td>0.57</td>
</tr>
<tr>
<td>( K_0 = 0.9(1 - \sin \phi') )</td>
<td>Jaky (1944) in Ref. 1, Fraser (1957)</td>
<td>0.52</td>
</tr>
<tr>
<td>( K = \left{ \frac{1 + \frac{2}{3} \sin \phi'}{1 + \sin \phi'} \right} (1 - \sin \phi') )</td>
<td>Jaky (1944) in Ref. 1</td>
<td>0.51</td>
</tr>
<tr>
<td>( K_0 = \tan\frac{45^\circ - 1.15(\phi' - 9^\circ)}{2} )</td>
<td>Rowe (1957), Abdelhamid and Krizek (1976)</td>
<td>0.52</td>
</tr>
<tr>
<td>( K_0 = 0.95 - \sin \phi' )</td>
<td>Brooker and Ireland (1965)</td>
<td>0.52</td>
</tr>
<tr>
<td>( K_0 = 0.44 + 0.42 \frac{PI}{100} )</td>
<td>Massarsch (1979)</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 4. Indirect determination of \( K_0 \) for overconsolidated soil

<table>
<thead>
<tr>
<th>( K_0 ) equation</th>
<th>Reference</th>
<th>( K_0 ) for Kaolin ( \phi' = 25^\circ, \ PI = 49 )</th>
<th>( OCR = 2 )</th>
<th>( OCR = 3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_0 = 1 - \sin (1.2\phi')(OCR)^{0.233 \log PI} )</td>
<td>Schmidt (1967)</td>
<td>0.71</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>( K_0 = (0.19 + 0.233 \log PI) \times OCR^{0.34} \cos \frac{\pi I_p}{2\pi} )</td>
<td>Kenney (1959)</td>
<td>0.80</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>( K_0 = 0.71 )</td>
<td>Alpan (1967)</td>
<td>0.77</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>( K_0 = 0.71 \sin \phi'(OCR)^{0.05} )</td>
<td>Mayne and Kulhawy (1982)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Researchers as shown in Table 4.

By comparison, the laboratory \( K_0 \) values are higher than the correlation equations for normally consolidated soil. Moreover, \( K_0 \) value of OCR = 2 from the laboratory test does not match well with those equations. On the contrary, very good matching is obtained in the case of OCR = 3. For the overconsolidated soil, the empirical equation proposed by Alpan (1967) gives \( K_0 \) value reasonably close to the experiment results in this study. However, more investigation at higher overconsolidation ratio are needed.

It can be seen that the correlation equations give \( K_0 \) estimation which are close to each other but those values are lower than the laboratory result in this study. Since Jaky (1944) proposed the equation for estimating \( K_0 \) value as a function of critical state parameter (internal angle of friction), some researchers; Hendron (1963), Wroth (1972), Mayne and Kulhawy (1982) also proposed the equations as a function of critical state parameter. Recently Watabe et al. (2003) noticed that the definition of \( \phi' \) should be concerned in order to estimate \( K_0 \) value. They reported that the use of \( \phi' \) corresponding to a critical state and peak state gives \( \pm 0.05 \) difference of \( K_0 \) value from their laboratory results. Nevertheless, Michalowski (2005) revised Jaky's equation and concluded that this equation is a reasonable prediction which is somewhat coincidental due to the state at rest of soil below the critical state level. Consequently, it can be seen that the use of empirical equation to estimate \( K_0 \) value is still ambiguous and seems not to be precise enough especially for the work such as the initial conditions for soil/water coupled finite element analysis in which \( K_0 \) is an essential input parameter such as Sekiguchi and Ohta (1977), Hashiguchi and Chen (1998), Asaoka et al. (2002), and Dafalias et al. (2003).

Consequently, from the test results, it can be concluded that the performance of COWK triaxial apparatus is practical enough for estimation of \( K_0 \) both normally and overconsolidated soil with many advantages over the existing \( K_0 \) estimation methods such as less time consumption, and low cost of operation.

in Table 2 are obtained by Casagrande's (1936) suggestion by three of staffs in the laboratory who are not involved with this study. It can be seen that \( K_0 \) values from this method vary due to preconsolidation pressure differently estimated by each of the interpreters. The \( K_0 \) values 0.83–0.96 with the average of 0.89 are higher than those obtained by the two previous methods.

**K₀ from Empirical Equation**

Many researchers have proposed empirical or semi empirical correlations of \( K_0 \) with the angle of shearing resistance and plastic limit as shown in Table 3. In this study, the effective angle of friction obtained from constant volume shear box test shown in Fig. 11 is \( \phi' = 25^\circ \) and the plasticity index \( I_p \) of kaolin from the laboratory test is \( I_p = LL - PL = 77 - 28 = 49 \).

Moreover, the correlation equations of \( K_0 \) for overconsolidated soil have also been proposed by some
CONCLUSIONS

In view of the theory and experiments presented in this study, the following conclusions can be drawn:

— The estimation method of $K_0$ values using COWK (Cambridge-Ohta-Wrotch-Kyoto) triaxial apparatus is proposed both from theory and experimental technique.

— Kaolin clay is used as a soil specimen in the verification the performance of COWK triaxial apparatus. $K_0$ values from the proposed method fall in the range of 0.68–0.75 for normally consolidated kaolin sufficiently well agreeing with $K_0$ triaxial consolidation method.

— The estimation of $K_0$ of kaolin based on Oedometer tests on vertical and horizontal samples suggested by Tavenas et al. (1975) has a difficulty in estimating the preconsolidation pressures which are different by interpreter. Moreover, $K_0$ value tends to be higher than the other methods.

— Empirical correlations of $K_0$ both of normally and overconsolidated soils proposed by many researchers give $K_0$ values lower than experimental study except the correlations proposed by Kenney (1959) and Alpan (1967). However, the use of empirical equation seems not to be precise enough especially for the work that needs the accuracy in calculation result.

— The COWK triaxial apparatus has many advantages over the existing methods in the aspects such as the simple device, comparable result to $K_0$ triaxial consolidation, less time consumption and low operation cost.

REFERENCES


for automatically simulating $K_0$ consolidation and $K_0$ swelling in the conventional triaxial cell, *Geotechnique*, 27, 593–596.


