C_{HP} VALUE FROM PIEZOCONE DISSIPATION TESTS

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ABSTRACT

A comprehensive understanding of soil properties requires time consuming and costly laboratory tests. There has been a lot of research for directly obtaining soil parameters from soil field investigation report to save both time and money. A similar approach has been taken in this study to correlate soil parameters with most commonly used soil investigation tools CPT (Cone Penetration Test). Piezocone test (uCPT) is now widely used as an economic and efficient site investigation method in geotechnical engineering. From the results of piezocone penetration and dissipation tests, soil profile and some of engineering properties of sub-soil, such as undrained shear strength (s_u) of clayey deposits, in situ hydraulic conductivity in horizontal direction (k_h) and coefficient of consolidation in the horizontal direction (c_{hp}) can be estimated. The symbol c_{hp} is used to emphasized the value is from piezocone test result. For a standard piezocone with filter for pore water pressure measurement at the shoulder of the cone (u_2 type), there are two types of dissipation curves. Standard and Non-standard curves are observed from the field piezocone dissipation tests. Two existing methods for estimating in-situ coefficient of consolidation in the horizontal direction (c_{hp}) from "non-standard" piezocone dissipation curves (initial u increased for a short period and then dissipated) are applied to the test results in 6 sites in Japan, Bangladesh, USA, UK, Italy and Canada. One method is correcting t_{50}, the time period of measured pore water pressure (u_2) dissipated from its maximum value to 50% of the maximum value (t_{50c} method), and another is extrapolating $\sqrt{t}$ (t is elapsed time) ~ u_2 curve ($\sqrt{t}$ method). The analysis results show that for most cases t_{50c} method results in higher c_{hp} value than that of $\sqrt{t}$ method, and it is reasoned that c_{hp} value from t_{50c} method is closer to the field "true" value. Comparing c_{hp} values from t_{50c} method with the corresponding laboratory measured coefficient of consolidation in the vertical direction (c_v) indicates that for most data c_{hp}/c_v ratios are varied from about 3 to about 10.

***Keywords**: Piezocone test, Dissipation test, Coefficient of consolidation, Pore water pressure, Soil profile.*

1. INTRODUCTION

Piezocone test (uCPT) is now widely used as an economic and efficient site investigation method in geotechnical engineering (e.g., Campanella & Robertson 1988; Lunne et al. 1997). From the results of piezocone penetration and dissipation tests, soil profile and some of engineering properties of sub-soil, such as undrained shear strength (s_u) of clayey deposits (e.g., Campanela & Robertson et al. 1988), in situ hydraulic conductivity in horizontal direction (k_h) (Chai et al. 2011; Robertson 2010) and coefficient of consolidation in the horizontal direction (c_{hp}) (e.g., Teh and Houlsby 1991; Chai et al. 2012a) can be estimated. The symbol c_{hp} is used to emphasized the value is from piezocone test result.

For a standard piezocone with filter for pore water pressure measurement at the shoulder of the cone (u_2 type), there are two types of dissipation curves observed from the field piezocone dissipation tests. One type shows monotonic decreasing of measured pore water pressure (u_2) with elapsed time and it is designated as "standard" curve (Baligh & Levadoux 1986; Teh and Houlsby 1991). Generally this type of curves occurs in normal or lightly over-consolidated clay deposits. Another type is that when dissipation test started, u_2 first increasing from an initial value to a maximum, and then decreasing to a hydrostatic value, which is referred as "non-standard" curve (Burns and Mayne 1998; Sully et al. 1999; Chai et al. 2012a), which often occurs in heavily over-consolidated clay deposit or dense sand deposit. Several methods have been proposed to estimate c_{hp} values from the standard dissipation curve, and perhaps Teh and Houlsby (1991)'s method is the widely used one. As for the non-standard curve, only few methods are available, such as Sully et al. (1999)'s methods of shifting time origin and extrapolation root-time ($\sqrt{t}$) verses pore water pressure curve and Chai et al. (2012a)'s method which corrects the time corresponding to 50% dissipation of the measured maximum u_2 value. However, Sully et al.'s shifting time origin method ignored the effect of redistribution of u values around the cone during the process of u_2 reaches the maximum value, and the method of extrapolation of $\sqrt{t}$ curve ($\sqrt{t}$ method) does not has a fundamental basis.

For the two methods proposed by Sully et al., $\sqrt{t}$ method can result in a slightly higher c_{hp} value than the shifting time origin method (Chai et al. 2012a). In this study, $\sqrt{t}$ method and t_{50c} method have been used to interpret field c_{hp} values from available field measured non-standard piezocone dissipation curves in the literature. It is demonstrated that generally, t_{50c} method results in a higher c_{hp} value. Comparing the estimated c_{hp} values with available laboratory measured corresponding coefficient of consolidation in the vertical direction (c_v), possible ratios of c_{hp}/c_v are investigated.

2. METHODS FOR ESTIMATING c_{hp} VALUE FROM NON-STANDARD DISSIPATION CURVES

2.1 Sully et al.'s $\sqrt{t}$ Method

Fig. 1 illustrates a non-standard dissipation curve of u_2 verses $\sqrt{t}$ (t is elapsed time) plot. $\sqrt{t}$ method issues that the initial part of measured dissipation curve is wrong, and can be corrected by extrapolating the close to linear part of the curve after the maximum value of u_2. Taking the value of u_2 at the intersecting location of extrapolation line and vertical axis as initial value of u_2 (u_{20}), the t_{50} is the time for u_2 dissipated to 0.5 u_{20}.

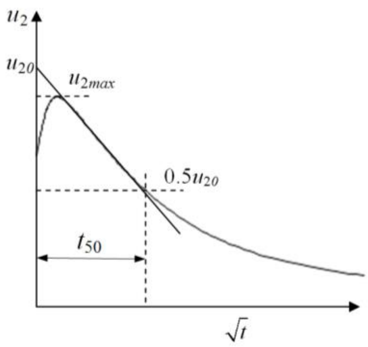


Figure 1: u verses $\sqrt{t}$ plot

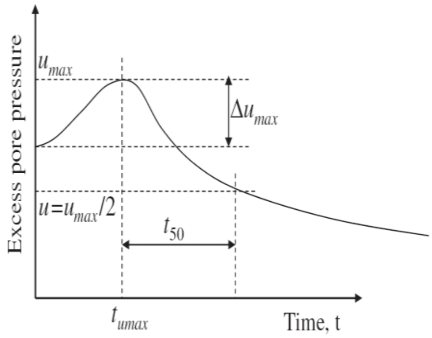


Figure 2: "Non-standard" curve (Chai et al. 2012a)

Then the value of c_{hp} is calculated as (Teh and Houlsby 1991):

$$c_{hp} = \frac{c_p . r_0^{\ 2} . \sqrt{I_r}}{t_{50}} \tag{1}$$

where: r_0 is the radius of the cone, and I_r is the rigidity index of soil. c_p is a factor corresponding to 50% degree of consolidation, which is related to the location of the filter element. For a cone with a shoulder filter element, c_p = 0.245 (Teh and Houlsby 1991).

2.2 Chai et al.'s t_{50c} Method

The reasons considered for causing the non-standard dissipation curves are: (1) cone penetration induced dilatancy of danse sand or over-consolidated clayey soil adjacent to the face of the cone and (2) partial unloading effect when a soil element moves from the face to the shoulder of the cone in case of a standard piezocone (Chai et al. 2012a). The dilatancy and partial unloading effects will result in an initial excess pore water pressure (u_2) at the shoulder of the cone lower than that in the zone adjacent and slightly away from the shoulder. Then the non-standard dissipation curve is the result of the "non-standard" initial excess pore water pressure distribution around the cone. By conducting uncoupled dissipation analysis with different initial u distribution using finite difference method, Chai et al. (2012a) proposed an empirical equation for correcting t_{50}, the time period for u_2 dissipated from its maximum value to 50% of the maximum value of the non-standard dissipation curve. Then with the corrected t_{50c}, c_{hp} value can be estimated using Eq (1). Fig. 2 illustrates a non-standard dissipation curve with some variables illustrated. The correction equation by Chai et al. (2012a) is as follows:

$$t_{50c} = \frac{t_{50}}{1 + 18.5\left(\frac{t_{u\max}}{t_{50}}\right)^{0.67}\left(\frac{I_r}{200}\right)^{0.3}} \tag{2}$$

where $t_{u\max}$ is time for measured excess pore pressure to reach its maximum value. Then substitute t_{50c} into Eq. (1) in the place of t_{50} to calculate value of c_{hp}.

3. c_{hp} VALUES FROM "NON-STANDARD" DISSIPATION CURVES

Non-standard dissipation curves at 6 sites in Japan, Bangladesh, UK, USA, Italy and Canada are collected and analyzed.

3.1 A Site in Saga, Japan

In Saga plain, around the Ariake Sea in Japan, exists a clayey soil (Ariake clay) deposit with a thickness of about 10 to 30 m. Piezocone penetration tests as well as dissipation tests at several depths were conducted at the site with its location shown in Fig. 3.

The test site is at the toe of a river embankment (Chai et al. 2004). At this site, the thickness of soft clay soil is about 12-14 m. The top crust is about 2.0 m thick and in an apparent over-consolidated state. Below it, the soil is normally to slightly over-consolidated. There is a borehole (BH) adjacent to piezocone test points (Fig. 4). Figure 5 shows some physical and mechanical properties of the soils retrieved from the BH. As shown in Fig. 4, piezocone penetration tests at six locations were arranged in three pairs, and each pair involved a continuous penetration test (Test point TA 1-1, 2-1 and 3-1) and a separate test that paused at about 1.0 m intervals to measure the dissipation of excess pore water pressure generated during the preceding penetration (Test point TA 1-2, 2-2 and 3-2). For the dissipation tests conducted at TA 3-2, there are some abnormal phenomena, and we judged that they are less reliable and excluded here. The ground-water level was about 0.8 m below the ground surface at BH location. Figure 6 shows some of the normalized field non-standard u_2 dissipation curves at TA 1-2 and TA 2-2 respectively. The normalization is made using the following equation:

$$U = \frac{u(t) - u_0}{u_{\max} - u_0} \quad (3)$$

where $u(t)$ is total pore water pressure at time t, $u_{\max}$ is maximum measured total pore water pressure, and u_0 is the equilibrium in situ pore water pressure at the depth of interest.

Figure 3: Location of the piezocone test site in Saga, Japan

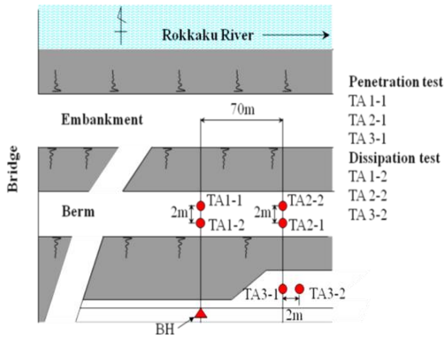
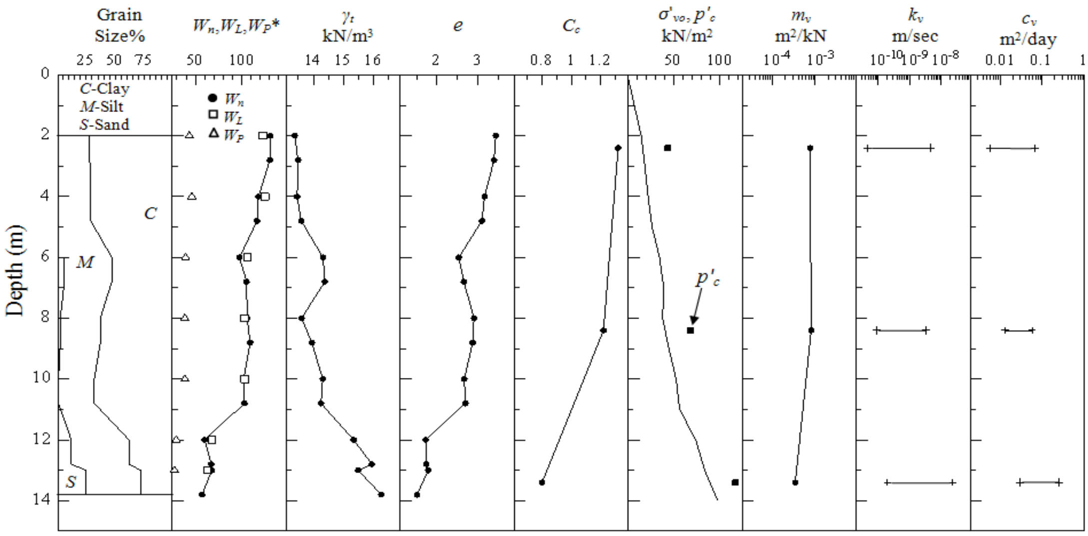


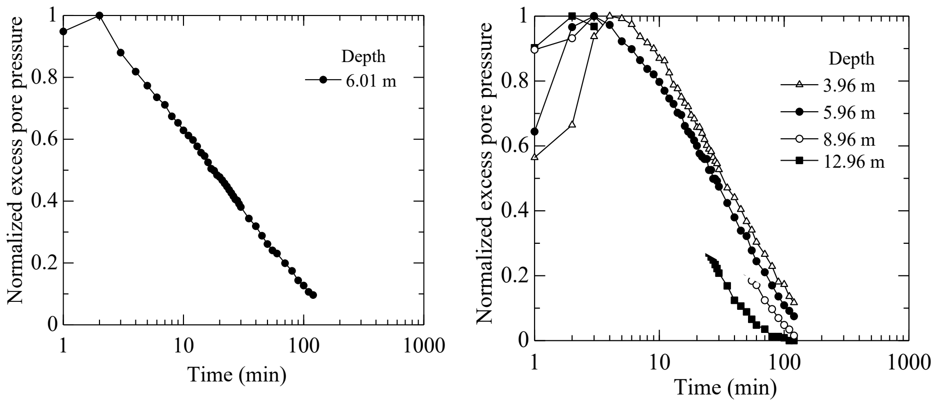
Figure 4: Plan layout of field tests (after Chai et al. 2004)



*W_n; Water content, W_l; Liquid limit, W_p; Plastic limit, γ_t; Unit weight, e; Initial void ratio, C_c; Compression index, m_v; volume compressibility; σ'_{vo}; vertical effective stress, p'_c; preconsolidation pressure, k_v; hydraulic conductivity and c_v; coefficient of consolidation in the vertical direction.

Figure 5: Some physical and mechanical properties of soil at Saga site

Most reported non-standard dissipation curves have been for heavily over-consolidated clayey deposits (Burns and Mayne 1998, Sully et al. 1999). The test results at Saga site indicate that the phenomena can also occur in some lightly over-consolidated soils. Using Eqs (1) and (2) to calculate c_{hp} value, I_r value of the deposit is needed. It has been reported that the Ariake clay deposits in Saga area has a ratio of E_{50}/s_u (E_{50} is the secant modulus at 50% of peak deviator stress from unconfined compression tests, s_u is undrained shear strength) between 100 and 200 (Chai et al. 2005). Assuming a poisson's ratio of 0.5 (undrained) and E_{50}/s_u ratio of 150, an I_r value of 50 can be obtained and it has been used in calculations.



TA 1-2 TA 2-2

Figure 6: Non-standard dissipation curves at TA site, Saga, Japan

c_{hp} values have been calculated by using $\sqrt{t}$ method and t_{50c} method from non-standard dissipation curves. The calculated c_{hp} values and some available values of coefficient of consolidation in the vertical direction (c_v) from laboratory consolidation tests are listed in Table 1.

Table 1: Summary of the field dissipation and laboratory consolidation test results at Saga site

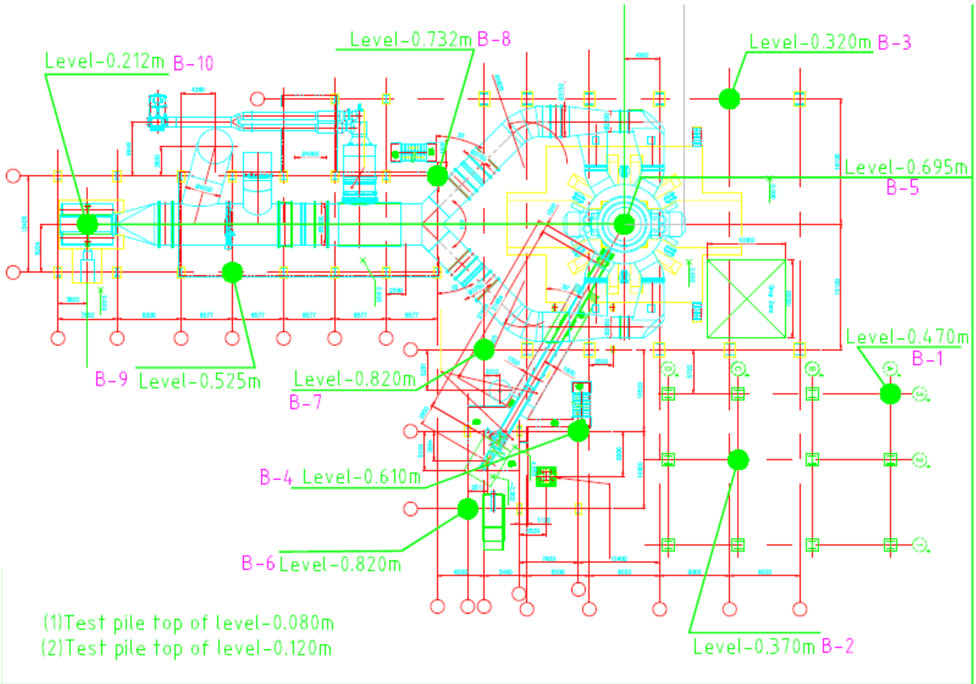
Test point No.	Depth (m)		t_{umax} (min)	u_{max} (kPa)	t_{50} (min)	t_{50m} (min)	c_{hp} (cm^2/min)		c_v (cm^2/min) Oedometer
	CPTu	Oedometer					$\sqrt{t}$ method	t_{50c} method	
TA 1-2	6.01	2.40*	2	252.12	16.00	3.97	0.831	1.400	0.375
TA 2-2	3.96		4	175.73	29.50	7.02	0.699	0.790	
	4.96		3	197.31	28.00	7.50	0.160	0.740	
	5.96		3	209.66	25.00	6.33	0.224	0.877	
	6.96		3	218.88	19.00	4.18	0.338	1.330	
TA 2-2	8.96	8.40	3	277.04	16.70	3.43	0.343	1.620	0.305
	9.96		2	301.35	21.00	5.95	0.275	0.932	
	10.96		2	324.01	21.00	5.95	0.276	0.932	
	11.96		2	349.90	22.50	6.59	0.308	0.842	
TA 2-2	12.96	13.40	2	391.87	11.50	2.40	0.537	2.310	0.711
	13.46		2	359.61	5.40	0.74	1.090	7.480	

*The value is the average depth of about 0.8 m long sample obtained by a thin-wall tube.

3.2 A Site in Munshiganj, Bangladesh

The data obtained through geotechnical investigation of proposed 'Shah Cement Vertical Roller Mill (VRM) Project was Situated in Muktarpur, Munsiganj, Bangladesh. Figure 7 shows The VRM project location map. SPT and Cone penetration and dissipation test was conducted at this site. Figure 8 shows the SPT and CPT Test locations in VRM project Site (DCL, 2016). There are 10 SPT test and 10 CPT tests are conducted which are shown in Figure 8. There are 15 piezocone dissipation tests were conducted. SPT test was conducted by 125mm diameter boring and soil sample are collected by soil sampler, 72mm diameter at the depth up to 50m. Test assessment and analysis was particularly concerned with the potential for the existing subsoil to support the proposed plant recommended foundation and to evaluate the groundwater conditions.

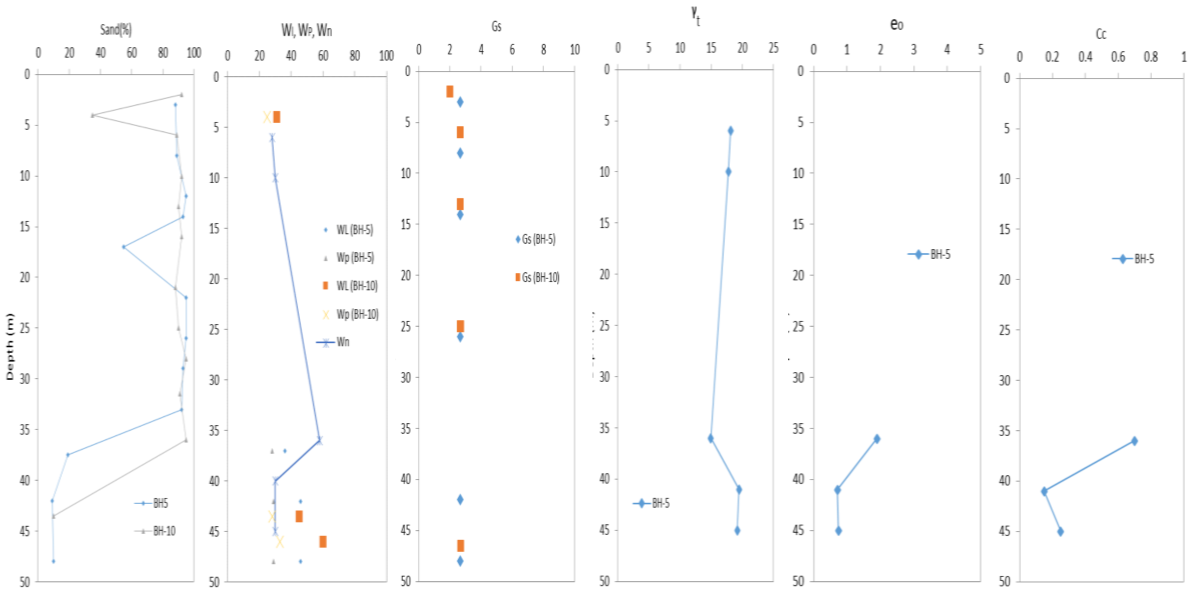
Figure 7: Location of the CPT test site in VRM Project, Munshiganj, Bangladesh



Shah Cement Bore Hole Level and Location Map	
Borehole/CPT No.	**Elevation (m)**
CPT-1/BH-1	-0.470
CPT-2/BH-2	-0.370
CPT-3/BH-3	-0.320
CPT-4/BH-4	-0.610
CPT-5/BH-5	-0.695
CPT-6/BH-6	-0.820
CPT-7/BH-7	-0.820
CPT-8/BH-8	-0.732
CPT-9/BH-9	-0.525
CPT-10/BH-10	-0.212
Test Pile#1	-0.080
Test Pile#2	-0.120

Figure 8: SPT and CPT Test locations in VRM project Site (DCL, 2016)

Figure 9 shows the summarize of some physical and mechanical properties of soil at the VRM project sites in Munshiganj. The test site is at the Pashur river embankment (DCL 2016). At this site, toplayer the thickness of sensitive, fine grained soil is about 0-.5 m. The top crust is about 0 to 2.0 m thick clayey silt to silty clay. Below it, the soil is fine sand normally to slightly over-consolidated at the depth of 2-3m. The condition of the soil 3 to 5m is clay silt to silty clay and 6m to 40m layer is sand mixed with silty clay. Clayes clay to silty clay are present in 40m to 50m depth.



*w_n: Water content, w_l: Liquid limit, w_p: Plastic limit, G_s: Specific gravity, γ_t: Unit weight, e_o: Initial void ratio and C_c: Compression Index

Figure 9: Some physical and mechanical properties of soil at Munshiganj Site, Bangladesh

Cone penetration was carried out using cones 60^0 apex angle and 225 cm^2 friction sleeve area advance using a 20 Ton hydraulic penetrometer. Throughout the test the cone was advanced by applying thrust on 1m long 36mm diameter rod at a rate of 2.0cm/sec. Tip resistance of the cone, slave friction and pore water pressure are measured from cone penetration test in Munshiganj VRM site which is shown in Figure 10 (DCL, 2016). 15 nos cone penetration dissipation tests are conducted in this site. From dissipation curves it is depicted that 13 nos curves are Standard dissipation curves and 2 nos are Non-standard dissipation curves.

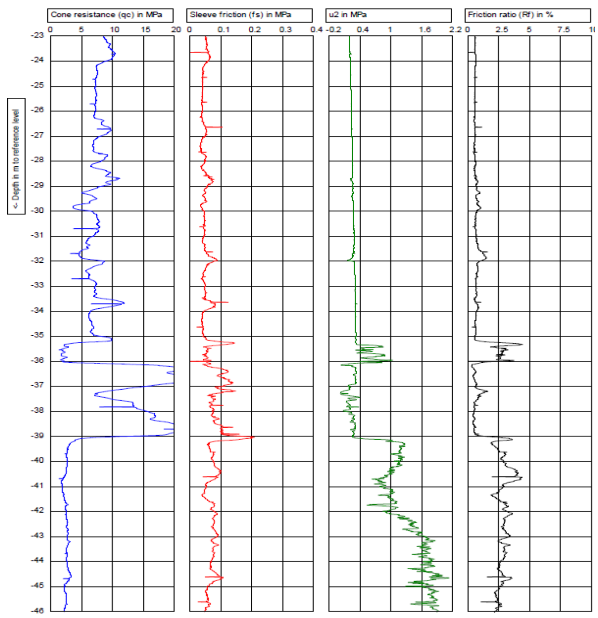


Figure 10: Cone Penetration Test (test-1) results in VRM project Site (DCL, 2016)

Figure 11 show the normalized non-standard dissipation curves at Munshiganj sites in Bangladesh. Table 2 presents a summary of the field CPTu dissipation test results and calculated c_{hp} values. In the calculation I_r of 100 has been assumed.

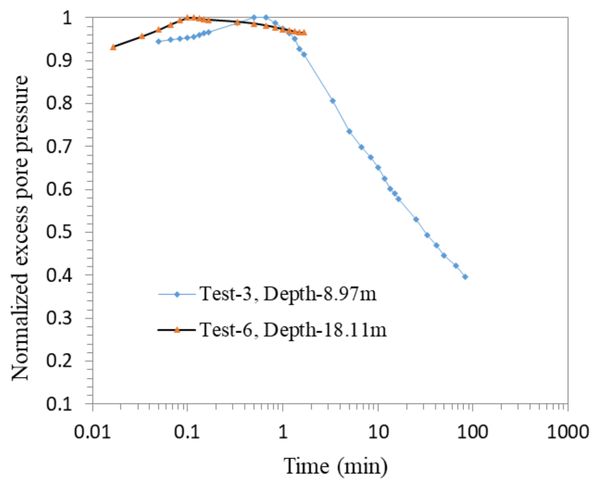


Figure 11: Non-standard dissipation curves at Munshiganj Sites, Bangladesh

Table 2: Field dissipation test results at Munshiganj Site in Bangladesh

Test point No.	Depth (m) CPTu	t_{umax} (min)	u_{max} (kPa)	t_{50} (min)	t_{50m} (min)	c_{hp} (cm^2/min) $\sqrt{t}$ method	c_{hp} (cm^2/min) t_{50c} method
C T 3-1	8.97	0.67	83	32.66	15.46	0.112	0.356

3.3 Other Available Sites

The results of four (4) field cases, Canon's Park; UK (Bond and Jardine 1991), St. Lawrence Seaway; N.Y. (Lutenegger and Kibir 1987); Taranto, Italy (Battaglio et al. 1986) and University of British Columbia test site (Sully et al. 1999) with "non-standard" dissipation curves are summarized in Table 3. The corresponding normalized dissipation curves are shown in Fig. 12.

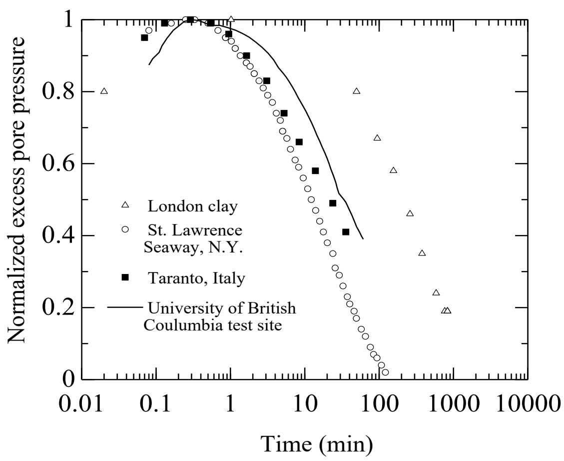


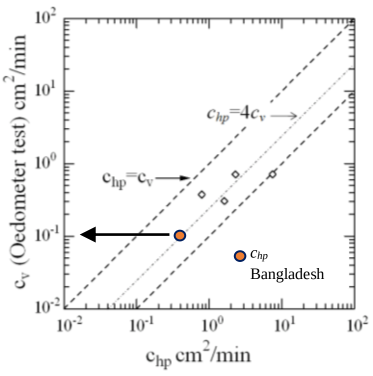
Figure 12: Non-standard dissipation curves at others test sites (Chai et al. 2012a)

Table 3: Field dissipation and laboratory consolidation test results at four sites

No	Site	Depth (m)	Diameter of cone (mm)	u_{max} (kPa)	I_r	OCR	c_{hp} (cm²/min) $\sqrt{t}$ method	c_{hp} (cm²/min) t_{50c} method	c_v (cm²/min) Oed.	References
1	Londone clay at Canon's Park, UK	5.70	102.0	377.6	100	14	0.040	0.408	0.012-0.018	Test data from Bond and Jardine (1991); Burns and Mayne (1998)
2	Crust of soft clay at St. Lawrence Seaway, N.Y.	6.10	35.7	291.2	50	3.5	0.603	1.032	0.15-0.48	Lutenegger and Kibir (1987); Burns and Mayne (1998)
3	Cemented clay, Taranto, Italy	9.00	35.7	1693.8	200	26	0.658	1.032	0.06-0.15	Battaglio et al. (1986); Burns and Mayne (1998)
4	Strong pit clay, University of British Columbia test site	6.65	35.7	1261.1	200	4.0	0.441	0.630	OC:0.12-0.3 NC:0.042-0.06	Sully et al. (1999)

4. COMPARISON OF c_{hp} AND c_v VALUES

From the results in Tables 1, 2 and 3, it clearly shows that c_{hp} values estimated by t_{50c} method are higher than that from $\sqrt{t}$ method. Since $\sqrt{t}$ method does not consider the fundamental mechanism of causing non-standard dissipation curve, and we believe that the results from t_{50c} method are closer to "true" field values. Therefore, comparisons of the values of c_{hp} from t_{50c} method and laboratory c_v values are plotted in Figs. 10 for one site in Saga, Japan, and other four sites, respectively. c_v values are not got available from Munshiganj sites, so it is not possible to comparison of c_v and c_{hp} values. For almost all cases, $c_{hp} > c_v$. Although the data are scattered, for the data from the site in Saga, Japan *chp~4cv*. There are two reasons for $c_v < c_{hp}$. One is that the laboratory c_v is generally lower than the corresponding field value. Chai and Miura (1999) reported that for Ariake clay deposit in Saga, Japan, field c_v value is about 2 times of the corresponding laboratory value. Another reason is due to anisotropic consolidation behavior of clay deposit, and normally the coefficient of consolidation in the horizontal direction is higher than that in the vertical direction. For Ariake clay, Chai et al. (2012b) reported a c_h/c_v ratio of about 1.6 from laboratory constant rate of strain (CRS) consolidation test results. Combining these two factors, a c_{hp}/c_v ratio of about 3.2 can be obtained. Therefore, for the results from the site in Saga, Japan, c_{hp}~$4c_v$ is quite reasonable. The data from Munshiganj, Bangladesh the values corresponding c_v are measured from c_{hp} values with an average c_{hp}/c_v ratio of about 4 (Fig. 13 (a)). For other four (4) sites investigated, c_{hp} is about 3 to 30 times of c_v.



Saga, Japan

Figure 13: Comparisons of c_{hp} and c_v (Oedometer) values

5. CONCLUSIONS

Two methods, for estimating field coefficient of consolidation in the horizontal direction (c_{hp}) from non-standard piezocone dissipation curve (measured excess pore water pressure (u_2) initially increases and then decreases), namely, Sully et al. (1999)'s extrapolation of root time versus u_2 plot ($\sqrt{t}$ method) and Chai et al. (2012a)'s correcting t_{50} method (t_{50c} method) are applied to field measurements from 11 sites in Japan, Bangladesh, USA, UK, Italy and Canada.

The estimated c_{hp} values from both the methods are compared each other as well as with the laboratory measured coefficient of consolidation in the vertical direction (c_v).

(1) Generally t_{50c} method results in higher c_{hp} value than that of $\sqrt{t}$ method. Using the available information about Ariake clay deposit in Saga, Japan, it has been shown that with c_{hp} value from t_{50c} method, the ratio of c_{hp}/c_v is closer to the "true" field value.
(2) For most of the data from 11 sites, c_{hp}/c_v ratios varied from about 3 to about 10.
(3) From the data of Munshiganj site c_v value is measured from the correlation of c_{hp}/c_v ratios which is reasonable.

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