AN ANALYTIC STUDY ON ESTIMATING THE HORIZONTAL COEFFICIENT OF CONSOLIDATION THROUGH CPTU DISSIPATION TEST FOR COHESIVE SOIL IN DHAKA

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ABSTRACT

Consolidation is a fundamental process, especially in clayey soil, which provides some essential parameters in prediction of settlement phenomenon of clayey soil under a foundation. Because of capillary action and the layered arrangement of clayey soil, water consolidates more horizontally than vertically within the soil medium. Hence, it is essential to assess the horizontal coefficient of consolidation with an accurate estimation. This study presents the results of ten dissipation tests conducted using Cone Penetration Testing (CPTu) on cohesive soils within the Dhaka division. The primary objective of this research is to determine the in-situ horizontal coefficient of consolidation (c_h) through the analysis of dissipation tests. Pore water dissipation in normally consolidated (NC) clay typically displays a monotonic pattern whereas stiff overconsolidated clay exhibits a dilatory or concave dissipation pattern. To estimate the coefficient of consolidation (c_h) from the dissipation tests, four distinct methods were employed. These methods include Tortensson's approach (1977), Houlsby and Teh's (1988) techniques etc. The most significant method is Mayne (2001), which employed a combination of cavity expansion theory and critical stress methods to the radial consolidation equation. In this investigation, the field consolidation rate (c_h) was estimated using all these methods. Nevertheless, Mayne's iteration model yielded more practical results, particularly in stiff clay. Houlsby and Teh's approaches gave better outcomes for sandy or silty clay. The in situ c_h value obtained from the analysis from Houlsby and Teh's methods ranges from 0.25 cm^2/s to 0.98 cm^2/s for sandy clay and 0.001 cm^2/s to 0.0415 cm^2/s for stiff clay with varying Rigidity Index (I_r). On the contrary, the value of c_h obtained from Mayne's iteration method ranges from 0.00024 cm^2/s to 0.1 cm^2/s for different soil types. Besides, soil collected from some points of CPTu tests were also experimented in laboratory Odometer tests to identify the vertical co-efficient of consolidation. Overall, The research will contribute to geotechnical engineers to determine in-situ consolidation coefficient value in a practical approach.

Keywords: *CPTu (ConePenetration Test), Horizontal coefficient of consolidation (ch), cavity expansion theory, Monotonic and Dilatory, Overconsolidated clay.*

1. INTRODUCTION

The geotechnical attributes of Dhaka clay have been investigated by many researchers in past 3-4 decades. Madhupur Pleistocene clay with subsurface deposit makes a comprehensive characteristic of Dhaka clay which contains a significant amount of sand and silt. Both Islam et al. (2009) and Islam & Alam (2009) state that intermediate to high plastic silty clay is exposed in the top 2.0 m to 8.0 m of soil layer based on the boring evidence. That is why, clay soil combined with silt and sand exhibits complex consolidation behaviour. In the field of geotechnical engineering, consolidation parameters is important as they influence the settlement behaviour of clayey soil When soil is subjected to an impact load, it experiences a punching shear and an octahedral normal shear effect (Burns & Mayne, 1998). In this situation, pore water pressures in clayey soil generally radiate in the horizontal direction and thus it's necessary to measure the horizontal coefficient of consolidation (c_h).

The vertical coefficient of consolidation (c_v) is usually estimated through mechanical tests such as one-dimensional Oedometer test. Using the c_v value and permeability co-efficient (k) obtained from the laboratory test, the horizontal coefficient of consolidation (c_h) can be estimated. (Farsakh & Nazzal, 2005). There might be differences between laboratory results and actual field behavior due to sample disturbance and small sample size. Besides, the oedometer test can take a significant amount of time to finish. As a result, this test may not be ideal for time-sensitive projects or situations (Cai et al., 2005). Due to the limitations of the laboratory test, in-situ tests offer a more direct and realistic assessment of the coefficient of consolidation. Over the past few decades, various methods of in situ testing have been used to determine the c_h values. The dissipation test, used in conjunction with the Cone Penetration Test (CPTu), is becoming increasingly popular for measuring the in-situ coefficient of consolidation nowadays. This paper presents the findings of 10 dissipation tests conducted in clayey soil of Dhaka division using various theories and models by several authors.

2. METHODOLOGY

CPTu is a widely recognized and effective method for continuous soil stratification based on several parameters like cone resistance (q_t), frictional resistance (f_s) and pore water pressure (u_2). In this paper, only the pore pressure dissipation results are presented in different approaches.

The system mainly consists of a dual-cylinder hydraulic pushing system of 200kN capacity, a data acquisition system and a Piezocone. A cone-shaped penetrometer tip, featuring a 60° apex angle and a cone base area of 10 cm^2, is driven into the soil at a steady pace of 20 mm/s. Piezocone can detect pore water pressure generated during the advancement of the penetrometer tip through the use of an electronic pressure transducer. These advanced piezocones make measurements collected at intervals of at least 50 mm of penetration. When the pore water pressure stabilizes, it signifies the measurement of the equilibrium value that is designated as u_0.

In this investigation, all dissipation tests were carried out by Prosoil Foundation Consultant, a renowned Geotechnical investigation Company in Bangladesh. Ten dissipation tests were conducted in different locations of Dhaka division where the presence of clayey soil was previously anticipated. All the Piezocone dissipation tests are designated consequentially CPTu-01 to CPTu-10. The location and other information of all CPTu Dissipation tests are given in Table 1. The soil samples from the dissipation tests at CPTu points were collected to investigate the index properties of soil. (Table 2)

Table 1: Information related to CPTu Dissipation test

CPTu Dissipation Test Point	**Location**	**Coordinates of test Point**		**Depth of Dissipation test**	**Depth of WaterTable**
		Easting	**Northing**		
		°	°	m	m
CPTu-01	Tejgaon (Firmgate)	233300	2630027	30.44	3.5
CPTu-02	Tejgaon (Firmgate)	234359	2628712	7.8	4.5

CPTu-03	Khamarbari	233577	2629914	18.34	7.1
CPTu-04	Khamarbari (Farmgate)	2333577	2629914	19.58	6.5
CPTu-05	Panam City(Narayanang)	257920	2618673	18.35	10.5
CPTu-06	Panam City(Narayangang)	253988	2619101	27.95	7.8
CPTu-07	Badda	249749	2622108	13.57	7.13
CPTu-08	Badda	246726	2623365	10.5	5.15
CPTu-09	Bausundhara	238860	2625666	10.92	4.1
CPTu-10	Bausundhara	246578	2623274	18.25	16.2

Table 2: Index properties of the soil collected from points of Dissipation tests

CPTu Dissipation test Point	**Soil Type (from grain size and hydrometer test)**	**Liquid Limit**	**Plastic Limit**	**Specific Gravity**	**Bulk Unit Weight**
		(%)	(%)		kN/m^3
CPTu-01	Clay with Silt	58	18	2.71	20.1
CPTu-02	Silty Clay	42	22	2.719	19.78
CPTu-03	Silty Clay	48	23	2.709	22.5
CPTu-04	Sandy Clay	47	26	2. 721	22.1
CPTu-05	Sandy Clay	41	28	2.7	20.45
CPTu-06	Silty Clay	38	26	2.697	19.87
CPTu-07	Clay	56	21	2.71	18.97
CPTu-08	Clay	52	19	2.709	19.57
CPTu-09	Clay	54	16	2.705	18.7
CPTu-10	Clay	50	16	2.724	19.5

3. ILLUSTRATIONS

As mentioned before, many theories have been developed to describe the phenomenon of dissipation in clayey soil. The first theoretical approach was made by Torstensson (1977) who explained this phenomenon using a Cavity Expansion considering both Cylindrical and Spherical Cavity. In the Early 80s. Teh & Houlsby (1991) updated the theory using the strain path method combined with the finite element of the strain path. Then the most significant method was proposed by Professor Mayne who incorporates critical state soil mechanics in Cavity Expansion theory.

When the cone penetrates into the ground, the pore water dissipates in the radial direction. The excess pore pressure generated around the cone results from the change of octahedral normal stress and shear stress due to the shear deformation of the surrounding soil. The octahedral normal stress is caused by the displacement. The stresses along with the cavity zone are explained in Figure 1.

$u_i = u_{oct} + u_{shear}$

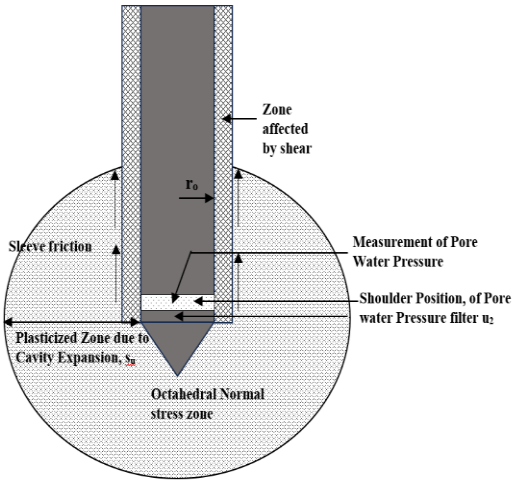


Figure 1: Stresses along with cavity expansion zone during cone penetration

The excess pore pressure tends to decrease over time for NC clay. In stiff over-consolidated clay, the gradient of pore pressure initially rises to a peak value before decreasing to equilibrium pressure. The pattern of excess pore pressure for normally-consolidated and over-consolidated soil are termed as Monotonic and Dilatory patterns of curves respectively.

3.1 Tortession's Theory for Dissipation

While penetrating through the ground, the cone causes large pore water pressure and reduction in effective stress due to the compression. When the dissipation mode is halted, pore pressure tends to dissipate and the effective stress rises which signifies the recompression mode. Torstensson (1977) assumed that by the time at 50% dissipation, soil regains its recompression mode and starts to consolidate naturally. Several interpretations of theory measure the time at 50% of dissipation.
According to Torstensson (1977) the value of c_h is calculated by Equation 1.

$$c_h = \frac{r^2 T_{50}}{t_{50}} \qquad (1)$$

Where, t_{50}=time for 50% dissipation, T_{50}=Dimensionless Time Factor, r_o=radius of the piezocone=1.75 cm.
As, Torstensson (1977) considered both cylindrical and cavity expansion, Tsegaye (2000) proposed two equations to estimate the value of T_{50}
For spherical dissipation

$$T_{50} = 0.2+0.0012E/ c_u \qquad (2)$$

for cylindrical dissipation

$$T_{50} = 0.7+ 0.0078\, E/ c_u \qquad (3)$$

E is the secant modulus of soil and c_u is undrained shear strength
T_{50} is calculated by taking the average of two values based on the E/c_u ratio. The difficulty in estimating the secant modulus for particular soil leads to overestimating the value of the co-efficient of consolidation. This is one of the limitations of this method.

3.2 Teh and Houlsby's (1991) Method

Teh & Houslby (1991) modified Torstensson's equation by incorporating Rigidity Index, (I_r) which is shown in Equation 4

$$T_{50}^{*} = \frac{c_h t_{50}}{r^2\, I_r^{0.5}} \qquad (4)$$

Where, T^*_{50}= modified time factor at 50% dissipation (T^*_{50}= 0.245 when pore pressure filter is placed at shoulder of the cone)
I= rigidity index = G/s_u (G is the shear modulus and s_u is the undrained shear strength). Teh and Houlsby (1991) established c_h values for a range of Ir value (25-500) for more accessible applications. The determination of t_{50} using The and Housble's method is quite straightforward for Monotonic types of Dissipation curves compared to in dilatory types (Cai et al., 2001). The explanation of determining t_{50} for both types of curves is provided in the following sections.

3.2.1 Interpretation of t_{50} in Monotonic Dissipation for NC soil

For monotonic response, t_{50} is directly measured when the degree of consolidation (U) is reached to 50% from the initial. The degree of consolidation (U) at any time (t) can be calculated as

$$U_t(\%)=\frac{u_t-u_0}{u_i-u_0} \tag{5}$$

Where, u_t= Pore water pressure measured at any time t, u_0= equilibrium pore water pressure, u_i= initial maximum pore pressure at t=0 sec.

3.2.2 Interpretation of t_{50} in Dilatory Dissipation for OC soil

For the dilatory response, The direct method of determination of $t_{50.}$ cannot be applied. Sully (1991) proposed a method of Square root of time vs pore pressure plot ($t^{1/2}$ vs u_2) which uses a back-extrapolation technique on a square-root of time plot. In this graph, the dissipation following the peak shows an initial straight-line segment. This segment can be extrapolated back to t = 0 to derive an adjusted u_i for the corrected dissipation curve (Figure 2). t_{50} is taken at the point when 50% dissipation occurs at $\frac{1}{2}(u_i - u_0)$.

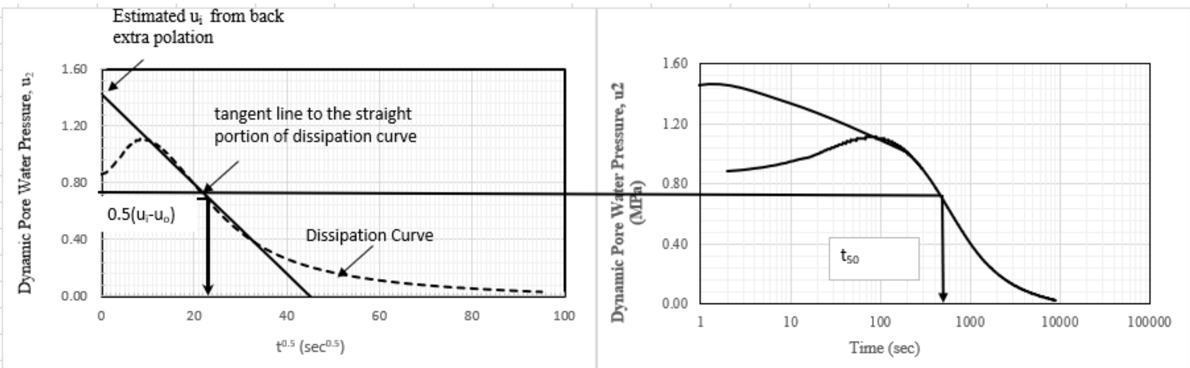


Figure 2: Estimation of t_{50} for dilatory curves using Square root of time proposed by Sully et al., (1999)

3.3 Mayne's Curve Fitting Model

However, the approaches suggested by Sully et al. (1999) and the utilization of Equation 1 (Teh and Houlsby,1991) for evaluating the c_h value represent a straightforward technique, Cai et al. (2005) pointed out that Sully's time square root method tends to overestimate the value of time at 50% consolidation. Hence, he recommended a method proposed by Burns and Mayne (1998) and Mayne (2001). Instead of matching only one point at 50% of dissipation, Mayne (2001) fitted the entire in-situ dissipation curve to fit their model, to obtain the approximately correct value of field consolidation.. The excess pore pressure at any time, t can be obtained according to Mayne (2001), which is given in Equation 6.

$$u_2 = \frac{u_{oct}}{1+50T} + \frac{u_{shear}}{1+5000T} + u_0 \tag{6}$$

Where, u_0= equilibrium pore water pressure,

$$u_{oct} = \frac{2}{3} M \sigma'_{v0} \frac{OCR}{2} \ln I_r \tag{7}$$

$$u_{shear} = \sigma'_{v0} \left(1 - \frac{OCR}{2}\right)^{\Delta} \tag{8}$$

Δ= volumetric strain ratio and its value 0.8 is used (Burns and Mayne, 1998), σ'_{v0} =Effective Over Burdon Pressure at certain depth, I_r= Rigidity index and

$$M = \text{slope of the critical straght line} = \left(\frac{6sin\varphi'}{3-sin\varphi'}\right) \tag{9}$$

The soil stiffness is usually represented by the rigidity index $I=G/s_u$,where G is the shear modulus and s is the undrained shear strength.

In Equation 6 the modified time factor for dilatory curves ,T is defined as:

$$T = \frac{c_h t}{r^2 \, {I_r}^{0.75}}$$

It is observed that c_h is function of some factors such as effective stress, volumetric strain, Rigidity Index and Over Consolidation Ratio (OCR). Therefore, the optimal curve is derived through a trial-and-error process, where Equation 6 is employed with different values of c_h and Ir. This iterative approach continues until the resulting curve closely aligns with the field curve, and the associated c_h value is deemed as the field consolidation coefficient for the specific soil.

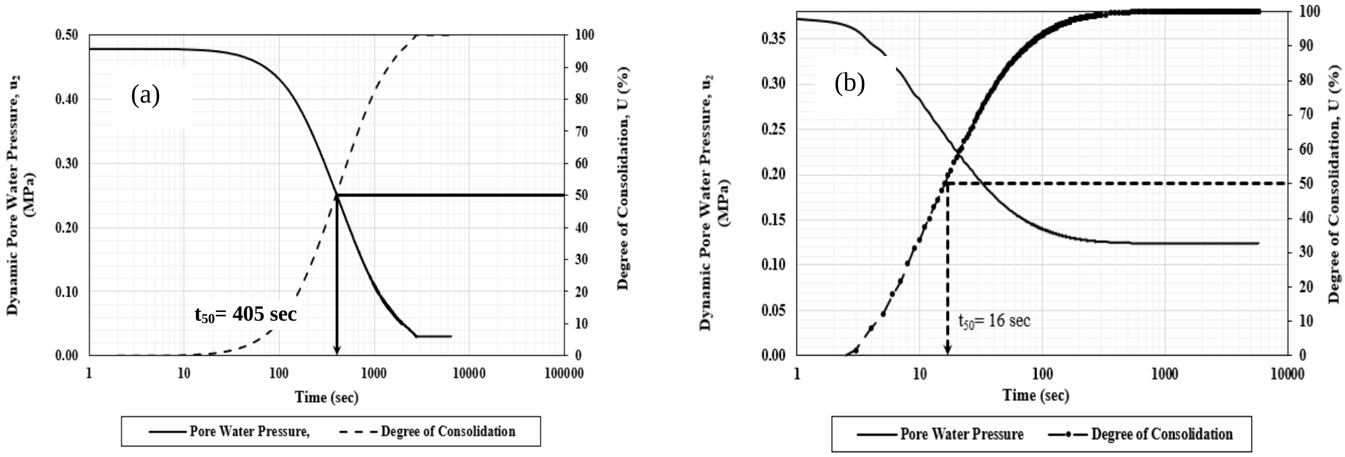
4. RESULTS AND DISCUSSIONS

The horizontal co-efficient of consolidation for all 10 CPTu tests were estimated using all the methods described in the previous section. In this section, the values of c_h obtained from different methods will be compared.

4.1 Results from Teh & Houlsby (1991) Method

The t_{50} value predicted from Teh & Houlsby (1991) method for monotonic pore pressure curves using Equation 5 are illustrated in Figure 3. It should be emphasized that dissipation tests conducted at points 02, 03.04, 05, and 06 exhibited monotonic behavior due to the presence of moderate amount of silt and sand in the clay soil at those regions. As a result, the obtained t_{50} from dissipation curves is less and the calculated c_h values for this type of soil are higher. The dilatory curves for Overconsolidated stiff clay at CPTu points 01, 07, 08, 09 and 10 result in higher values of t_{50} and much lower c_h values. For dilatory responses, t_{50} are estimated from the root square time curve by Sully (1991). (Figure 4)

Table 3 presents the c_h value for different types of soil for a range of I_r values which is further demonstrated in Figure 5



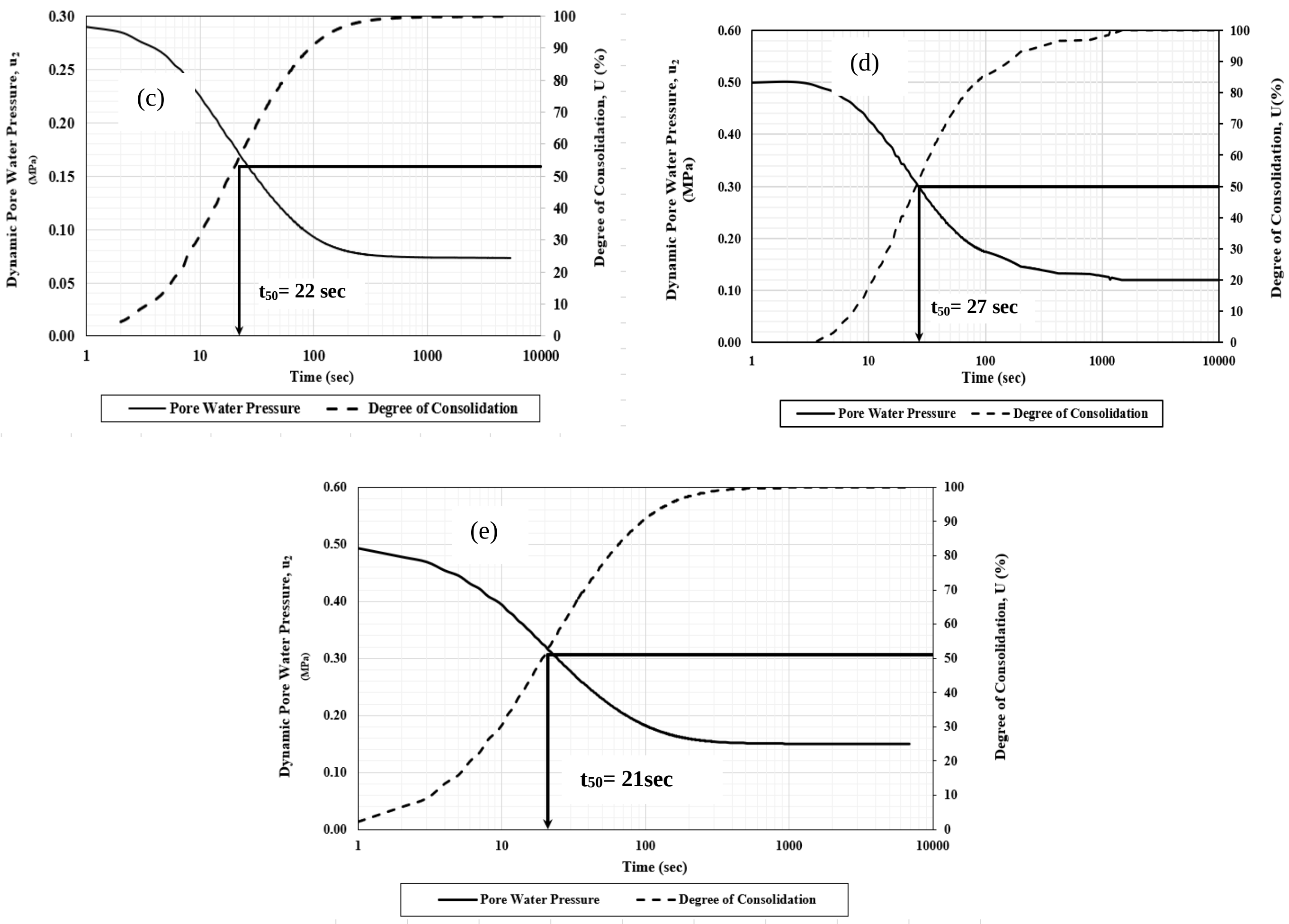


Figure 3: Determination of t_{50} from monotonic curve for (a) CPTu -02, (b) CPTu -03, (c) CPTu-04

(d) CPTu -05 and (e) CPTu -06

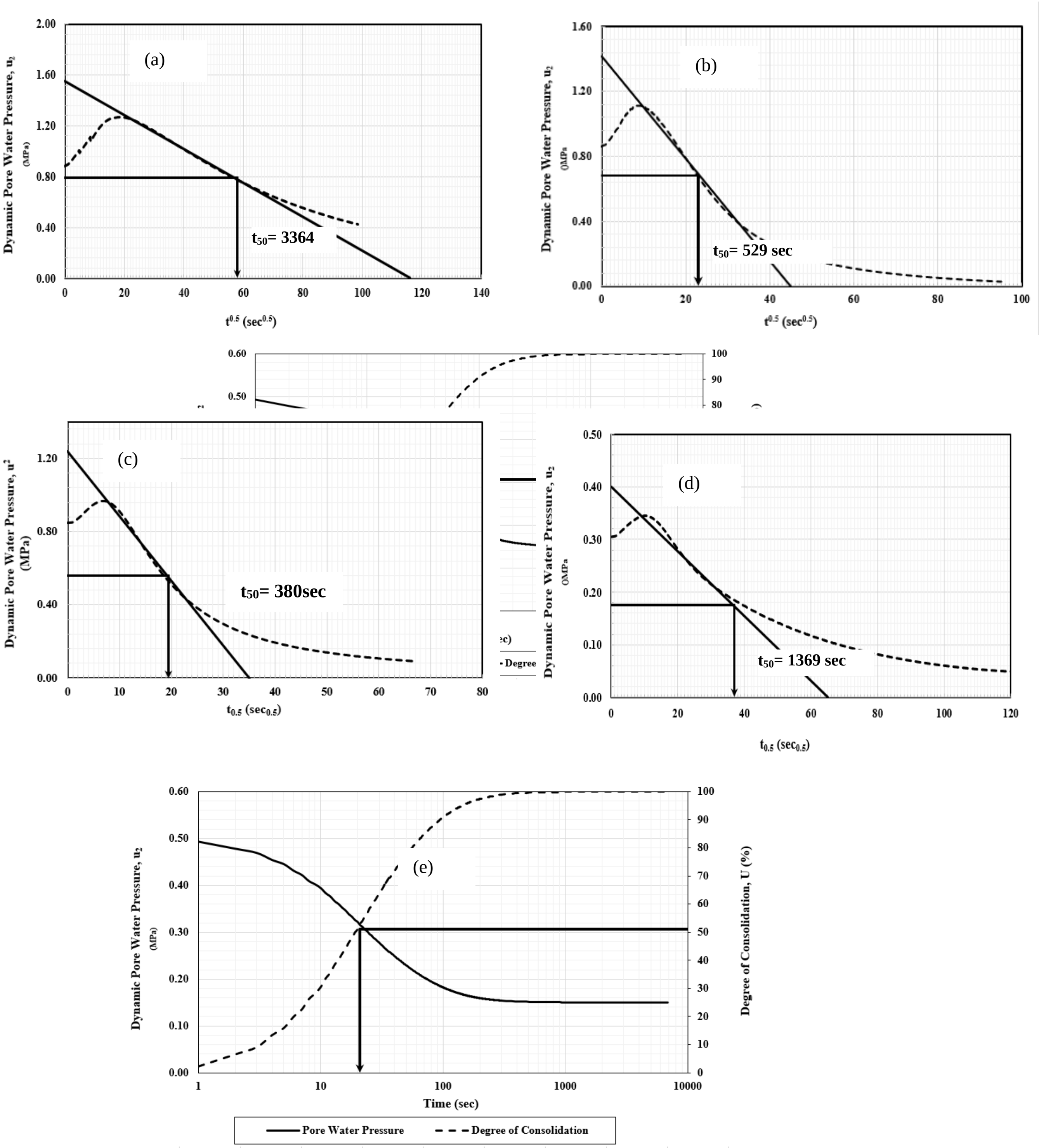


Figure 4: Determination of t_{50} from dilatory curves using Sully et al. (1991) method for (a)CPTu-01, (b) CPTu -07, (c) CPTu -08, (d) CPTu -09 and (e) CPTu -10

Table 3: Summary of t_{50} and c_h value for different types of soil for a range of I_r values (using Sully et al., 1999 and Teh & Houlsby, 1991 method)

CPTu Dissipation test Point	Dissipation Type	Soil Type	Estimation of t_{50} from the graph	c_h (I_r=50)	c_h (I_r=100)	c_h (I_r=200)	c_h (I_r=500)
			sec	(cm²/s)	(cm²/s)	(cm²/s)	(cm²/s)
CPTu-01	Dilatory	Clay with Silt (OC Clay)	3364	0.0015	0.0022	0.0031	0.0049
CPTu-02	Monotonic	Silty Clay (NC)	405	0.013	0.0185	0.026	0.0415
CPTu-03	Monotonic	Silty Clay (NC)	16	0.312	0.44	0.62	0.98
CPTu-04	Monotonic	Sandy Clay (NC)	22	0.24	0.34	0.48	0.76
CPTu-05	Monotonic	Sandy Clay (NC)	27	0.19	0.27	0.39	0.62
CPTu-06	Monotonic	Silty Clay (OC)	21	0.25	0.25	0.5	0.79
CPTu-07	Dilatory	Clay (OC Clay)	529	0.01	0.014	0.02	0.03
CPTu-08	Dilatory	Clay (OC Clay)	380	0.014	0.025	0.029	0.05
CPTu-09	Dilatory	Clay (OC Clay)	1369	0.0038	0.0054	0.0077	0.01
CPTu-10	Dilatory	Clay (OC Clay)	2704	0.0019	0.0027	0.0039	0.0062

It is evident from Figure 5 that higher values of the rigidity index (Ir) correspond to higher values of c_h.

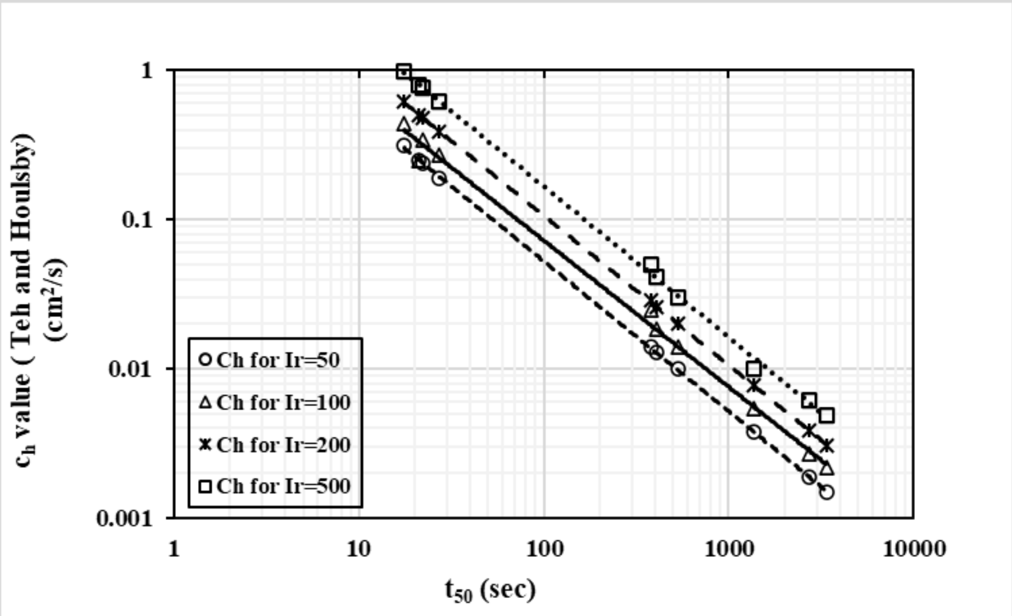


Figure 5: t_{50} vs c_h plot for Rigidity Index, Ir=50 to 500 using Teh & Houlsby (1991) method

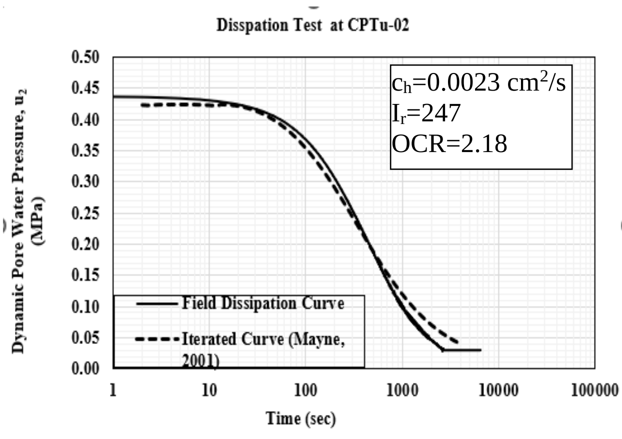
4.2 Results from Mayne's Method

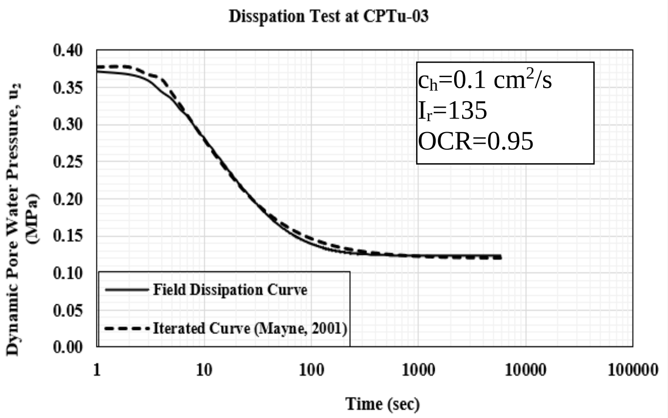
The most practical interpretation of c_h is using Mayne's (2001) iteration method which has been done for our analysis for all dissipation tests. The method has been described in section 3.3 And c_h is predicted using those formulas. In this trial and error method, the c_h, I_r and in some cases, OCR are considered as variables until the desired curve is matched with field dissipation curves. For the stiff clay soil, collected from the points CPTu- 01, 02, 07, 08, 09, and 10, laboratory consolidation tests were performed and the results of Laboratory OCR values are shown in Table 4. The Iteration Model for monotonic and dilatory dissipation curves are presented in Figures 6 and 7 respectively.

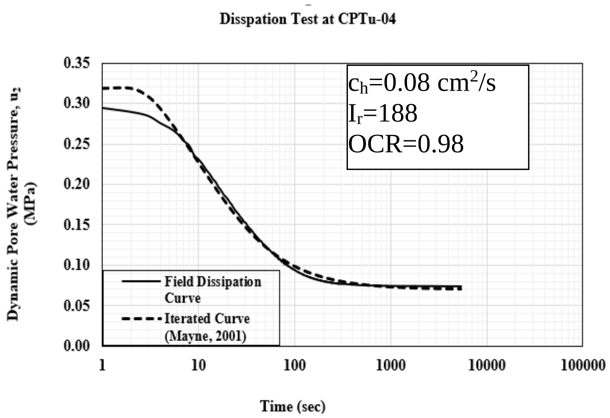
As evident in Table 5, although the silty clay at the point CPTu-02 and CPTu-05, exhibits monotonic dissipation, they are characterized as moderately overconsolidated clay.

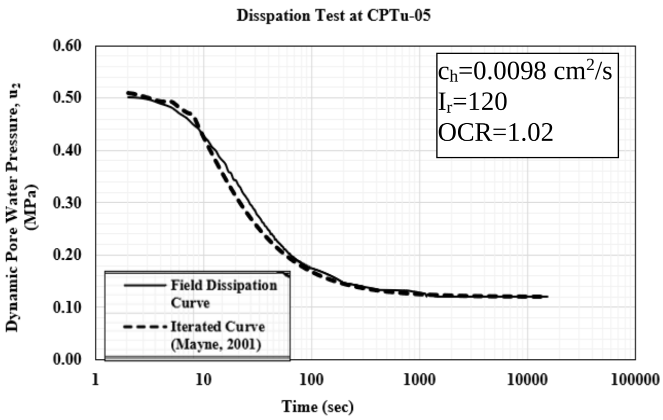
It is also observed that Rigidity Index is generally higher for NC or moderately OC clay which results in higher value of c_h. On the contrary, stiff overconsolidated clay gives comparatively lower values of both the Rigidity Index and c_h value.

It is apparent that The horizontal coefficient of consolidation, as determined through Mayne's Iteration method, indicates significantly lower values compared to those obtained through other methods such as Tortossion's cavity expansion theory and Teh and Houlby's theory. Considering that Mayne's model reflects more practical and approximately correct in field conditions, the c_h values from other methods might be overestimated.









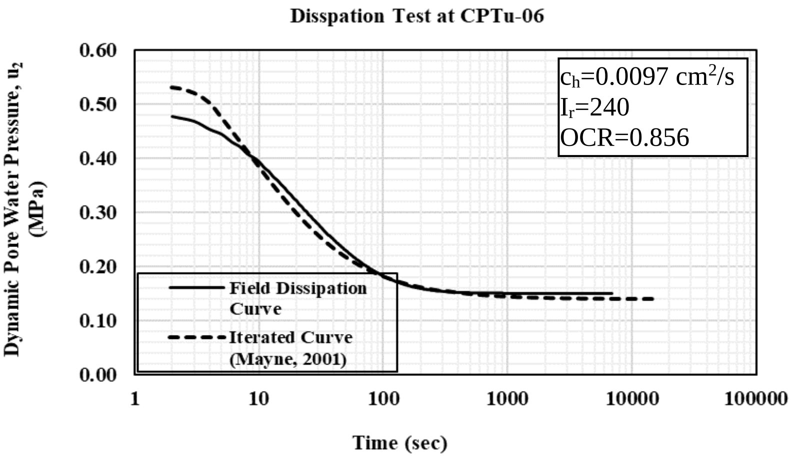


Figure 6: Determination of c_h using iteration method by Mayne (2001) for monotonic Curve at CPTu-02, CPTu-03, CPTu-04, CPTu-05 and CPTu-06

Table 4 presents optimal values of I_r and OCR for obtaining the the c_h value through trial and error method.

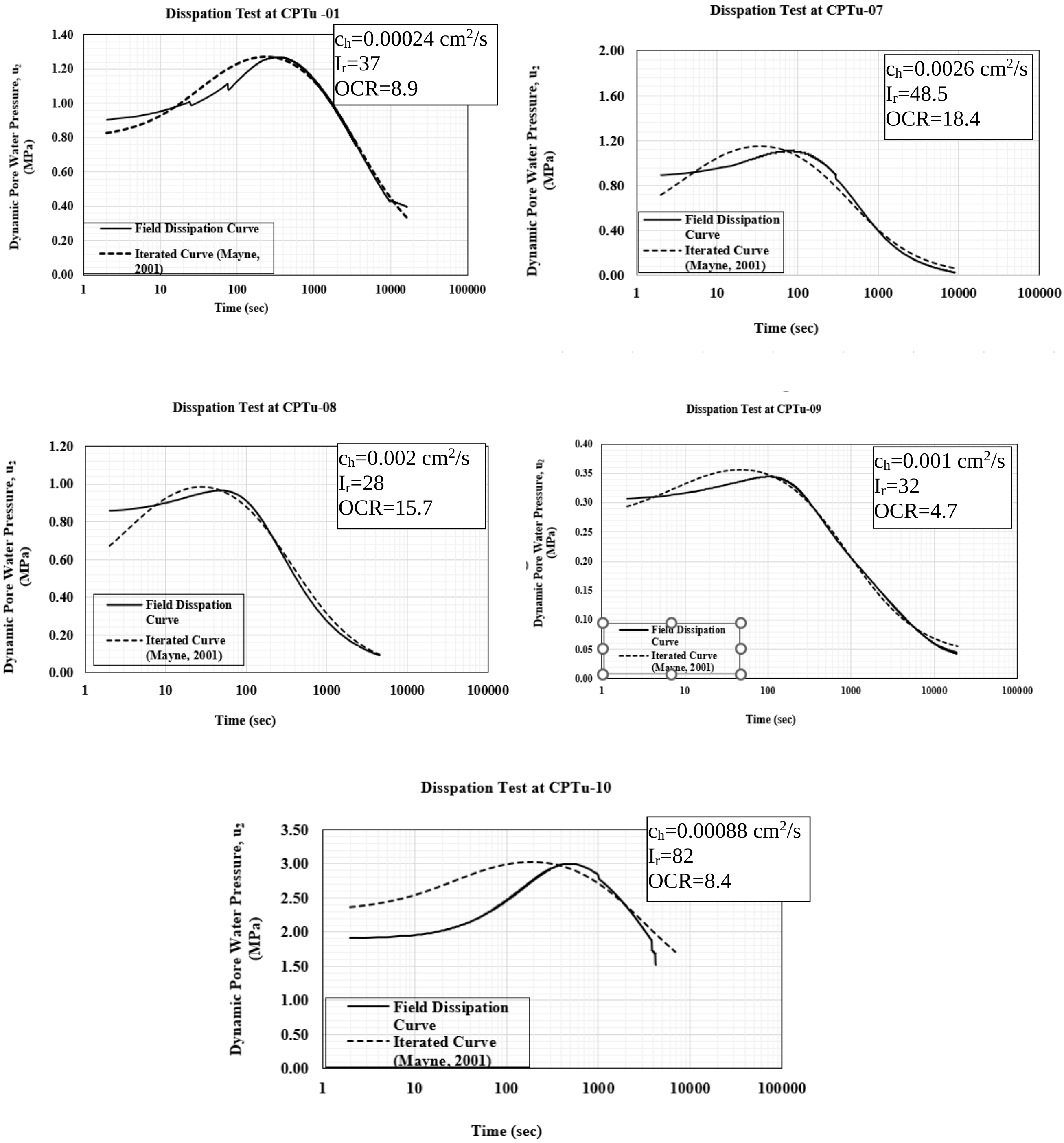


Figure 7: Determination of c_h using iteration method by Mayne (2001) for dilatory Curve at CPTu-01, CPTu-07, CPTu-08, CPTu-09 and CPTu-10

Table 4: Optimal values of the variables for the best-fit dissipation curve using Mayne's method

CPTu Dissipation Test Point	**Dissipation Type**	**Dissipation Depth (below EGL)**	**Water Table (below EGL)**	**Rigidity Index, I_r (in Iteration)**	**Over Consolidation Ratio (in Iteration)**	**Over Consolidation Ratio (from Laboratory test)**	**c_h (obtained from best-fit curve)**
		m	m				(cm^2/s)
CPTu-01	Dilatory	30.44	3.5	37	7.8	4.56	0.00024
CPTu-02	Monotonic	7.8	4.5	301	4.18	1.52	0.0023
CPTu-03	Monotonic	18.34	7.1	135	0.96	--	0.1
CPTu-04	Monotonic	19.58	6.5	188	0.95	--	0.088
CPTu-05	Monotonic	18.35	10.5	120	2.18	--	0.096
CPTu-06	Monotonic	27.95	7.8	240	0.85	--	0.097
CPTu-07	Dilatory	13.57	7.13	48.5	18.4	13.54	0.0026
CPTu-08	Dilatory	10.5	5.15	38	15.7	11.26	0.002
CPTu-09	Dilatory	10.92	4.1	32	4.7	2.3	0.001
CPTu-10	Dilatory	18.25	16.2	82	16.2	11.56	0.00078

4.3 Results from Tortensson's Method

Tortensson's method has been discussed in section 3.1.1. For both Cavity and Cylindrical expansion, T_{50} values have been estimated using the average of Equations 1 and 2 which came in a range of approximately 1.2-1.4. We considered the value of E/c_u = 100. Time for 50% dissipation has been obtained from Figure 3.1. The c_h value obtained from this method is approximately 0.17 cm^2/s, which is very close to the c_h values estimated using Teh and Houlsby's method. It should be noteworthy that this method is only applicable to monotonic curves.

4.4 Laboratory One-dimensional Oedeometer Test Result

One dimensional Oedometer test was performed for soil sample collected from six CPTu points which is shown in Table 5

Table 5: Vertical Coefficient of consolidation(c_v) value obtained from laboratory Oedometer test

CPTu Dissipation Test Point	**Dissipation Type**	**Sample depth (below EGL)**	**The Vercical Co-effient of Consolidation (c_v)**
		m	cm^2/s
CPTu-01	Dilatory	30.44	0.00134
CPTu-01	Monotonic	7.8	1.26
CPTu-07	Dilatory	13.57	0.0056
CPTu-08	Dilatory	10.5	0.0087
CPTu-09	Dilatory	10.92	0.0124
CPTu-10	Dilatory	18.25	0.00124

5.0 CONCLUSION

The piezocone dissipation test presents several advantages, particularly, in scenarios where laboratory facilities are inadequate. This paper provides an overview of the theoretical evolution of methods used to determine the horizontal coefficient of consolidation over time. Additionally, it analyzes data from ten dissipation tests conducted in Dhaka clay, employing several methods for the assessment. Five of the dissipation tests exhibited a monotonic behavior due to the presence of sand or silt in the clay, whereas the remaining five tests displayed a dilatory pattern.

For sandy clay or silty clay exhibiting monotonic dissipation curves, Teh and Houlsby's (1991) method yields better results compared to other approaches. However, Mayne's Iteration method has been considered to be more significant than all other methods for stiff clay or overconsolidated clay displaying a dilatory pattern of dissipation. This method not only yields approximately accurate value for in-situ c_h but also enables the interpretation of other parameters such as the Rigidity Index and OCR.

The laboratory OCR values were computed for the soils in some CPTu points to verify the accuracy of iterated values of OCR. In those points, The vertical consolidation coefficient (c_v) was also derived from the Laboratory Oedometer test, since this test does not directly provide the value for the horizontal coefficient of consolidation (c_h). Apart from Mayne's Iteration model or Teh and Houlsby's method, we can roughly estimate c_h value using Tortensson's cavity expansion equation for silty clay or Normally consolidated clay. The analysis of this paper has shown that the value of c_h obtained from Tortensson's equation is very close to Teh and Houlsby's approach.

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