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Evaluation of Degree of Consolidation, Over Consolidation Ratio and Coefficient of Consolidation from CPTu tests in Alluvium Clays

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ABSTRACT

Soft soil was found in several areas in Indonesia, one of them is in Kalimantan Island, which the soft soil in the island mostly formed by Alluvium. One of the characteristics of the soft soil is that they are likely still in under consolidating stage. The usage of CPTu was found to be suitable to the soft soil as the device can record small numbers continuously and able to record pore water pressure. Key features in performing CPTu in under consolidating soft soil is the dissipation test. However, often the dissipation test ended before the 50% excess pore pressure dissipated, which causes commonly used method for interpretation unable to estimate u_{50}. Inverse time (Whittle et. al., 2000; Lim et. al., 2014) and inverse square root time (Liu et. al., 2014) method was developed to overcame the limitation. Rahardjo et. al. (2016) also developed method for obtaining degree of consolidation (and OCR) using pore pressure ratio parameter (B_q) obtained from CPTu. Geotechnical investigation comprised advancing several cone penetration testings (CPTu) were carried out after failure occurred in a relatively flat area (RL +5m to +12m) after having built waste dump embankment to +70m elevation. Soft soil with 15m to 30m thickness was found beneath the embankment. This paper presents comparison of coefficient of consolidation using Teh & Houlsby (1991) method using parameters derived from inverse time and inverse square root time, also comparison for degree of consolidation and OCR in the Alluvium clays based on the dissipation data obtained from the testings. Result showed that the Alluvium clays in the upper 10m already over consolidated while between RL 0 to -20m are still under consolidating, with parameters obtained using inverse time and inverse square root time generally showing close value.

1. Introduction

Cone penetration testing with pore pressure measurement (CPTu) has been widely used since its first introduction in the 1940s and has been developed to incorporate more sensors than what was developed by Fugro in 1965 [1][2][3]. Even in Indonesia, CPTu usage has been increasing and more widely accepted compared to the 1990s when first introduced [4][5][6]. A CPTu testing typically is performed by pushing a probe equipped with sensors to record tip resistance (qc), sleeve friction (fs), pore pressure (u) and inclination (i) into the ground with the help of pushing equipment. Other sensors may be equipped are: temperature, seismic, electrical resistivity, and many others [3]. The advantages of using CPTu are: it provides continuous profile of the subsurface, results are reliable with wide range of data interpretation (i.e.: soil behavior, undrained shear strength, pore pressure parameter, stress history & over consolidation ratio) and is suitable to be use in very soft clay material. One useful test performed during CPTu is dissipation test. Several methods were developed in recent years to overcome short dissipation test (test ended before reaching u_{50}), such as inverse time method [7][8] inverse square root time method [9] or the hyperbolic curve fit method [10][11][12]. In this paper, the inverse time and inverse square root time method was used with most known method for interpreting coefficient of consolidation was proposed by [13]. Several methods were developed over the years for determining stress history of soil from CPTu such as the [14] method and [5] method. [8] introduced the status of consolidation to estimate the percentage of

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consolidation during dissipation test. This paper presents comparison of methods of interpreting degree of consolidation, OCR, and coefficient of consolidation in Alluvium clays.

2. Methodology

Coefficient of consolidation is a parameter depicting the compressibility of the soil and an important part for fine-grained soil as the value will inform us the rate the soil going through consolidation settlement. Over consolidation ratio (OCR) is defined as ratio of past maximum stress occurred in soil with current stress applied in the same soil. Higher OCR value indicates the soil have higher strength, lower permeability and lower settlement compared to what it used to have. This both parameters are essential to know when designing or analyzing in geotechnical especially in soft soil.

2.1 Estimation of Coefficient of Consolidation and Hydraulic Conductivity

Dissipation testing is a function of CPTu which is very useful as from this we can obtain excess pore pressure (Δu), horizontal coefficient of consolidation (ch), hydraulic conductivity (k) and degree of consolidation. The dissipation test curve for soil under consolidating can be either monotonic or dilatonic. There is a difference of pore pressure component for under consolidating soil, normally consolidated and over consolidated soil. For the soft soil under consolidating, the pore pressure contains excess pore pressure (Δu) and residual excess pore pressure (u_f). This component is visible during dissipation testing. In the normally consolidated and over consolidated soil, when the dissipation testing reaches final (u_{100}), its value will be at hydrostatic pressure ($u_{100} = u_w$) while in under consolidating soil the value of $u_{100} = u_f$.

Over the years, various studies have been made to interpret dissipation test for soft soils under consolidation [15] [16] [17] [18] [19] [11] [8] [20] [9] [5] [6] [4] [21]. Most known interpretation and correction for the dissipation test was log time and square root time [22]. with time shifting method for dilatonic dissipation curve. Study from [19]showed that when using shifting time method, the t_{50} should be corrected with tu-max (time needed from initial dissipation test to maximum pore pressure) and rigidity index. One limitation from dissipation testing was if the testing concluded before reaching the 50% dissipation (u_{50}) where it is resulted in difficulty to derive t_{50}. To overcame this limitation, the inverse time method [4][8] and inverse square root time method [9] was introduced, as shown in Figure 1.

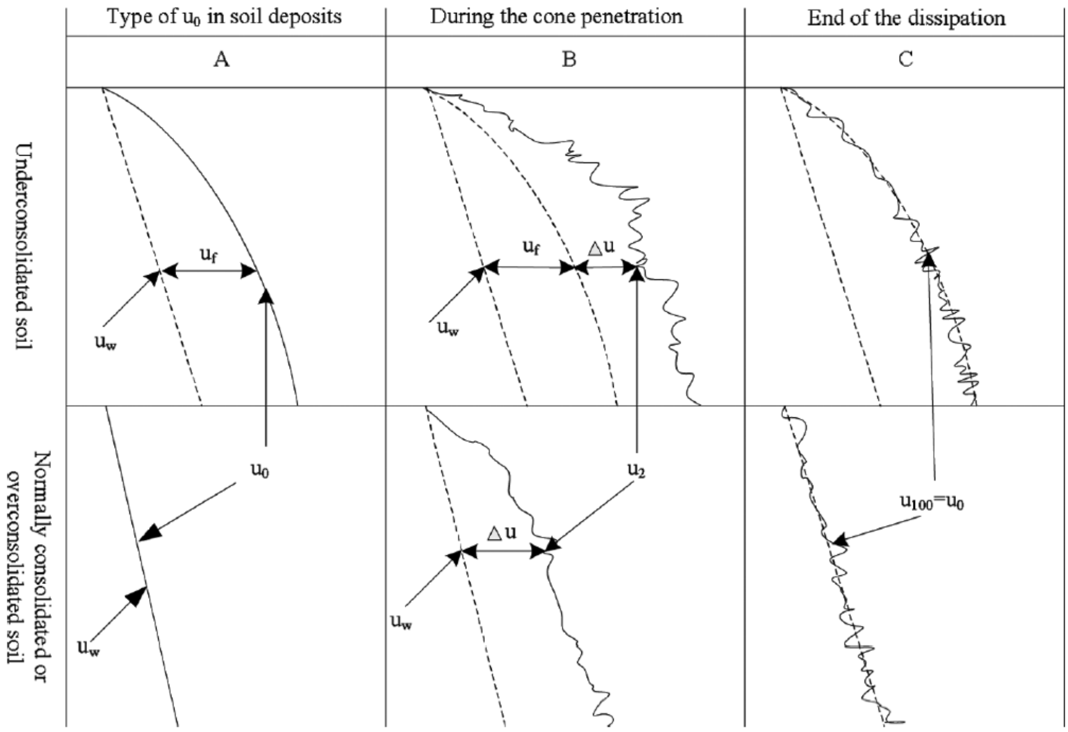
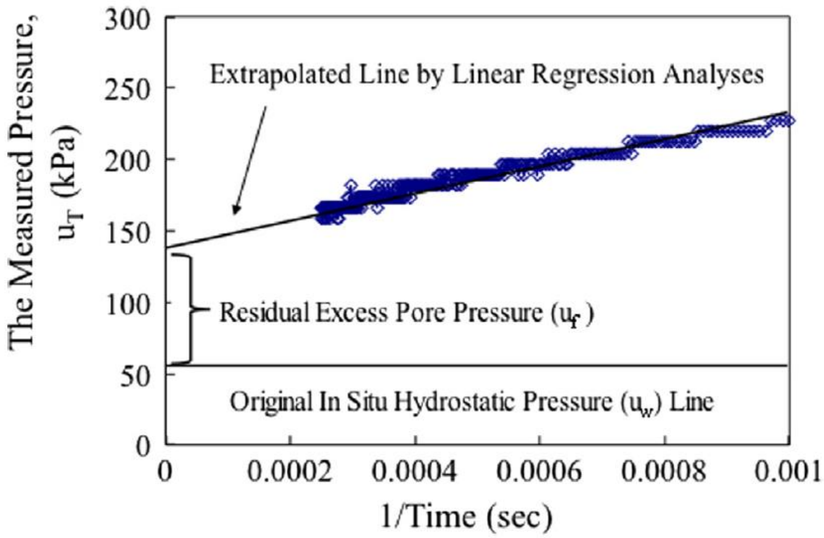
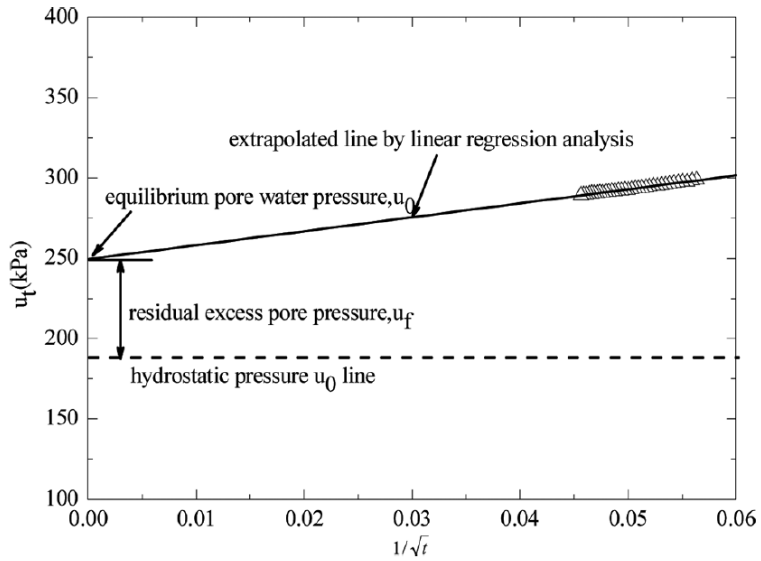


Figure 1. Difference of Dissipation Testing in Under Consolidating, Normally Consolidated and Over consolidated Soil [9]



(a)



(b)

Figure 2. (a) Inverse Time Method [19] and (b) Inverse Square Root Time Method [9]

The inverse time (1/T) and inverse square root time (1/√T) method was developed for completing partial dissipation testing. In this method, the end parts of the dissipation time were plotted against pore pressure, as depicted in Figure 2. The plotted value will show a linier trend line. Extrapolating this linier trend line to intercept the pore pressure axis will show the u_{100} value. From study conducted by [8] and [9], it is shown that the intercept for under consolidating soil will be above the hydrostatic value (u_w) which is showing the residual excess pore pressure (u_f) and for normally consolidated and over consolidated soil, the intercept will be at u_w or below u_w.

The parameter derived from inverse time and inverse square root time method then used with most well-known method for obtaining coefficient of consolidation (c_h) introduced by [13] for obtaining coefficient of consolidation. The formula is as follows:

$$c_h = \frac{(T^*_{50} r^2 Ir^{0.5})}{t_{50}} \tag{1}$$

where T_{50}* value is 0.245 for the position of u_2, r is cone radius (= 1.785cm for 10cm2 cone), I_r is rigidity index (= G/su) and t_{50} is the time needed for 50% dissipation.

2.2 Interpretation of Degree of Consolidation

Soil stress history can be interpreted using several methods. In this paper, the method will be used for comparison are [14] [8] and [6]. The [14] method showed that excess pore pressure value ($\Delta u = u_{max} - u_w$) is corresponding with 0.75 ($q_t - \sigma_{vo}$). The soil plotted above the line are showing the under consolidating soil while the soil plotted along the line is the normally consolidated soil and the soil plotted below the line is the over consolidated soil, as shown in Figure 3a. This method is quite simple; however, this method does not show how much is the degree of consolidation of the soil or the OCR value of the soil.

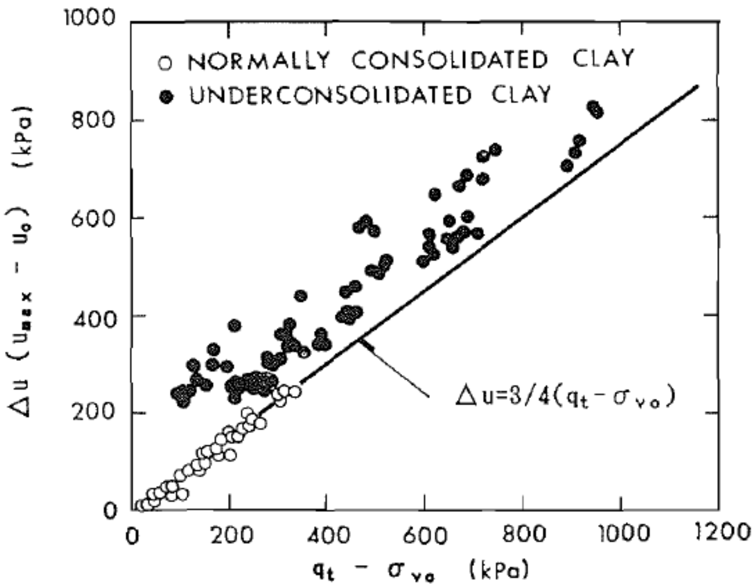
The [6] method was developed using pore pressure ratio (B_q) based on soft clay soil. In this method it is shown that the value of 1.0 (normally consolidated soil) correspond to 0.75 B_q value. This is similar to the [14] method where the normally consolidated clay are plotted along the line. In the [6], the value below 1.0 shows the degree of consolidation while if the value greater than 1.0 will show the OCR, as shown in Figure 3b. The correlation line can be obtain using the following formula:

$$U(or\ OCR) = \frac{1}{(1.2.Bq+0.1)} \text{x } 100\% \quad (2)$$

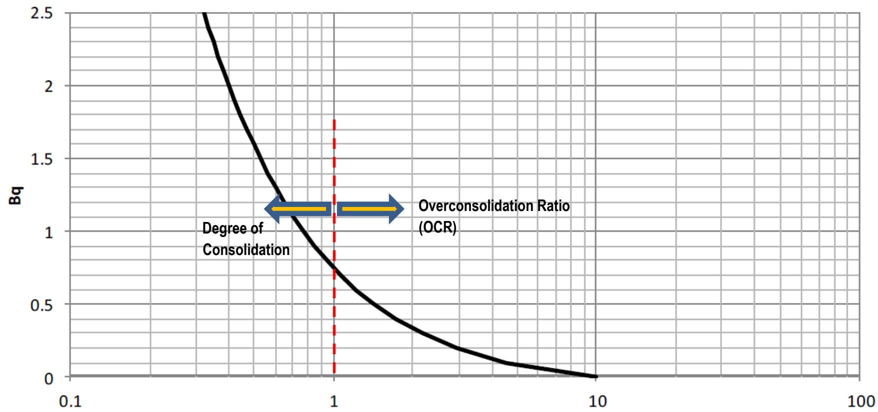
The status of consolidation method was introduced by [9]. This method showed the trend of degree of consolidation during dissipation testing of the soil by using the value of u_{100} obtained from inverse time or inverse square root time method. The formula for this method is as follows:

$$U = \frac{(u_i - u_{100})}{(u_i - u_w)} \text{x } 100\% \quad (3)$$

where u_i is the initial excess pore pressure at the beginning of the dissipation test, u_w is the hydrostatic pore pressure and u_{100} is the pore pressure value when 100% dissipation is reached. The value U is in percentage.



(a)



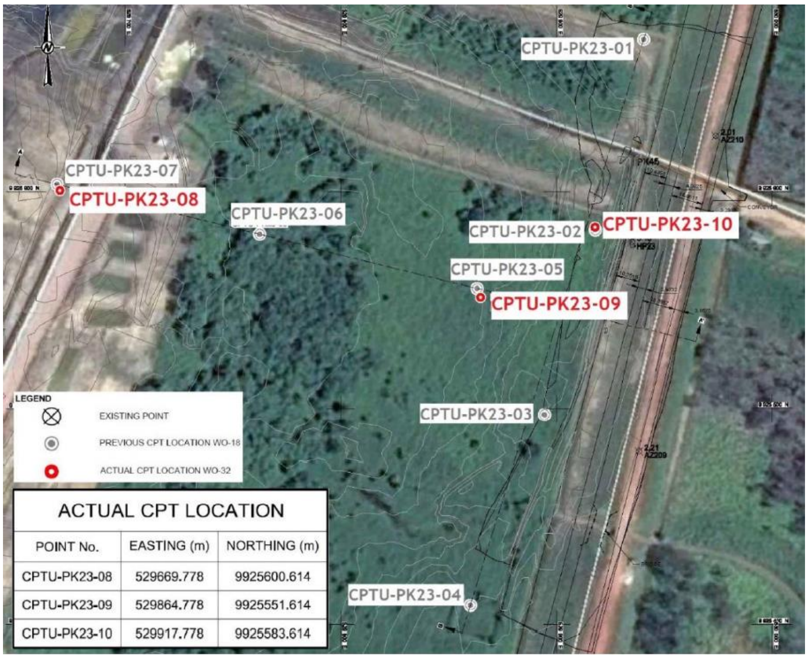
(b)

Figure 3. (a). [14] Method and (b). [6] Method

3. Case Study

A 42" pipeline transporting gas with +5m to +12m elevation from mean sea level located above the Alluvium clays in the Pendingin area, Sanga – sanga sub-district in the Mahakam Delta, East Kalimantan, Indonesia. In the northwest of the pipeline right of way (ROW) lies a coal mine company which during 2010 to 2016 constructed an overhead conveyor crossing the ROW and a 70m high overburden waste dump with its toe about 200m distance from the edge of the ROW. The area was relatively flat with Mahakam River located about 3km to the east. During the waste dump construction, a failure occurred in the newly constructed overhead conveyor causing it to tilted and fell in 2015. In 2016 a landslide occurred in the ROW causing the pipeline shifted about 6.8m distance from its original position and uplifted about 2m. After the failure, the waste dump material was removed leaving the area relatively into its former elevation.

(a)



(b)

Figure 4. (a). Geological Map of the Area and (b). Layout of CPTu Testing

A geotechnical investigation comprised 7 CPTu was carried out in 2016 to assess the situation. The geological map of the location and the CPTu test location is presented in Figure 4. It is found out that the area was overlying from

15m up to 30m of soft Alluvium clay. A typical result of CPTu is presented in Figure 5. It is then concluded that the excess pore pressure generated from the overburden waste dump construction was causing the landslide and pipeline shifting. Four inclinometers were installed to monitor the ground movement and additional 3 CPTu were carried out in 2018 and another 3 CPTu in 2020 to assess the excess pore pressure condition. As the purpose of the additional CPTu is for comparison, the 2018 and 2020 CPTu are in the same location as 3 CPTu in 2016. All CPTu test was accompanied with dissipation testing. The summary of dissipation testing performed is presented in Table 1 with dissipation test curve is presented in Figure 6. Some of the dissipation testing performed ended before reaching u_{50}.

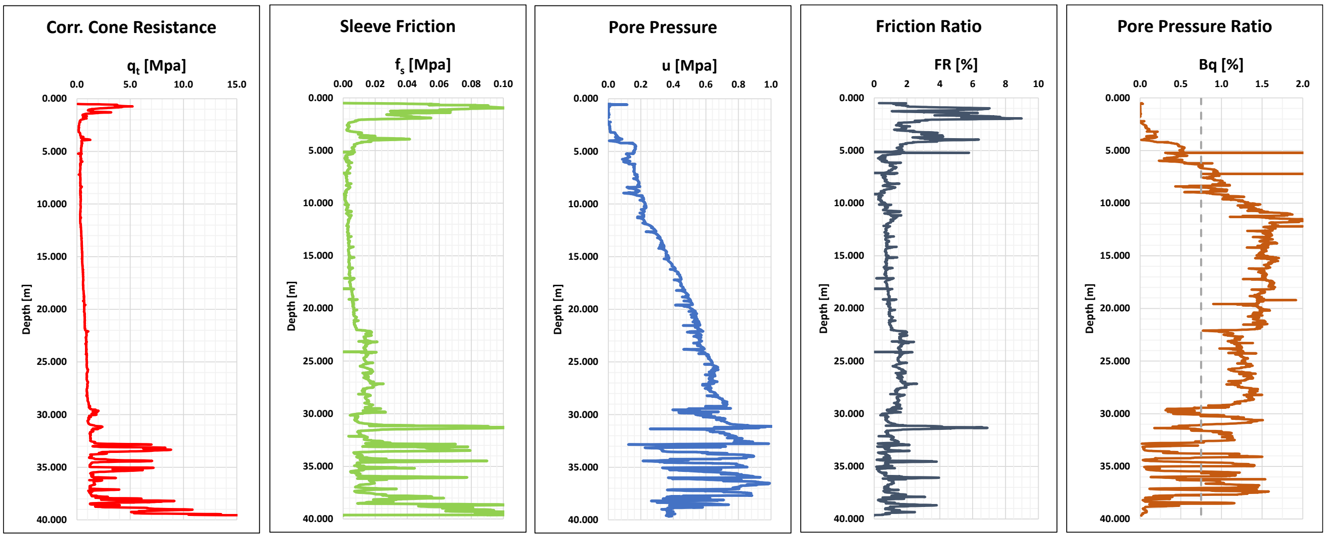


Figure 5. CPTu Result at CPTu-02

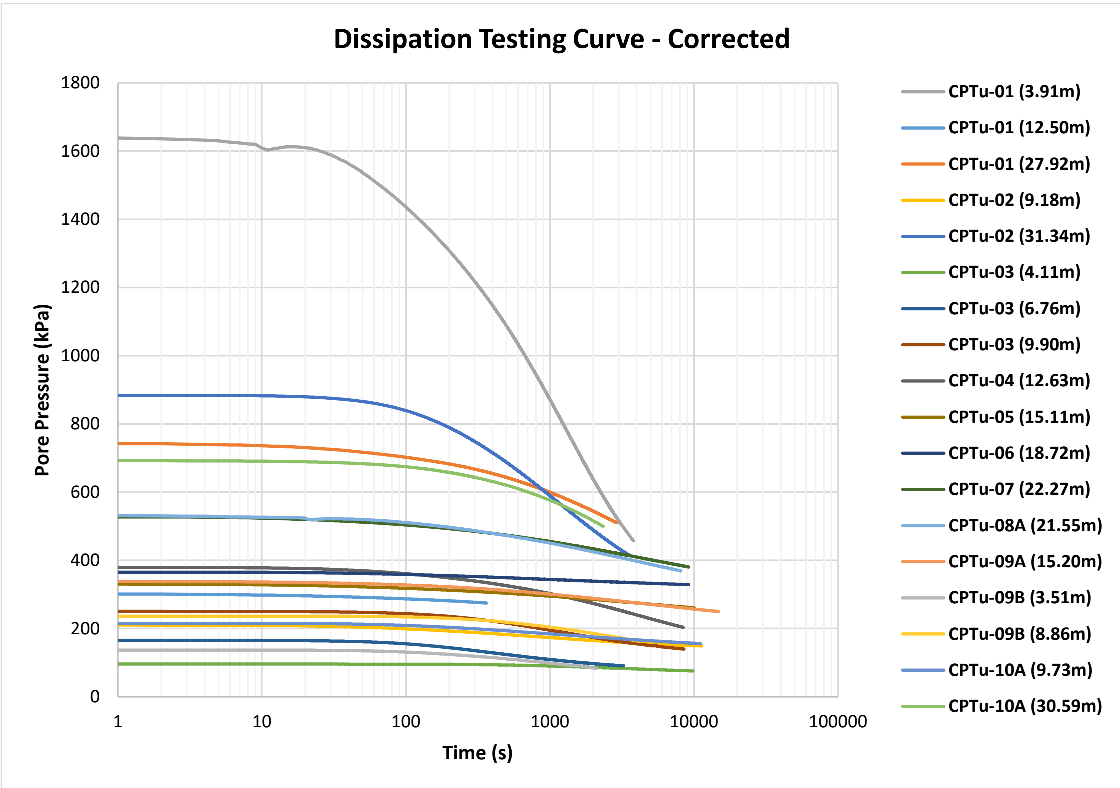


Figure 6. The Dissipation Curves

4. Analysis & Discussion

4.1 Coefficient of Consolidation

Figure 7 shown the comparison of c_h value obtained from several methods. It is clearly shown that the c_h values were scattered, especially for the surface soil (El +5 to -5 m).

The reason might due to the surface soils were overly consolidated. For the soil layer between El -5 to -10m, those four methods are generally close to each other. The reason might due to the soil is normally consolidated. According to this finding, it could be concluded that those four methods were suitable for normally consolidated soil. Meanwhile, for overly consolidated soil, there are no clear findings which methods are appropriate.

Table 1. Summary of Dissipation Testing

CPTu ID	Elevation [m]	GWL [m]	Penetration Depth [m]	Dissipation						
				qt [MPa]	fs [MPa]	u [MPa]	Depth [m]	Duration [s]	u_i [kPa]	u_w [kPa]
CPTu-01	6.65	0.0	31.30	0.3552	0.0055	0.1261	3.91	3799	139.70	31.78
				0.3689	0.0042	0.2734	12.50	362	301.30	122.63
				1.0178	0.0157	0.7019	27.92	2908	743.50	267.32
CPTu-02	6.62	2.0	39.68	0.3302	0.0011	0.1752	9.18	11340	208.00	70.44
				1.7621	0.1061	0.6979	31.34	3600	883.70	287.83
CPTu-03	6.24	4.0	39.33	0.2881	0.0063	-0.0167	4.11	10500	95.583	1.08
				0.4449	0.0073	0.1371	6.76	3327	165.32	27.08
				0.4084	0.0107	0.1909	9.90	8580	250.17	57.88
CPTu-04	4.55	1.0	22.20	0.6246	0.0136	0.3620	12.63	8460	378.87	114.09
CPTu-05	8.13	1.5	40.34	0.4224	0.0056	0.3199	15.11	10080	330.20	133.51
CPTu-06	11.09	4.0	40.32	0.4215	0.0115	0.3549	18.72	9210	361.10	144.40
CPTu-07	12.32	2.0	30.37	0.7181	0.0163	0.5381	22.27	9210	529.10	198.05
CPTu-08 A	12.86	2.0	30.26	-	-	-	21.55	8130	531.82	191.78
CPTu-08 B	11.36	1.180	28.39	1.0467	0.0183	0.4625	15.05	2640	480	306
				0.7062	0.0254	0.5401	21.10	7290	526	224
				7.1486	0.3384	1.0427	28.15	2250	1379	821
CPTu-09 A	8.47	0.0	29.93	-	-	-	15.2	14850	337.64	149.11
CPTu-09 B	7.79	2.40	31.45	0.3183	0.0136	0.1160	3.51	2160	137	55
				0.4741	0.0239	0.1716	8.86	4350	236	162
CPTu-10 A	5.64	0.0	40.13	-	-	-	9.37	11130	215.19	95.45
				-	-	-	30.59	2340	692.39	300.09
CPTu-10 B	5.78	2.50	40.03	0.3155	0.0107	0.1887	9.61	11610	204	145
				0.3226	0.0125	0.2044	10.05	9990	214	163

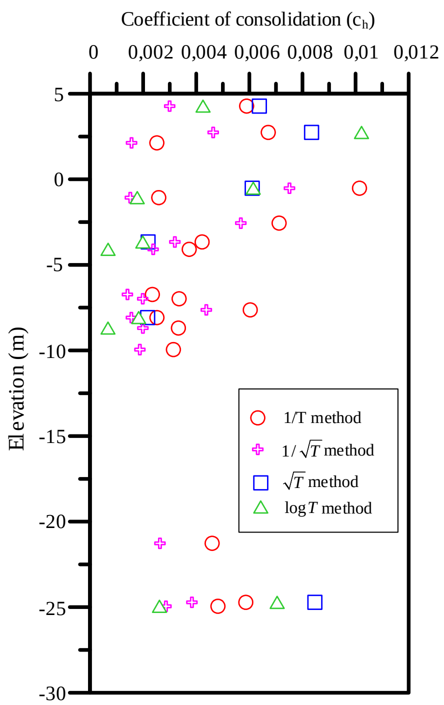


Figure 7. Comparison of c_h value obtained from several methods (cm^2/s)

4.2 Degree of Consolidation

Figure 8 shows the [14] chart to differentiate the soil consolidation status. The data below the line are classified as overly consolidated soil. Meanwhile, the data at the line are normally consolidated. In addition, the data above the line are under consolidated soil. From the plot, it could be concluded that some soil layers are under consolidated, that is from elevation -10 to -22 m. For the surface soil, it is clearly seen that it is at the over consolidated zone. This finding is aligned with [6] method, as depicted in Figure 9, where the surface soil is in over consolidated state. Moreover, [8] reveals that the soil at the ground surface were in under to normally consolidated condition. This result might not be correct because it is different from [6] [14] methods. Hence, [8] status of consolidation method might not be suitable to be used in this site.

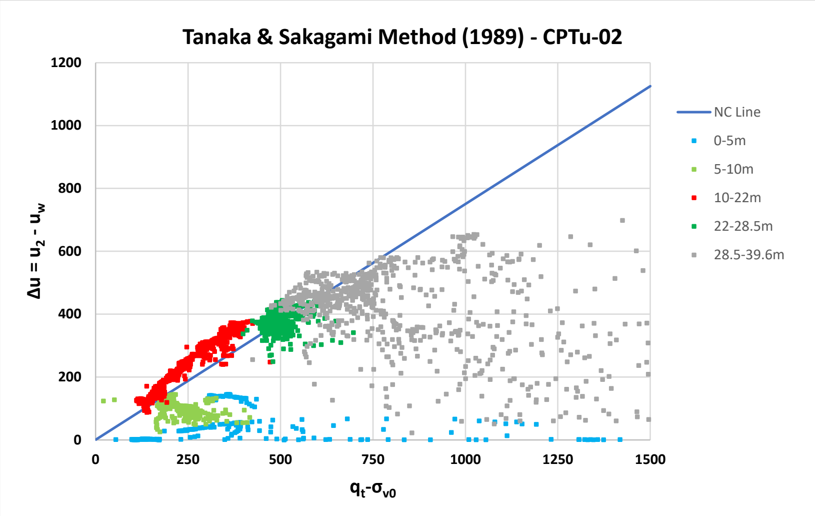


Figure 8. Tanaka & Sakagami Plot for CPTu-02

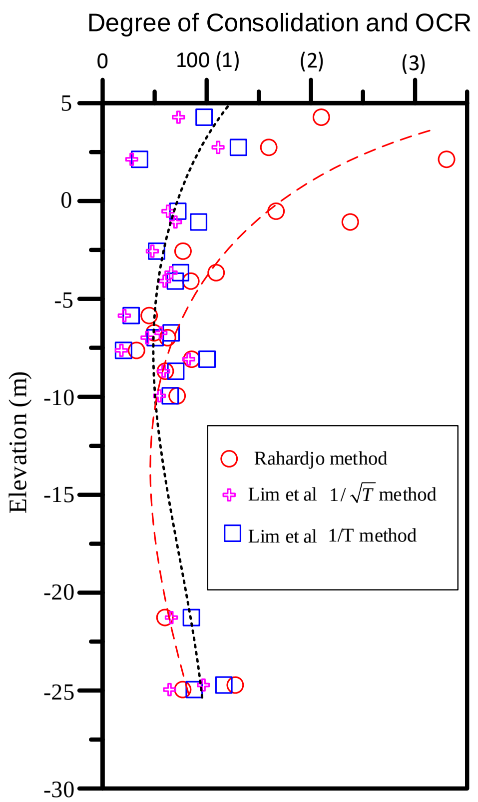


Figure 9. Comparison of Degree of Consolidation and OCR value (Note: number inside bracket indicates OCR value)

5. Conclusion

The horizontal coefficient of consolidation (c_h) was unable to be estimated when using the [22] method if the dissipation curve did not reach 50% dissipation. However, this can be overcome by using inverse time method [8] and inverse square root time [9] method.

From the calculation it is found out that the upper 10m soil (including soft soil located in this range) is already over consolidated while the soft soil from RL 0.0m to 20.0m is still consolidating.

The value of coefficient of consolidation (c_h) calculated using [13] method with parameters derived from [8] and [9] showing generally close value in under consolidating to normally consolidating soft clay layer

The [14] method and [6] method showed similar result in presenting over consolidated, normally consolidated and under consolidated soft clay layer. However, the [6] method showed an unreasonable value of degree of consolidation value when used in the crustal zone (over consolidated soil near the surface). In this case, the investigated area was filled up to +70m high overburden material and then removed.

The status of consolidation method [8] reveals that the soil at the ground surface were in under to normally consolidated condition. However, due to the nature of estimation is different compared to the [14] and [5], it is incomparable.

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