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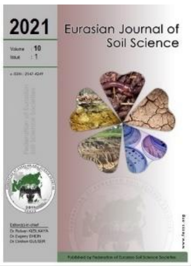

# Compressibility behaviour and engineering properties of North Borneo Peat Soil

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## Abstract

It is known that peat soil is highly compressible. A constituent of peat soil from Klias, Sabah covering a wide range of index properties of fiber contents, specific gravity, organic contents and moisture contents were subjected to one-dimensional consolidation tests. This paper presents the engineering properties and compressibility behavior of sapric type of tropical peat soil. In this role, the high compressibility of Klias peat stands out as a most significant engineering property. With this intention, the purpose of this paper is to provide a simple and analytical means for predicting the consolidation settlement of sapric peat deposit under loading. The rate of primary compression, after a certain time. Increases with the logarithm of time. Loading applied from low stress to high stresses started from 2, 6.25, 12.5, 25, 50, 100 and 200 kPa resulting in high compression index, $C_c$ and ratio, $C'_c$. The Klias peat soil represented sapric type of tropical peat with organic content is 98.43% and lower fiber content which is about 18% of the specimen. Compressibility index $C_c$, Coefficient of consolidation $C_v$, and Compression index, $C_c$, was identified as a crucial component of parameters in determination of settlements behaviour of peat soil. The coefficient of consolidation, $C_v$, was determined within the range of 1.264 to 12.911 $cm^2$/min and requires special considerations in laboratory testing procedures and interpretation of results.

**Keywords**: One-dimensional, peat, soil, settlement, behaviour, coefficient of consolidation.

## Introduction

Peat soil occur mainly in Southwest Sabah, or more precisely in northern part of Borneo island particularly on the Klias Peninsular, Lumadan, Bukau api-api and lower Kinabatangan area in west coast Sabah. Access into the area was by Kg. Luagan, Beaufort of or Lumadan agricultural area. The composition of peat soil consists of fragmented decayed plant material, organic matter and fibrous material. Peat is an organic soil which consists more than 70% of organic matters. Peat deposits are found where conditions are favorable for their formation and peat possess high organic content (Duraisamy et al., 2007; Zainorabidin and Mohamad, 2016b; Mohamad et al., 2020)

The high compressibility exists in unconsolidated state and cause an excessive settlement. The situation is also stressed (Jorat et al., 2013) where, the differential settlement or failure in structures built on such soils. Embankment technique to accelerate settlement by using granular material, clay or equivalent material that have high bearing capacities has been implemented in various method to enhance embankment stability

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issues associated with embankment construction on peat soils. Under those circumstances, this study performed to investigate the plastic deformation void-ratio reduction or known as settlement behaviour with function of time.

General characteristics and intrinsic properties of peat soil which is soft and easily compressed (Zainorabidin and Mohamad, 2015) is essential to develop reliable method and assess the settlement coefficient when a load applied to a saturated peat soil. Settlement behaviour of peat soil in Sarawak, which is located in northwest Borneo Island, the average compression index, $C_c$ was found for the undisturbed peat soil specimen test is 5.37 and ratio of $C_\alpha/C_c$ measured is 0.05 (Akeem et al., 2019). In particular, due to peat high compressibility properties and low shear strength material soil with known as heterogeneous behaviour, peat viewed as complexity geotechnical material (Mesri and Aljouni, 2007; De Guzman and Alfaro, 2018). In natural state, the fibrous peat exhibits large vertical strains and provides stiffness to stresses that are in an approximately vertical direction (Landva and Pheeney, 1980; Hendr et al., 2012).

The definition and method of testing mainly derived from peaty soils review in (BS 5930, 2015). Peat categories classified based on the extent and type of fibre content which are fibrous peat (>66% fiber), hemic (33-66% fiber) and Sapric (< 33% fiber) (Bujang, 2004). Oedometer test on peat were statistically analyzed for more than 2000 sets as a novel method for predicting the settlement of peaty grounds. The Noto method (Noto, 1991) was able to adequately reproduce the primary consolidation rate of peat. Due to the facts that they mainly cause large and primary long-term settlement, peat unsuitable for supporting structures (Mesri et al., 1997; Ajlouni, 2000; Munro and MacCulloch, 2006; Gofar and Sutejo, 2007). The $\alpha$ of peat was within the range of -0.55 to -0.9 (Oikawa et al., 1995). These values are smaller compared to Terzaghi's theory. From that, it is found that the primary consolidation rate of peat is higher in the early phase and lower in the later phase

With the aim of providing helpful information to geotechnical engineers for practical works and sufficient understanding on peaty grounds. This paper shows data on the settlement and compressibility behaviour of peat soil from Klias, Sabah, as well as analyses of the engineering parameters.

## Material and Methods

Samples were collected from Klias, Beaufort, Sabah as shown in Figure 1, Location of Klias, Sabah in northern part of Borneo Island. in undisturbed form and carefully transported to laboratory located in Universiti Malaysia Sabah (UMS). A detail description on classification of peat soil is significant to describe the physical appearance of soil based on the Von Post classification. The results of peat soil consolidation test for Klias peat soil are very much helpful in adding to information and providing knowledge in general for Klias peat. Certainly, results of consolidation test for Klias peat soil will help designer or engineer learn the special considerations from Coefficient of consolidation ($C_v$) and Compression Index ($C_c$) in order to design of a specific need on peat soil such as embankment and design of foundations.

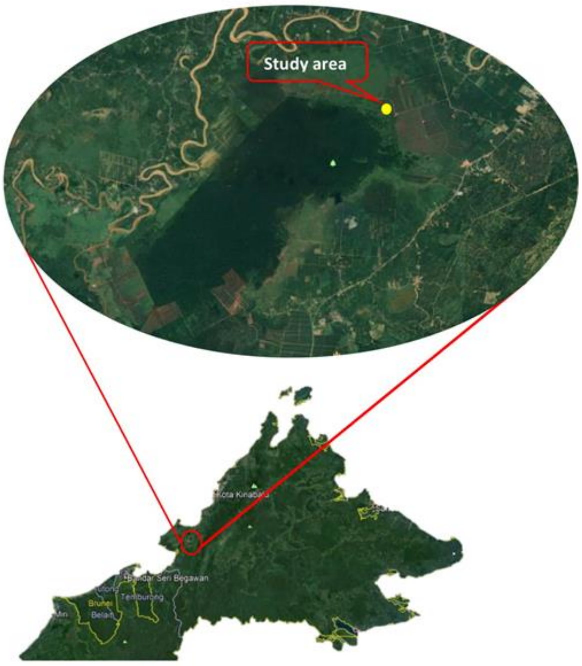

Figure 1. Location of Klias, Sabah in northern part of Borneo Island.

### Experimental design and laboratory work

The process of sampling are divided into two general categories, disturbed and undisturbed sampling methods which uses different method. Since clearing and grubbing done, excavation work started from removing top soil and up to 0.5 m depth beneath ground level evenly. Disturbed sample used as sampling to determine the characterization of peat and description of peat. Visual observation on the peat soil are done after collecting disturbed sample as mentioned according to Von Post classification system. Undisturbed samples allow this study to identify the properties of compressibility, as well as the fracture patterns among others. In this study, the depth requirement is up to 0.5 m depth. Tube sampler using PVC with size 50 mm diameter and 160 mm height. Drive samplers are pushed into the soil without rotation, displacing the soil as they penetrate.

Figure 2 shows the natural condition as location of sampling site in Klias at agricultural land bordering gazetted forest reserves. The area of peatlands have been exploited for agriculture at the left side and remained forestry area. Figure 3 shows the peat profile at 1.0 m below ground level, excavated by using peat sampler. In general, it seems fiberless, extremely soft and loose. These physical characteristics are generally in line with the statement which is, in Lumadan, Sabah (Zainorabidin and Mohamad, 2016a), the peat was fibreless, very soft and succulent.

Figure 2. Klias peat soil sampling site at agricultural land bordering gazetted forest reserves.

Figure 3. Peat soil condition below 0.5 m from ground surface

### Specific gravity, moisture content and pH test

In laboratory testing, the specimens of peat are workable with kerosene to determine the specific gravity rather than water. Water causes the particles of specimens floating and is difficult to determine the specific gravity. From the results, the specific gravity ($G_s$) observed that, Klias peat has 1.42. In this study, the moisture content determined using oven-dry method at 105°C from peat samples that was prepared from natural condition.

As seen in Table 1, the percentage of moisture content for Klias peat specimens is about 682%. While (Zolkefle, 2014) found peat can be reached up to 900%. In describing the salinity of peat soil, pH test are conducted. Klias peat has 4.25 at 1.0 m indicated as acidic. Due to different locations and natural activity decomposition matter, this is influenced the acidic factor of peat soil itself. When compared to other researchers, (Saadon et al., 2015) found that pH level of Sarawak peat ranges from 3.2 to 4.3 and acidic.

### Liquid limit, organic content and fibre content test

The liquid limit of the soil is the moisture content corresponding to a cone penetration of 20mm and fitted with 35mm long cone of stainless steel with an angle of 300 ± 1 sinks exactly 20 mm into a cup of remolded soil in a 5s period. Table 1 shows the results of liquid limit test for Klias peat. Furthermore, the liquid limit was in the range of 200 % to 500 % as reported (Bujang, 2004) in West Malaysia. The organic content is the ratio, expressed as a percentage, of the mass of organic matter in a given mass of soil to the mass of the dry soil solids. The organic content in this study was determined by using the loss of ignition (LOI) test. From Table 1, it showed the percentage of organic content for Klias peat is about 98.43%. (Duraisamy and Bujang, 2008) proposed that the organic content for peat from 70% to 80%.

On the other hand (Boyland and Long, 2014), peats which are formed from the accumulation of organic materials over thousands of years, are characterized by its high-water content, compressibility and low shear stiffness and shear strength. However, in soil sciences, the soils that have organic content more than 35% are classified as peat. However, in soil sciences, the soils that have organic content more than 35% are classified as peat. In addition to that, the definition of peat according to the (ASTM D4427, 2013), peat is defined as soil that is naturally available with high organic substance that is derived primarily from plant materials.

Fibre content determined from dry weight of fibres retained on 0.15 mm as a percentage of oven-dried mass and being set in the oven at 105°C. This study led for determining the quantity of fibres in a peat sample and it's also a significant parameter in predicting or defining the samples. In this study, Klias peat has 18% fibre content. By means of this, all peat sample in this research are classified with sapric peat which are formed with moderately to well decompose organic materials with 1 – 33% of fibre content.

Table 1. Index properties of Klias, North Borneo Island peat soil.

| No. | Parameters | Sample 1 |
|---|---|---|
| 1. | pH | 4.250 |
| 2. | Specific gravity, $G_s$ | 1.420 |
| 3. | Area of specimen, $cm^2$ | 19.634 |
| 4. | Moisture content, % | 682 |
| 5. | Fiber content, % | 18 |
| 6. | Organic content, % | 98.430 |
| 7. | Von Post classification | H4 |
| 8. | Peat type | Hemic |

From observations, peat has a high uncertainty margin. Uncertainties and difficulties of testing of peat soil to determine the strength with very high compressibility, which presents significant challenge in developing peat behaviour in research. Peat contains high water content hence causing the material to be very sensitive and soft. This is why many researchers described peat as a challenging soil.

### Oedometer test

The load transferred to the bottom pressure head is measured, and the friction in the oedometer ring is back-calculated (Michael et al., 2016). It was found that the friction has insignificant effect on the compression index, whereas swelling and recompression stiffness are influenced. Figure 4 shows the schematic drawing of floating-ring type which is employed in this study. The specimen size is about 20 mm thick and 50 mm in diameter. Specimen placed in a confining metal ring (19.63 $cm^2$).

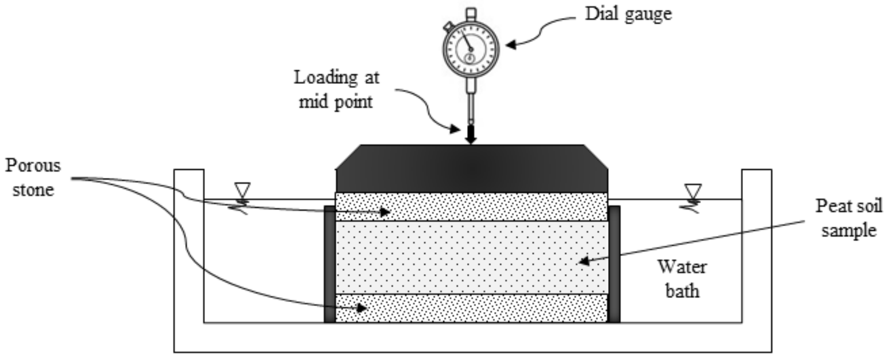

Figure 4. Schematic drawing of floating ring consolidometer setup for Klias peat soil.

### Consolidation testing programs

The peat soil specimen was projected about 5 mm on both end side of metal ring and trimmed the excess soil content on top and bottom by using spatula. Porous stones that have been saturated by submerging 4 hours in distilled water then placed in bottom and top metal ring. The consolidation test was proceeded by applying loads in a geometric progression started from low stress applied to high moderate loading, 2, 6.25, 12.5, 25, 50, 100 and 200 kPa with a load ratio.

$$\frac{\Delta p}{p} = 1 \tag{1}$$

Low stress applied to the peat soil is essential method that significant to its natural state which is highly compressible. To avoid quick settlement and unreliable consolidation measurements, first load increment of 2 kPa is applied and watch immediately started. Against time, the specimen was reliable compared to immediate high loading applied. It appears that, if the increment ratio as shown in Equation 1 is not large enough, the peat soil specimen internal resistance built against the load. The total deformation tends to less than in Equation 1. For each load increment, the specimen is reached the primary consolidation within 24 hours, in general.

The total volume of peat soil sample is determined from the initial height $H_i$ of the sample and the area $A$ to the Equation 2 as follow.

$$V_t = V_s + V_w \tag{2}$$

The changes in thickness at the end of each loading step used in determination of the Swelling Index ($C_s$), Compression Index ($C_c$) and the coefficient of consolidation ($C_v$). Figure 4 shows the consolidometer apparatus of Klias peat soil with incremental loading of oedometer test.

The unloading phase started once the 200 kPa loading completed and decremental of loading are set to be 50, 25, 12.5 and 6.25 kPa. Peat soil sample is carefully removed and its thickness and water content is measured when the test ended.

Subsequently, the height of the soil solids are computed after the oven-dried the soil cake. The total change in height of peat soil ΔH determined by using the Equation 3.

$$H_f = H_{Initial} - \Delta H \tag{3}$$

Which the $H_f$, is initial sample height and use of dial gauge readings. From that formula, the height of solids, $H_s$ (Equation 4) is

$$H_s = H_f - \frac{V_{wf}}{A} \tag{4}$$

$A$ is the area of consolidometer ring, while the initial height of voids are determined and computed by using Equation 5.

Figure 5. Laboratory testing of Klias peat soil with incremental loading of oedometer test.

$$H_v = H_{Initial} - H_s \tag{5}$$

Consolidation test of peat soil obviously removed the void ratio and the thickness of the peat sample be reduced. The soil particle and fibrous material in peat rearrange to create a tighter or compacted coin shape with lower void ratio. Following the change in height, the initial void ratio, $e_i$ determined with this Equation 6.

$$e_i = \frac{H_v}{H_s} \tag{6}$$

Compression index, $C_c$ determined from the straight-line part of the semilog plot of void ratio vs. log pressure as shown in the Equation 7. Accordingly, the swell index, $C_s$ obtained from the curve of unload branch in Equation 8. On account of the compression ratio $C'_c$ its defined as in Equation 9.

$$C_c = \frac{\Delta e}{\log p_2/p_1} \tag{7}$$

$$C_s = \frac{\Delta e_s}{\log p_2/p_1} \tag{8}$$

$$C'_c = \frac{\Delta \varepsilon}{\log p_2/p_1} \tag{9}$$

Coefficient of consolidation $C_v$ defined at the time 50 percent of consolidation, $t_{50}$ as in the Equation 10 as follows.

$$C_v = \frac{TH^2}{t} \tag{10}$$

Where $T$ is the time factor for $U$ = 50 percent (0.197), $t = t_{50}$, and the $H$ is the average length of the longest drainage path during the increment of load application.

## Results and Discussion

At the end of the consolidation test, the water content was calculated and the oven dry weight of peat soil, $W_s$ is 13.21 g. The height of solids, $H_s$ computed from Equation 5 is about 0.47381 cm. The sample cross sectional area, $A$ computed is 19.634 cm$^2$. As the stress increased from 2 kPa to 200 kPa, the internal friction influenced the mean settlement of peat soil. The initial height of sample, $H$ is 20 mm. The oedometer initial void ratio, $e_o$ that calculated from the oedometer test was 3.221.

### Coefficient of consolidation

Casagrande method were interpreted to this study (Casagrande, 1936) as shown in Figure 6. To identify the apparent coefficient of consolidation, $C_v$ for Klias peat soil, the stress-strain dial reading-log time curves were analysed using the same theory (Casagrande, 1936) in Figure 7. As seen from the Figure 6, the maximum obtained coefficient of consolidation, $C_v$ at various levels were very different. The highest $C_v$, was determined at lowest stress or at the beginning of loading stage, 2 kPa with 12.911 cm$^2$/min. Which was mainly due to the acceleration of stress and settlement. At this stage, the void ratio is considered high and the internal friction is still developed.

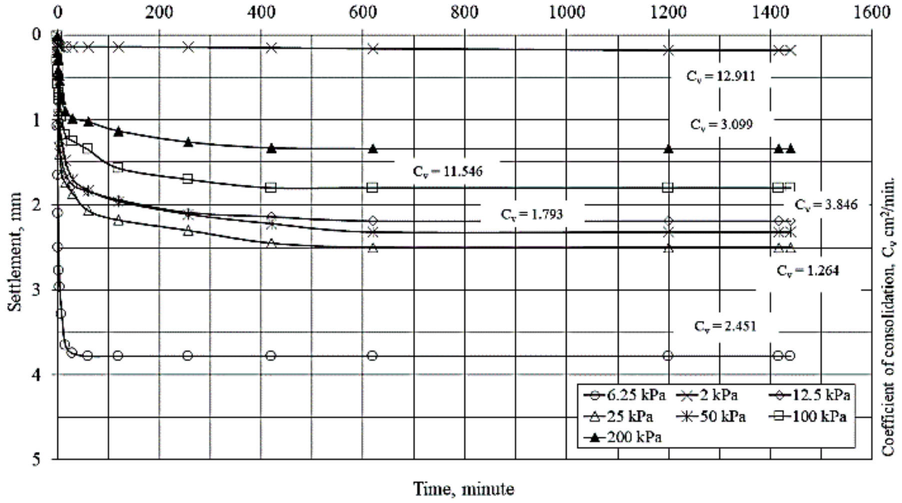

Figure 6. Coefficient of consolidation, $C_v$ for Klias peat soil

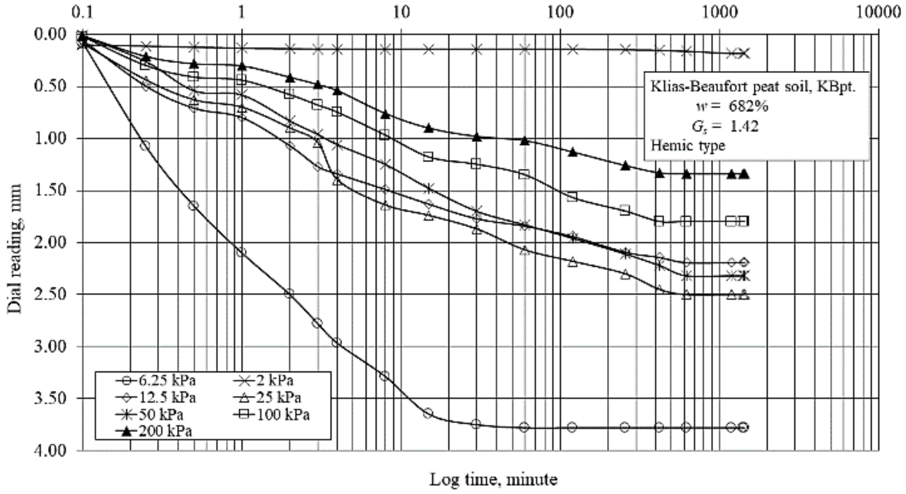

Figure 7. Dial reading versus time curves (log time, min.).

Prior loading stage, the initial void ratio is 3.221 and at the end of stress level 2 kPa, the void ratio decreased dramatically to 3.183, this is showing that, at even low and moderate loading, peat compressibility is high and void of ratio decreased simultaneously. This regime of void ratios decrement was continuously up to the 200 kPa. The internal friction acted on the first loading stepped causing the peat soil specimen getting dense or compressed. The loading was continued to 6.25 kPa and settlement was then recorded.

Obviously, due to the preloading process of 2 kPa, the void ratio continued stress with higher loading stress. Unfortunately, the void ratio value was less than previous loading. This is happened due to the loading and specimen reacted vertically compressed governed by the internal friction. The specimen was developed its internal friction due to the specimen has become denser and the particle was break from larger void, fall apart into small fragments, especially over a period of time as part of a process of settlement. The friction acted in the perpendicular direction of the applied load increment, which is contributed to the settlement and peat specimen compressed vertically. The stress at the bottom pressure was same when the specimen was in loading from top and vice versa when in unloading where sample swell accordingly. The individual specimens were then loaded up to 25 kPa, 50 kPa, 100 kPa and 200 kPa. The specimen dwindles against settlement. The increment of stress, (σ) kPa is in line with the contraction of coefficient of consolidation, $C_v$.

This situation is constant and settlement rates continue to be consistent with the removal of the void. Thus, peat has observably reacts toward loading in quick time and short time. The higher the load, the higher the settlement occurred. This is due to the restructuring of particles and fibers in peat soil that occurs with the removal of the void.

### Dial reading versus time curves

The alternate loading reacts as stress applied to the peat soil specimen. At the end of primary consolidation test, the result compiled at plotted to time, t-log (min) vs dial reading (mm) as shown in Figure 7, where each loading plotted from 2, 6.25, 12.5, 25, 50, 100 and 200 kPa. The appearance of curve depending on stress applied and degree of consolidation for each loading stage. Obviously, the trendlines expressed as the corresponding to 50 percent, % consolidation, $D_{50}$ at a given time within a soil mass under a given stress consolidation.

Thereupon, dial reading vs $\sqrt{time}$, were plotted to determine $Do$, where a straight line drew through the first several plotted points and the line extended until intersected in the ordinate. As shown in Figure 7 which is the intersection of the ordinate established, $D_o$. The coefficient of consolidation $C_v$ defined at the time 50 percent of consolidation, $t_{50}$ as in the Equation 10 and extracted from Figure 7. The $\sqrt{time}$, has a slight diminution with the increasing of stress applied, but it keeps in a range of 0.30 – 2.80. The ordinate value is arbitrarily taken as $D_{90}$. At 12.5 kPa, the $C_v$ value is 11.546 cm²/min. The values of coefficient of consolidation $C_v$ are slightly higher than the West Johor, Peninsular Malaysia peat (10.305 cm²/min) found (Johari et al., 2016). The compressibility of Klias peat and immediate settlement had been observed, the basic properties are shown significant in determination of peat settlement behaviour.

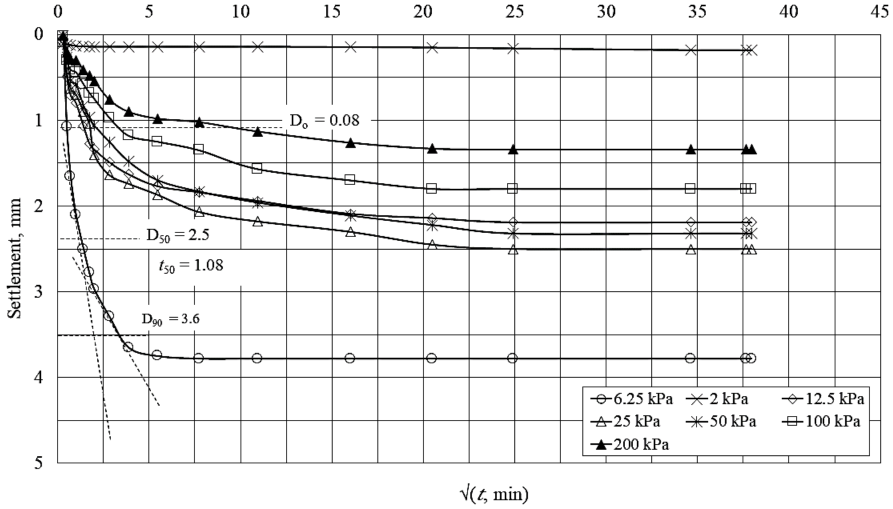

Figure 8. Settlement versus √time (min.)

### Void ratio and compression index

The instantaneous void ratio appeared to be abstracted by plotted linear void ratio on $e$/log $p$, pressure, kPa given in Figure 9. The relationship of $e$ and pressure, $p$ (kPa) as a function of $a_v$, compression of compressibility as shown in Figure 10. The points in Figure 11 for the Plot of strain, $\varepsilon$ versus log pressure, $p$ (kPa) of the pressure applied.

However, subsequent to the void ratio, $e$ versus log pressure, $log\ p$ for Klias, peat soil, it drops to an average of 1.500. The initial void ratio, $e_o$ was 3.221 and decreased to 0.256 at stress 200 kPa. Klias peats have the initial void ratio $e_o$ value 3.221 from sapric peat type, whereas the amorphous granular peat in West Johor, Malaysia has an average the values for the initial void ratio 8.359 (Johari et al., 2016). Based on that void ratio results, the Klias peat soil was likely were very porous and the soil texture soft, spongy and fibreless. Given these points, due to the high organic content in Klias peat about 98.43% in the tested specimen.

Coupled with lower fibre content (18%) that concluded the specimen is organic dominants than fibre makes the peat sample frictionless (Zainorabidin and Mohamad, 2016a).

The $p_c$ and $C_c$ values was obtained from the graph, *e* vs log pressure as shown in Figure 9. The sample normally consolidated when $p = p_o$. Unfortunately, this study discovered $p > p_o$ which means the soil is preconsolidated and the value identified as $p_c$. The compression index, $C_c$ value is 13.895. The first segment of compression index, $C_c$ has a relatively steep slope and hence, a high compression index for Klias peat was discovered about $C_c = 13.895$.

The swelling index, $C_s$ for Klias peat less than $C_c$ value, obviously ($C_s = 0.154$). From an arithmetic plot of *e* $v_s$ pressure, *p* (kPa), the coefficient of compressibility, $a_v$ can be obtained as shown in Figure 10. The $a_v$ value was 1.61 x $10^{-3}$. The laboratory test results indicate the presence of a coefficient of compressibility for the peat sample. Compressibility and effective stress compressibility hold true at any time effective stress, and void ratio during consolidation.

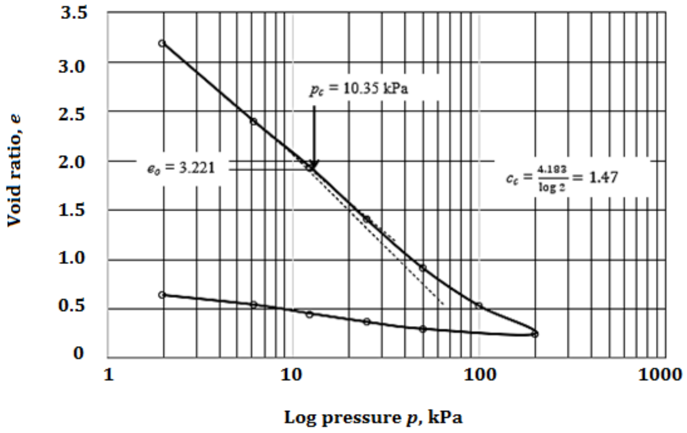

Figure 9. Void ratio, *e* versus log pressure, log *p* for Klias, peat soil.

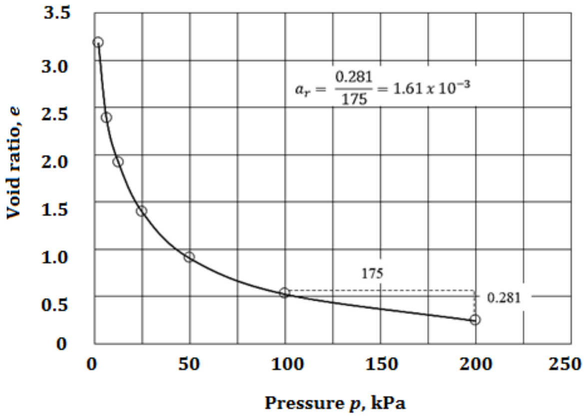

Figure 10. Void ratio, e versus pressure, *p*.

## Consolidation behavior

The consolidation behaviour of peat soil designated for the one-dimensional time-dependent compression. Strain, *ε* and logarithm of pressure, *p* has relationship at first increment of loading for peat sample as shown in Figure 11. An instantaneous, strain, ε takes place immediately after the application of a stress or pressure from loading increment. The result of the compression of air voids and the elastic compression of the peat. The results of consolidation test have shown that peat soil has high settlement rate. From the results as stated in Table 2, the $C_v$ value notched as high as 12.911 and classified as excessive towards the level of settlement.

Graph strain, *ε* vs *log pressure* was plotted. The typical plot is in Figure 11. From that graph, the identical in shape where the slope of the straight line drew in the curve and called the compression ratio, $C'_c$ and defined as in the Equation 9. The compression ratio, $C'_c$ value determined is about 3.194. (Duraisamy et al., 2007) have found the compression ratio using the formula, $C_C/1+e_o$ which is related to compression index of fibric, hemic and sapric are in the range of 0.2 to 0.4 and classified as very compressible. In this study, Klias peat has higher value 3.194 which is categorized as highly compressible.

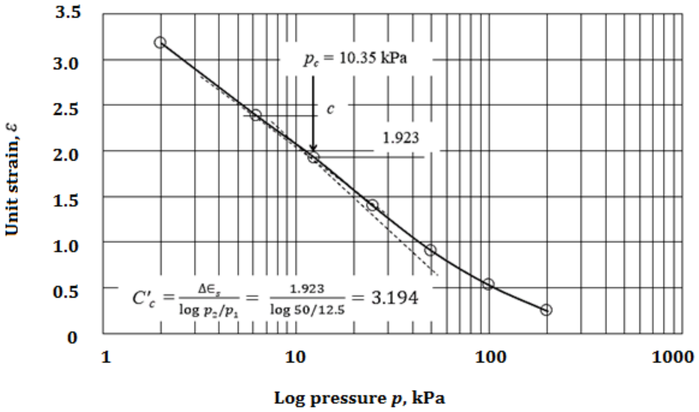

Figure 11. Plot of strain, ε versus log pressure, p (kPa).

The highly compression ratio characteristic of Klias peat soil contributed by high contains of organic in the specimens. The compression ratio for peat in the range in between 0.20 to 0.35 were very compressible (O'Loughlin and Lehane, 2003). Table 2 shows the computation of void ratio, *e* and compression index, $C_v$ and related parameters in this study.

Table-2. Computation of void ratio, *e* and compression index, $C_v$.

| Load Increment (σ, kPa) | Initial dial reading (mm) | Change in sample height, ΔH (mm) | Unit strain, ε | Average height for load, (mm) | Time for 50% consolidation$t_{50}$, min | Coefficient of consolidation, $C_v$, (cm$^2$/min) |
|---|---|---|---|---|---|---|
| 2 | 0.000 | 0.180 | 3.193 | 19.910 | 0.300 | 12.911 |
| 6.25 | 0.080 | 3.780 | 2.385 | 18.070 | 1.080 | 3.099 |
| 12.5 | 0.060 | 2.190 | 1.923 | 18.875 | 0.300 | 11.546 |
| 25 | 0.090 | 2.500 | 1.395 | 18.705 | 0.900 | 3.846 |
| 50 | 0.010 | 2.320 | 0.906 | 18.835 | 2.800 | 1.264 |
| 100 | 0.020 | 1.800 | 0.526 | 19.090 | 2.000 | 1.793 |
| 200 | 0.010 | 1.340 | 1.151 | 19.325 | 1.500 | 2.451 |

## Conclusion

At the end of this analysis, the following are the main observations from the one dimensional-consolidation oedometer test and described in this paper; The index properties that obtained, the moisture content and specific gravity of North Borneo Island especially in Klias tropical peat correlate accordingly with the finding proposed (O'Loughlin and Lehane, 2003). The void ratio, *e* versus *log pressure*, *log p* for Klias, peat soil, it drops to an average of 1.500. The initial void ratio, $e_o$ was 3.221 and decreased to 0.256 at stress 200 kPa. The highest $C_v$, was determined at lowest stress or at the beginning of loading stage, 2 kPa with 12.911 cm$^2$/min. Which was mainly due to the acceleration of stress and settlement. The initial void ratio is 3.221 and at the end of stress level 2 kPa, the void ratio decreased dramatically to 3.183, this is showing that, at even low and moderate loading, peat compressibility is high and void of ratio decreased simultaneously. This study discovered p > po which means the soil is pre-consolidated and the value identified as pc. The compression index, Cc value is 13.895. The first segment of compression index, Cc has a relatively steep slope and hence, a high compression index for Klias peat was discovered about Cc = 13.895.

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