Piezoprobe test interpretation on soft clay

Interprétation du test piézométrique sur l'argile molle

Francisco Gabriel Hernández Martínez
Engineering and Design, Barr Engineering Co., USA, FHernandezMartinez@barr.com

Alireza Mirdamadi
Offshore Geotechnics, NGI Houston, USA

Tom Lunne, Shaoli Yang
Offshore Geotechnics, NGI Oslo, Norway

ABSTRACT: This paper describes and compares different methods to interpret dissipation tests on soft clays by using piezoprobe tests. Emphasis is given to estimate initial pore-water pressure (u_i), in situ equilibrium pore-water pressure (u_0) and horizontal coefficient of consolidation (c_h). In this regard, it is important to interpret precise values for u_i and u_0 in order to better define dissipation curves and obtain more reliable c_h values. Current approaches to estimate u_i are visual inspection and a $\sqrt{t}$ method whereas attitudes to evaluate u_0 fall into simple-empirical (e.g. 1/t and $1/\sqrt{t}$ methods) and numerical back analysis. Further c_h is commonly evaluated based on methods such as Torstensson, Levadoux and Baligh, and Houlsby and Teh. In this study, these methods are described and they are used for interpreting dissipation tests on clay obtained at an onshore site and five different offshore sites. c_h estimated from dissipation tests are compared with corresponding laboratory results.

RÉSUMÉ: Cet article décrit et compare différentes méthodes pour interpréter les tests de dissipation sur les argiles molles en utilisant des tests piézométriques. L'accent est mis sur l'estimation de la pression interstitielle initiale de l'eau (u_i), de la pression interstitielle d'équilibre de l'eau (u_0) et du coefficient de consolidation horizontal (c_h). A cet égard, il est important d'interpréter des valeurs précises pour u_i et u_0 pour mieux définir les courbes de dissipation et obtenir des valeurs c_h plus fiables. Les approches actuelles pour estimer u_i sont l'inspection visuelle et la méthode $\sqrt{t}$ alors que les attitudes pour évaluer u_0 tombent dans des méthodes empiriques simples (par exemple, les méthodes 1/t et $1/\sqrt{t}$) et numériques. De plus c_h est couramment évalué sur la base de méthodes telles que Torstensson, Levadoux and Baligh, et Houlsby et Teh. Dans cette étude, ces méthodes sont décrites et sont utilisées pour interpréter des essais de dissipation sur de l'argile obtenue sur un site onshore et cinq sites offshore différents. c_h estimés à partir des essais de dissipation sont comparés avec les résultats de laboratoire correspondants.

KEYWORDS: Piezoprobe, dissipation tests, coefficient of consolidation, soft clay.

1 INTRODUCTION

Determination of reliable measurement of in situ equilibrium pore-water pressures (u_0) and whether it deviates from hydrostatic conditions is relevant for better understanding stability of sediments. In geohazards studies, pipeline and foundation designs, and prediction of formation pore-water pressure for tophole well integrity, certainly of excess pore-water pressure presence will have consequences since it affects effective stresses in the soil and hence the shear strength properties.

Generally, in situ pore-water pressure values are not available for foundation design so hydrostatic pore-water pressure is commonly assumed. This assumption could not always be the case because at some sites, in situ pore-water pressure differs from hydrostatic conditions. Such cases may occur due to: rapid sedimentation of low permeability material on the soil layer in young sedimentary basins (Flemings et al., 2008), fluid seepage, gas hydrate dissociation-dissolution, and sudden loading such as earthquake (Sultan and Lafuerza, 2013). Moreover, in offshore environment water density varies with depth so it is difficult to calculate the hydrostatic pressure accurately at the test location. Thus, determining pore-water pressure is relevant for confirming whether hydrostatic pore-water pressure prevails.

Measurement of in situ pore-water pressure is commonly determined by using piezocone dissipation tests but such tests are often not that cost-effective due to the long time required to reach equilibrium conditions mainly in clayey soils (e.g. one or more days) (DeGroot and Lunne, 2002). Because the time to achieve full dissipation for a cylindrical probe is proportional to the square of the probe diameter, it would be desirable to use a smaller diameter probe than the standard piezocone (with standard area of 10 or 15 cm^2) as this would significantly reduce the required dissipation time.

Small diameter piezoprobes (with typical areas of 0.32 cm^2) have been developed to accelerate the dissipation decay (Figure 1). Piezoprobes have been introduced by different shapes but the most common geometry is a tapered piezoprobe with a pore-water pressure sensor located at tip with radius = 3.2. Whittle et al. (2001) showed that there is not significant improvement in the total time dissipation in the piezoprobe as the dissipation around the small diameter rod is influenced by the larger diameter shaft above. This event generates a plateau (bench) at the end of the dissipation curve observed in log scale that may be mistaken as the equilibrium pressure in interpreting the curve.

Figure 1. Piezoprobe and piezocone (DeGroot and Lunne 2002).

In order to overcome this drawback, Whittle et al. (2001) proposed a modification on the tool by placing a second porous filter above the tapered section and estimating the in situ pore-water pressure by two-point matching of incomplete dissipation records. However, DeGroot and Lunne (2002) indicated that the proposed interpretation method by Whittle et al. (2001) could still be improved since there are too many uncertainties assorted with using the proposed method. Therefore, caution should be taken for implementing this into practice.

In order to minimize uncertainly on the dissipation tests interpretation, this paper has the purpose to describe the available methodology for interpreting dissipation tests with emphasis on three key parameters u_i, u_0 and c_h.

1 .1 *Initial pore-water pressure, u_i*

Determination of accurate initial pore-water pressure from dissipation tests is important since this directly affects the evaluation of other parameters, u_0 and c_h. It is therefore necessary to differentiate between initial pore-water pressure and penetration pore-water pressure at the beginning of the measurement. The difference in these values are due to: drainage along the probe surface from the tip to the shaft, and the redistribution of stresses after probe penetration (Soares et al., 1987) and consequently a correction is needed. Soares et al. recommended two methods to correct the initial value of pore-water pressure; i) visual inspection and ii) √t method.

The visual inspection method consists of observing the initial part of the dissipation test and to determine whether or not recorded data have good quality. Dubious data have to be deleted. In the √t method according to Soares et al. the following four steps are suggested for performing an initial pore-water pressure correction: i) Plot the measured pore-water pressure (u) versus √t after deployment of the tip into the soil, ii) Back extrapolate the curve with a straight line for the time period covering less than 10% of pore-water pressure dissipation, iii) Find the u-intercept (√t = 0) and iv) Report the u value as the u_i. In the step ii) in order to have better regression value for the straight line one may need to ignore some initial points.

1 .2 *In situ equilibrium pore-water pressure, u_0*

The significance of finding equilibrium pore-water pressure is the main interest for evaluating effective stresses of the soil and consequently better define problems related to geotechnics. Different methods for estimating u_0 are available. These vary from coupled numerical analyses to simple empirical. Coupled models have been presented to extrapolate the partial pressure dissipation data and interpret the in situ pore-water pressure (Randolph and Wroth, 1979; Whittle et al., 2001; Long et al., 2007; Sultan and Lafuerza, 2013). These methods require extensive geotechnical testing and numerical analysis in order to calibrate the parameters and predict the in situ equilibrium pore-water pressure.

In this paper, two simple empirical approaches, 1/t (Davis et al., 1991) and 1/√t (Flemings et al., 2008), have been used to extrapolate in situ pore-water pressure. There is no theoretical proof for these methods (Flemings et al., 2008), however, they are very efficient in interpretation of u_0. Flemings et al. found that the 1/√t method can predicts u_0 in earlier time (using only partial dissipation curve) with a better accuracy than 1/t method. Figure 2 shows an example of error comparison between 1/t and 1/√t methods. This example shows that the 1/√t method predicts u_0 with error of less than 5% at early dissipation time while the error from the 1/t method is always larger than the 1/√t method. Note that in Figure 2, δu is the difference between the predicted value and the actual value; Δu is the pressure induced during insertion.

Briefly, herein *u_0* interpretation was done by using two simple empirical methods. The procedure is similar in both methods and consist of four steps: i) Plot pore-water pressure (u) versus 1/t or 1/√t, ii) Extrapolate the curve at the last section of measured pressure with straight line, iii) Find the u-intercept (1/t = 0 or 1/√t = 0), and iv) Report the u value of this point as u_0.

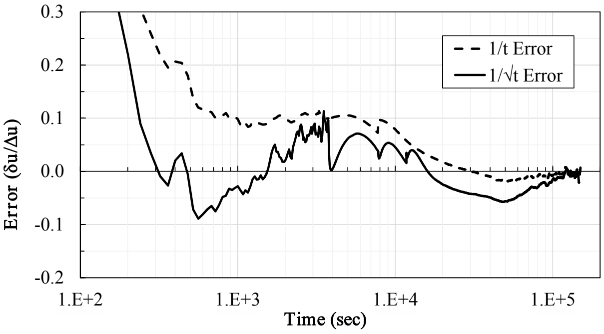

Figure 2. Predicted error in estimating in situ equilibrium pore-water pressure (u_0) versus corresponding prediction time.

1 .3 *Horizontal coefficient of consolidation, c_h, from dissipation test*

One of the important output from piezocone or piezoprobe dissipation tests is the horizontal coefficient of consolidation and as a result the horizontal coefficient of permeability (k_h). Several methods have been developed and used to estimate the c_h value (Torstensson, 1977; Randolph and Wroth, 1979; Levadoux and Baligh, 1986; Gupta and Davidson, 1986; Soares et al., 1987; Houlsby and Teh, 1988). In some literature, the value of k_h is calculated directly from the dissipation curve (Whittle et al., 2001). In this study, estimation of c_h was done based on three well known methods: Torstensson, Levadoux and Baligh, and, Houlsby and Teh. The c_h is calculated by matching the dissipation curve to the analytical one. For all of the methods normalized time (T) different degree of consolidation are given.

The most common picked T is at 50% of consolidation. Table 1 presents the features of the theoretical methods used in this study in order to estimate c_h. Notation in Table 1 is as follows; c_h = Horizontal coefficient of consolidation, T_{50} = predicted time factor at 50% consolidation degree for a selected location and assumption, r = radius of the cavity, t_{50} = measured time to reach 50% consolidation degree and I_r = Rigidity index of the soil= G/s_u.

Table 1: Solutions to calculate c_h from piezocone/piezoprobe dissipation tests (Lunne et al., 1997)

Author	*Soil model*	*Consolidation*	*Equation*
Torstensson	Elastoplastic	1-D	$c_h = \frac{T_{50} \cdot r^2}{t_{50}}$
Levadoux and Baligh	Non-linear (I_r=500)	2-D	$c_h = \frac{T_{50} \cdot r^2}{t_{50}}$
Houlsby and Teh	Non-linear	2-D	$c_h = \frac{T_{50} \cdot \sqrt{I_r} \cdot r^2}{t_{50}}$

The first approach suggested by Torstensson is based on cylindrical or spherical cavity expansions. The pore-water distribution trend and time factor depend on the rigidity index of the soil. The other two methods use the strain path method to calculate the initial pore-water pressure and pore-water pressure distribution around the piezocone. They modeled the shape of piezocone and present the T value for different locations on the piezocone. Table 2 tabulates the proposed values of T at different levels of consolidation and different assumption for each of the three used methods. In this study the results are based on cylindrical expansion, 60° cone base, and cone shoulder, respectively.

Table 2: T-factors at different level of consolidation (Torstensson, 1977; Levadoux and Baligh, 1986; Teh and Houlsby, 1991).

Author and assumption		Consolidation level, U% 80%	60%	50%	40%	20%
Torstensson	$E/s_u = 200$	0.18	1.06	2.32	3.82	10.13
	$E/s_u = 300$	0.24	1.38	2.81	5.37	16.29
	$E/s_u = 400$	0.30	1.75	3.57	6.79	21.0
	$E/s_u = 500$	0.34	2.14	4.29	8.33	23.6
Levadoux and Baligh	60° tip	0.44	1.90	3.70	6.50	27.0
	60° cone base	0.69	3.00	5.60	10.0	39.0
	60° shaft	7.30	22.0	33.0	47.0	114.0
Houlsby and Teh	Cone tip	0.001	0.027	0.069	0.154	0.829
	Cone face	0.014	0.063	0.118	0.226	1.04
	Cone shoulder	0.038	0.142	0.245	0.439	1.60
	5r above cone shoulder	0.294	0.756	1.11	1.65	4.10
	10r above cone shoulder	0.378	0.995	1.46	2.14	5.21

2 EXAMPLE ON RECOMMENDED METHODOLOGY

The Norwegian Geotechnical Institute (NGI) has been involved in several projects where piezoprobe test were conducted and data is available. Results are accessible for an onshore site located in Norway (Onsøy), and offshore sites located in the Caspian Sea (CS), the Gulf of Guineas (GoG) and the Gulf of Mexico (GoM). For simplicity, an example is presented which follows the recommended methodology. The example uses dissipation tests performed at 10m depth in the Norwegian onshore Onsøy site.

2 .1 *Onsøy site data*

The Onsøy site consists of a thick deposit of a uniform marine clay and has been used for research purposes by NGI for many years (Lunne et al., 2006). The clay has a plasticity index (PI) between 30 to 50% and the permeability (k) ranges between 5×10^{-10} m/s to 5×10^{-9} m/s with anisotropy factor of one (DeGroot and Lunne, 2002).

A set of piezocone and piezoprobe tests were performed on this site during 2000 and 2002. The employed piezoprobe in this project was the modified version of piezoprobe presented by Whittle et al., (2001) which includes a second porous filter above the taper section (Figure 1). For this case, the u_0 (which in this case equals to hydrostatic pressure) was measured by a separate test with piezometer. The first investigation on the data indicates that measure pore-water pressure, u, at piezoprobe-tip tends to dissipate faster as compared to values obtained at the shaft and from piezocone. The methodology used herein is separated in four steps as follows.

2.1.1 *Step 1, estimation of u_i*

In order to get the initial pore-water pressure (u_i), the visual inspection and √t methods were used. Figure 3 presents the u versus √t at piezoprobe tip sensor. As indicated in the figure, the first point was neglected (simple inspection) in order to have the best regression and a straight line was fitted on the linear part of the curve. The u_i=270 kPa is estimated based on the u axis intercept.

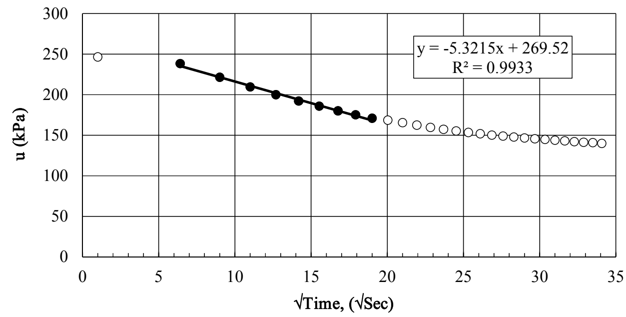

Figure 3: Pore-water pressure at the beginning of the piezoprobe test versus

2.1.2 *Step 2, estimation of u_0*

Next step is to compute u_0 which should be equal to u_h (hydrostatic pressure) for the case of the Onsøy site. Figure 4 presents a figurative procedure of both 1/t and 1/√t methods in one chart to predict u_0 at different times for piezoprobe-tip results only. The predicted errors versus corresponding time from both methods are presented in Table 3. As it is shown in Figure 2, generally the error is less using the 1/√t method as compared to the error obtained using the 1/t method and besides by using the 1/√t method u_0 could be determined in shorter time (e.g. with the 1/√t method 5% error is obtained just after 250 sec of measurement while the error using 1/t method becomes less than 5% after 10000 sec). These results show a good consistency with those reported by Flemings et al. (2008).

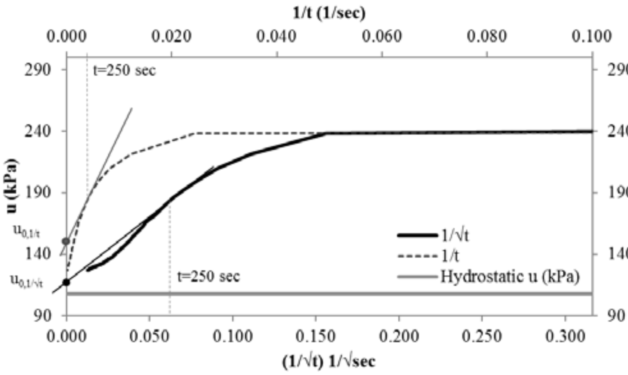

Figure 4: u versus 1/t and 1/√t

2.1.3 *Step 3, estimation of c_h*

After estimation of u_i and u_0 one can determine the consolidation curve and the dissipation time corresponding to 50% of consolidation (t_{50}). According to Figure 5, the t_{50} is 220 sec using piezoprobe test and 3000 sec using piezocone test. Note that a small change in estimations of initial and equilibrium pore-water pressure may alter the t_{50} value in range of 10 times (Levadoux, 1980).

Using t_{50} and described solutions, the c_h value is calculated. In the calculation, the piezoprobe tip radius of 3.2 mm and piezocone and piezoprobe-shaft radius of 17.8 mm are used. In the Onsøy site the E/s_u was estimated 300 therefore $I_r=G/s_u=E/3s_u=100$ (Soares, 1985). The interpreted c_h at 50% consolidation from Torstensson, and Houlsby and Teh are in a same range. Levadoux and Baligh method on the other hand, estimates higher value of c_h. Vertical coefficient of consolidation, c_v, from laboratory test is a range from 3 to 5 m^2/year (Soares, 1985), which agrees with the interpreted c_h knowing that for this site anisotropy factor equals to 1.

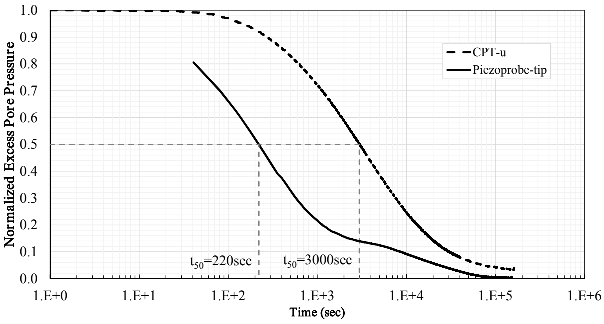

Figure 5: consolidation curve of piezoprobe and piezocone and t_{50} estimation

2.1.4 *Step 4, Dissipation curve vs normalized time*

The final outcome after finding c_h value is the pore-water dissipation curve versus normalized time (T).

3 RESULTS

The methodology described above for the Onsøy site is used for five offshore sites as well where dissipation tests are available. The calculated u_i, u_0, and c_h with different methods at each site are presented in Table 3. Based on site history and geophysical data, in-situ pore pressure in all sites is assumed hydrostatic and the values of u_0 and c_h are predicted based on 50% pore-water pressure dissipation meaning that the test data is partially measured until half of consolidation.

Table 3: Summary of dissipation results for one onshore site and five offshore sites

	Initial pore pressure		Equilibrium pore pressure					Coefficient of consolidation			
Site	Simple inspection	Root time	Calculated hydrostatic	1/t	1/√t	Error (%)		Torstensson	Baligh & Levadoux	Houlsby & Teh	Laboratory
	u_i (kPa)		u_0 (kPa)			$\left(\frac{\Delta u_{0,\frac{1}{t}}}{\Delta u_i}\right)$	$\left(\frac{\Delta u_{0,\frac{1}{\sqrt{t}}}}{\Delta u_i}\right)$	c_h (m^2/yr)			c_v (m^2/yr)
Onsøy	281	296	93	143	99	27%	3%	9.4	18.8	8.2	3-5
	252	264	93	140	109	30%	10%	9	18	7.9	
	247	270	108	154	118	33%	7%	4.1	8.2	3.6	
CS	2718	2740	2230	2377	2240	30%	2%	3.3	4.3	2.4	10.4
	8468	8574	2910	4683	3566	32%	12%	0.8	1.6	0.7	0.7
GoG1	14500	14550	13900	14142	13985	40%	14%	9.6	19.2	8.4	7
	15790	15830	14500	14863	14548	28%	4%	11.1	22.1	9.7	5.2
	14500	14560	13800	14034	13903	33%	15%	7.4	14.7	6.4	7.3
	15672	15727	14460	14851	14689	32%	19%	20.1	40.1	17.6	
	16507	16538	14760	15377	14974	35%	12%	18.5	36.8	16.1	
GoG2	12167	12168	12037	12060	12019	18%	-14%	5.7	11.3	5	0.4-1.5
	12460	12475	12283	12331	12288	27%	3%	4.4	8.8	3.8	1.3-3.6
	11556	11555	11093	11233	11143	30%	11%	0.4	0.8	0.4	0.6-1.7
GoM1	22194	22208	-	21957	21885	-	-	0.05	0.10	0.04	1.55 - 2.86
	22109	22120	-	21968	21940	-	-	0.09	0.18	0.08	-
	22003	22016	-	21866	21835	-	-	0.62	0.82	0.46	24.6-24.8
	22273	22307	-	22000	21940	-	-	0.77	1.00	0.57	24.6-24.8
	21656	21683	-	21366	21277	-	-	1.25	2.49	1.09	0.74-1.12
	21358	21371	-	21258	21230	-	-	0.82	1.60	0.71	0.43-0.90
GoM2	19154	19192	18871	18960	18890	31%	7%	3.7	7.4	3.2	0.4-0.7
	19200	19214	18954	19034	18984	33%	12%	2	4	1.8	0.5-1.2

4 CONCLUSIONS

From results obtained, the following conclusions can be drawn; Results show that √t method gives us a higher estimation of u_i than simple visual inspection. The average of difference between root time and visual inspection method over excessive pore-water pressure, $(u_{inspection}-u_{root})/(u_{inspection}-u_0)$, is +6% with standard deviation (S) of 4%.

For in situ prediction, 1/√t method can predict the u_o in earlier time and with better accuracy compare to 1/t method. However, this method can under predict the u_0 in specific dissipation time frame.

The calculated c_h from field tests results using different solutions are also compared with c_v evaluated from the laboratory tests. Although, it is difficult to compare the vertical and horizontal coefficient of consolidation, according to the results in the sites (e.g. Onsøy and GoG1) where the anisotropy factor is about 1, the Torstensson and Houlsby and Teh estimations are more reliable than those obtained using the Baligh and Levadoux method. Generally, the method by Baligh and Levadoux gives c_h values in the high side (2 to 4 times), a reason of this discrepancy could be the fact that this method use a higher I_r (500).

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