Interpretation of incomplete dissipation tests of excess pore pressure generated during cone penetration test

Interpretação de ensaios incompletos de dissipação de excessos de poropressão gerados durante ensaio de penetração de cone

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ABSTRACT: This paper analyzes the results of incomplete and complete dissipation tests of excess pore pressure generated during piezocone penetration tests on clayey soils from an iron mining tailings dam. Two methods were used to determine the time required to dissipate 50% of the excess pore pressure (t_{50}) and calculate the coefficient of horizontal consolidation (c_h). The first method, by Houlsby & Teh (1991), involves waiting for pore pressure stabilization, which can be time-consuming. In this method, the excess pore pressure was graphed against the square root of time, and the rectilinear section was extended to indicate the pore pressure at time zero, then plotted against time on a logarithmic scale with data shifted to determine the pore pressure at time zero. The second method, by Pereira (2017), used only part of the dissipation test readings simulating incomplete tests. Comparing the results, the t_{50} values from the second method generally fell between those calculated using the first method, graphed as a function of the square root of time and with the time on a logarithmic scale. The second method offers a practical way to reduce test durations, though it is important to consider potential differences in calculated horizontal consolidation coefficients compared to the first method.

KEYWORDS: pore pressure, dissipation test, horizontal consolidation coefficient, test duration.

1 INTRODUCTION

Rosa and Marques (2019), when studying the estimation of the consolidation coefficient from the results of dissipation tests of excess pore pressure conducted during CPTu (cone penetration test with pore pressure measurement) tests, report the difficulty in interpreting the data due to the incomplete dissipation of excess pore pressure (definition of the stabilization pore pressure). Baroni (2010) exposes difficulties in achieving 70% dissipation, even with waiting time on the order of three hours. According to Krage et al. (2015), low permeability clays may require a test time of 6 to 24 hours to obtain the t_{50} value (time required for 50% dissipation of excess pore pressure generated due to CPTu penetration), making it expensive and difficult to complete such a test in one day. This dissipation time is necessary for calculating the horizontal consolidation coefficient and the permeability of the medium where the CPTu test is being conducted.

Considering this issue, Pereira (2017) proposed a methodology for determining the t_{50} value by performing a polynomial fit to the excess pore pressure dissipation curve obtained during CPTu tests. This adjustment allows the dissipation test to be performed in reduced time.

Therefore, this article aims to evaluate the methodology proposed by Pereira (2017), comparing the results provided by it with the methodology proposed by Houlsby and Teh (1991), which, according to Bihs et al. (2021), has been the most used for interpreting dissipation tests of excess pore pressure generated due to the execution of undrained condition of CPTu. This comparison is made using the results of tests carried out on tailings dams and allows verifying if the two methodologies lead to similar t_{50} and c_h (horizontal consolidation coefficient) values, indicating that the time gain in test execution does not compromise the interpretation of the results.

2 METHODOLOGY

2.1 *Studied area*

To interpret the dissipation of excess pore pressure generated during the CPTu test, an area was selected where the same tests were carried out and lasted more than three hours to reach pore pressure stabilization. This choice enabled a direct comparison between the results calculated considering the tests to be complete, i.e. all the readings until stabilization, using the methodology of Houlsby and Teh (1991), and considering the results as if the tests were incomplete, i.e. without reaching pore pressure stabilization and, consequently, as if they had ended with a shorter duration, using the methodology of Pereira (2017).

These tests were carried out along the massif of an iron ore tailings dam, built in a single stage, located in the Iron Quadrangle of Minas Gerais, southeast of Brazil. The research campaign included three CPTu and, in each of them, dissipation tests were carried out at various depths, as shown in Table 1.

Table 1. Summary of the tests studied

Hole	*Test number*	*Depth (m)*	*Soil behavior*
CPTu-1	*1*	4	Clay
	2	6	Clay

Hole	Test number	Depth (m)	Soil behavior
	3	15,5	Clayey silt to silty clay
CPTu-2	4	5	Clay
	5	6	Silty sand to sandy silt
	6	7	Clay
	7	8	Clay to silty clay
CPTu-3	8	5	Clay
	9	11,5	Clay
	10	13,5	Clay
	11	14,5	Clay to silty clay
	12	15,5	Clayey silt to silty clay

The undrained condition of the piezocone penetration was considered because it registered positive pore pressure variations throughout the soil profile during the tests.

2.2 *Calculation of the horizontal density coefficient according to the Houlsby and Teh method (1991)*

The coefficient of horizontal consolidation was calculated (see Eq. 1) according to the method proposed by Houlsby and Teh (1991) which, according to Mayne (2007) and Bihs et al. (2021), is the most popular method for evaluating this coefficient from the dissipation test.

$$c_h = \frac{T^* \cdot r^2 \cdot \sqrt{I_r}}{t_{50}} \quad (1)$$

Where c_h (m²/s) is the horizontal densification coefficient; T* is the modified time factor; r (m) is the radius of the piezocone; Ir is the Stiffness Index; t50 (s) is the time taken for 50% of the excess pore pressure to dissipate.

2.2.1 *Calculating t_{50}*

The stabilization pore pressure u_0 was considered to be equal to the last value observed on the curve of recorded pore pressure values plotted against time, as long as this curve tended to be horizontal. This pore pressure stabilization was assumed after confirming repeated readings at the end of the test.

To calculate the initial pore pressure u_i it is necessary to adjust the dissipation curve, since there may be a discharge effect and local redistribution of pore pressure before dissipation begins, which according to Sully et al. (1999) can be characterized by the initial increase in pore pressure before its decay. These authors discuss two possible procedures for this adjustment. The first procedure considers an extension of the rectilinear section of the pore pressure excess dissipation curve versus the square root of time up to time zero. In this way, the values of t_{50} are calculated as being equal to half the difference between $u_{i,ext,}$ and u_0, as illustrated in Figure 1.

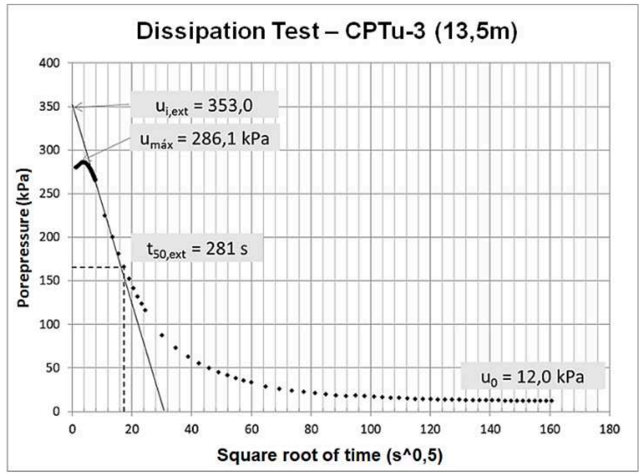

Figure 1. Calculation of $u_{i,ext}$, and t_{50} using first procedure suggested by Sully et al (1999).

The second procedure used to determine the initial pore pressure and t_{50} is done by shifting the curve of excess pore pressure dissipation *versus* time on a logarithmic scale so that the point of maximum pore pressure read is located at time zero, disregarding the initial increase in pore pressure. The values of t_{50} are equal to half the difference between u_{transl} and u_0, as shown in Figure 2.

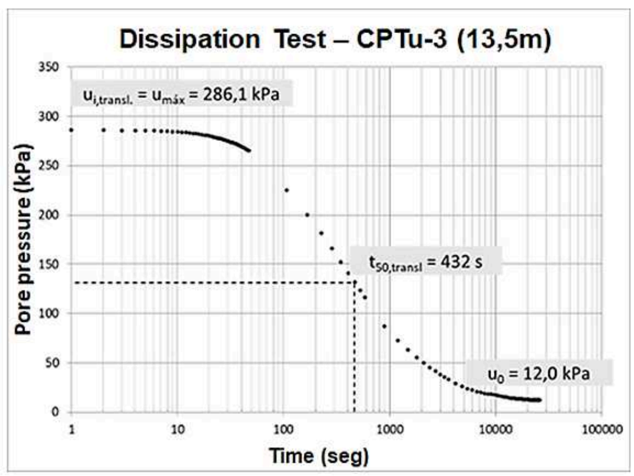

Figure 2. Calculation of $u_{i,transl}$ and $t_{50.}$ using second procedure suggested by Sully et al. (1999)

2.2.2 *Definition of the modified time factor (T*) and stiffness Index (I_r)*

Since the piezocone used has a pore pressure sensor positioned just after the conical tip and the calculation in question refers to 50% dissipation, a modified time factor was used which, according to Houlsby and Teh (1991), is equal to 0.245. The stiffness index of the tested soil was considered to be equal to 250, a value close to those found by Agaiby and Mayne (2018) when evaluating the stiffness index in clays under undrained loading conditions, since the results of the CPTu tests were undrained and indicated the profile's behavior as being clayey.

2.3 *Calculation of the horizontal density coefficient according to the polynomial method proposed by Pereira (2017)*

The polynomial method proposed by Pereira (2017) requires, according to the author himself, a minimum of 40% dissipation of excess pore pressure so that the calculations can be carried out with acceptable precision. However, based on the assumption that the equilibrium pore pressure may not be known, it was considered the test data up to the first point on the downward stretch of the curve with a value immediately below 60% of the maximum pore pressure ($u_{máx}$) read during the test. In this way, it is considered that a minimum of 40% dissipation of excess pore pressure is guaranteed and the operation of the test does not depend on knowing the equilibrium pore pressure, which cannot always be easily obtained or reliably measured (Mantaras et al., 2015). Thus, a new dissipation curve was drawn as a function of the logarithm of time, in which the entire test was reduced from 7 hours and 10 minutes to just 5 minutes (Figure 3). The maximum pore pressure value read in this test was 286.1 kPa and the last point considered, with a duration of 300 seconds, has a pore pressure value of 165.8 kPa, which is 58% of the maximum value. As proposed by Pereira (2017), the downward linear section of the curve should be extrapolated until a degree of dissipation equal to 70% dissipation is reached. However, as illustrated in Figure 3, considering the possibility of not knowing the value of the equilibrium pore pressure for defining this 70%, we considered extrapolating the linear section up to 30% of the value of $u_{máx}$ recorded, which, in this case, corresponds to the value of 85.8kPa.

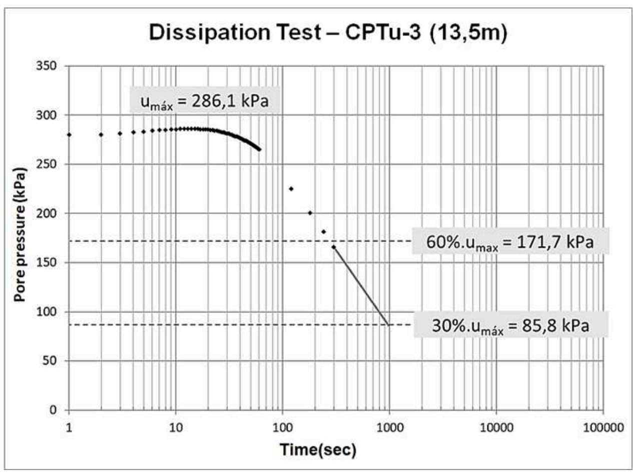

Figure 3. The linear section is extrapolated using the method suggested by Pereira (2017).

2.3.1 *Polynomial fitting, 1st and 2nd derivatives, and calculations of u_{50} and t_{50}*

Based on the new dissipation curve found with the extrapolation of the straight stretch shown in Figure 3, the PROJ.LIN function in Excel was used to calculate the 8th-degree polynomial function that governs the regression of the curve. After that, the first and second derivatives of the polynomial function found were calculated, where, at the time when the first derivative is minimal and the second derivative is equal to zero, there is the inflection point. According to Pereira (2017), this inflection point refers to the dissipation of 50% of the excess pore pressure generated during driving. Thus, the values of the curve found by the polynomial function, the derivatives, and the original curve must to be plotted on the same graph, with their respective results of t_{50}. Figure 4 illustrates the result of this procedure. Once these curves are determined, it is possible to compare the final results of t_{50} obtained by the methodology of Houlsby and Teh (1991), considering the t_{50} obtained from the extrapolated curve (pore pressure versus square root of time) and the translated curve (pore pressure versus time on a logarithmic scale), and the polynomial methodology proposed by Pereira (2017).

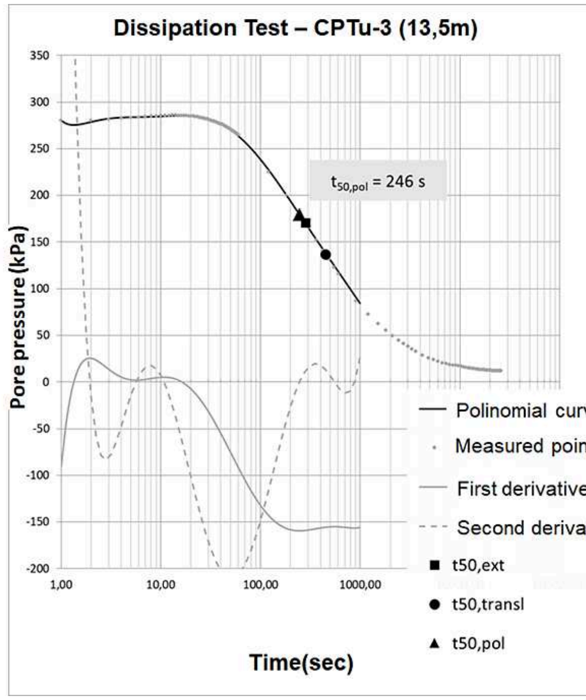

Figure 4. The dissipation curve and t_{50} were calculated using the methodology proposed by Pereira (2017).

3 RESULTS

The method described in this work, as set out in the previous section, was applied in the same way for each of the selected tests. The results were the horizontal consolidation coefficients calculated from the complete dissipation curves and their polynomial approximations, with the respective values of t_{50} and c_h calculated using the same values for T* (modified time factor) and I_r (stiffness index) considered in section 2.2.2.

3.1 *Test duration*

Table 2 shows the duration of the tests carried out until the dissipation curve of the excess pore pressure generated by the CPTu was stabilized, which is necessary for calculating the t_{50} according to Houlsby and Teh (1991), compared to the test time required to apply the method proposed by Pereira (2017). It can be noticed the enormous gain in time that the second method provides.

Table 2. Required duration of the test according to the method used

Hole	*Test number.*	*Depth. (m)*	*Test time if the method of Houlsby and Teh (1991)*	*Test time if the method of Pereira (2017)*
CPTu-1	1	4,0	04:20	00:15
	2	6,0	04:10	00:20
	3	15,5	07:10	00:25

CPTu-2	4	5,0	06:20	00:15
	5	6,0	06:40	00:03
	6	7,0	07:00	00:06
	7	8,0	07:30	00:04
CPTu-3	8	5,0	07:30	00:03
	9	11,5	04:20	00:25
	10	13,5	07:10	00:05
	11	14,5	07:40	00:30
	12	15,5	03:20	00:20

3.2 *Time to dissipate 50% of excess pore pressure (t_{50})*

Table 3 and Table 4 show the results of t_{50} and c_h, respectively, both calculated according to Houlsby and Teh (1991), using the extrapolation of the excess pore pressure curve versus the square root of time, when the t_{50} obtained was called T_{50Ext}, and the excess pore pressure curve versus time on the logarithmic scale, and where the t_{50} obtained from this was called $T_{50Trans}$, and for the calculation following the proposal by Pereira (2017), where the t_{50} obtained from this was called T_{50Pol}, with the appropriate adjustments for this study, as discussed in item 2.3. To compare the results using the different approximations of initial pore pressure values, the relative differences between the results were calculated.

Table 3. The difference between t_{50} results obtained by different methods

Test no.	*T_{50} Ext (s)*	*T_{50} Trans (s)*	*T_{50} Pol (s)*	*Difference between*		
				Pol-Ext	*Pol-Transl*	*Ext-Transl*
1	446	634	820	84%	29%	42%
2	649	975	956	47%	-2%	50%
3	1337	2287	1249	-7%	-45%	71%
4	658	1158	1019	55%	-12%	76%
5	113	165	127	12%	-23%	46%
6	249	386	297	19%	-23%	55%
7	195	284	249	28%	-12%	46%
8	106	159	121	14%	-24%	50%
9	855	1446	1287	51%	-11%	69%
10	281	432	246	-12%	-43%	54%
11	1242	1678	1979	59%	18%	35%
12	1059	1943	1119	6%	-42%	83%

Table 4. The difference between c_h results obtained by different methods

Test no.	*C_h Ext (s)*	*C_h Trans (s)*	*C_h Pol (s)*	*Difference between*		
				Pol-Ext	*Pol-Transl*	*Ext-Transl*
1	3,03E-06	2,13E-06	1,65E-06	-46%	-23%	-30%
2	2,08E-06	1,39E-06	1,41E-06	-32%	2%	-33%
3	1,01E-06	5,91E-07	1,08E-06	7%	83%	-42%
4	2,05E-06	1,17E-06	1,33E-06	-35%	14%	-43%
5	1,20E-05	8,19E-06	1,06E-05	-11%	30%	-32%
6	5,43E-06	3,50E-06	4,55E-06	-16%	30%	-35%
7	6,93E-06	4,76E-06	5,43E-06	-22%	14%	-31%
8	1,28E-05	8,50E-06	1,12E-05	-12%	31%	-33%
9	1,58E-06	9,35E-07	1,05E-06	-34%	12%	-41%
10	4,81E-06	3,13E-06	5,50E-06	14%	76%	-35%
11	1,09E-06	8,06E-07	6,83E-07	-37%	-15%	-26%
12	1,28E-06	6,96E-07	1,21E-06	-5%	74%	-45%

4 COMPARING THE OBTAINED RESULTS

The results from all three different approaches were compared. It was considered the horizontal consolidation coefficient calculated from the method of the polynomial curve (Pereira, 2017), the extrapolated curve (pore pressure versus square root of time), and the translated curve (pore pressure versus time on a logarithmic scale), the last two according to Houlsby and Teh (1991). In the graphs illustrated in Figures 5 through 7, the dots are the values of the horizontal consolidation coefficients calculated by the two methods that are being directly compared. The darker solid line is the trend correlating these points. The coefficient of correlation (R^2) was calculated to check the adequacy of the obtained trend line. The closer the R^2 value is to one, the better the trend line describes the phenomenon (Peternelli, 2004). The dashed line is obtained when considering that the values of horizontal consolidation coefficients calculated by the two methods being compared have the same value, resulting in a 45-degree slope line. A region was delimited considering a variation of 30% in relation to this ideal line (45 degrees slope line), delimited by lighter (gray color) continuous lines. If the darker (black) continuous line, obtained from the relationship between the calculated points using the two methods, is higher or lower than the ideal line (dashed), one can easily notice which method tends to provide larger or smaller values of horizontal consolidation coefficient.

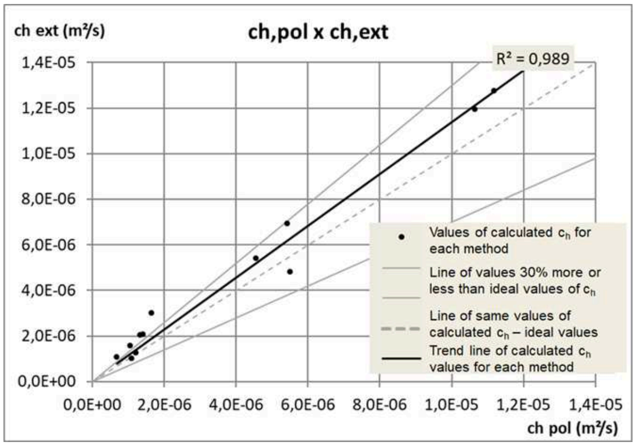

Figure 5: Comparison between the calculated values of $c_{h,pol,}$ (Pereira, 2017) and $c_{h,ext}$ (Houslby e Teh, 1991, using the square root of time graph method).

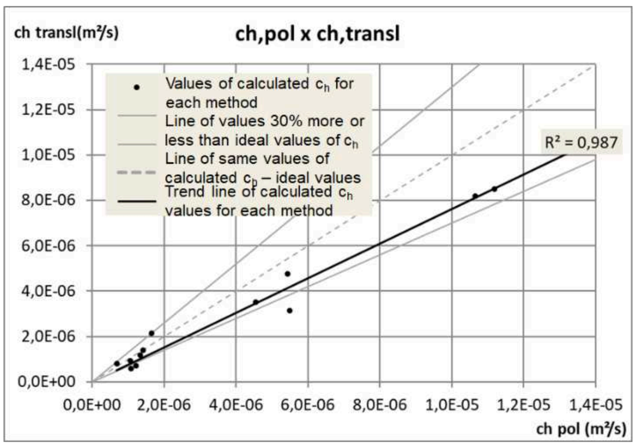

Figure 6. Comparison between the calculated values of $c_{h,pol,}$ (Pereira, 2017) and $c_{h,transl}$ (Houslby e Teh, 1991, using the log of time graph method).

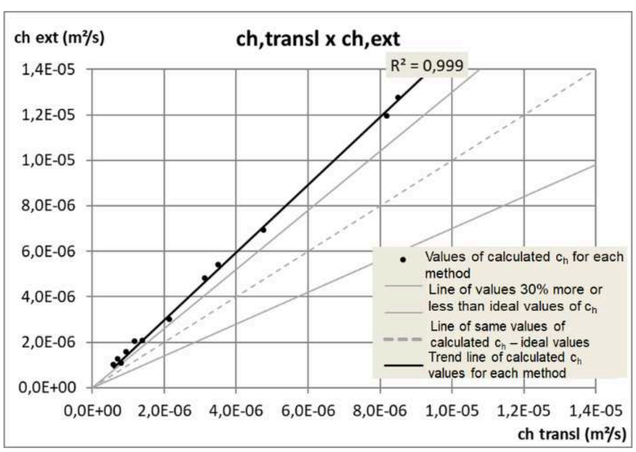

Figure 7. Comparison between the calculated values of $c_{h,transl,}$ (Houslby e Teh, 1991, using the log of time graph method) and $c_{h,ext}$ (Houslby e Teh, 1991, using the square root of time graph method).

5 CONCLUSIONS

A total of twelve (12) excess pore pressure dissipation tests from CPTu tests were analyzed, all carried out until the excess pore pressure had completely dissipated, i.e. until the pore pressure had stabilized. Working with the complete excess pore pressure dissipation curves is an advantage since one have directly measured results of the stabilized pore pressure, not depending of data interpretation or interpolation. This, therefore, makes the comparison of the t_{50} obtained from the different methodologies more reliable because it is a value dependent of the stabilized pore pressure and this value was very well defined in this research. All the excess pore pressure dissipation test curves considered in this work showed non-monotonic decay and only positive values. Therefore, excess pore pressure dissipation curves that started with negative pore pressure values or that did not have an initial redistribution of pore pressure, resulting in an initial increase in values during the test, as indicated by Sully et al. (1999), were not considered.

The method of Houlsby and Teh (1991) was applied to calculate the horizontal consolidation coefficient, with the determination of t_{50} being done either by an extension of the initial linear stretch of the excess pore pressure versus square root of time curves or by a translation of the excess pore pressure versus time on the logarithmic scale curves to define the initial pore pressure value, u_i. Values of horizontal consolidation coefficient were also determined by the method proposed by Pereira (2017), developed to be applied to incomplete excess pore pressure dissipation data, i.e. without reaching the stabilized pore pressure. This method considers an 8th-degree polynomial regression of the data and calculates the inflection point of the curve in its decay.

The use of the method proposed by Houlsby and Teh (1991) using the extrapolated methodology (pore pressure versus square root of time) demands care in choosing the straight part of the curve to be extended for estimating the initial pore pressure, since any deviation can result in significant differences in the values of t_{50} and, therefore, in the c_h values.

The dissipation tests considered in this study took from 3h20min to 7h40min to achieve the stabilization of pore pressure (complete dissipation of the excess), which makes them difficult to carry out in day-to-day geotechnical investigations. These same tests, if analyzed using the polynomial method proposed by Pereira (2017), would demand only between 3 and 30 minutes to be completed in the field, since this method does not depend on the value of the stabilized pore pressure.

Comparing the final results of the horizontal consolidation coefficient (c_h), it is possible to notice that the results calculated applying the polynomial approach proposed by Pereira (2017) show small differences to those results calculated using the more traditional method, proposed by Houlsby and Teh (1991), both from the extrapolated curve (pore pressure versus square root of time) and translated (pore pressure *versus* time on a logarithmic scale).

Just as Pereira (2017) concluded, when comparing the results found in this work for the horizontal consolidation coefficients, it was noted that these values were less than 20% different when compared to the values obtained by Housby and Teh (1991) using t_{50} defined from the extrapolated curve (pore pressure versus square root of time). It can be seen that the values calculated of the horizontal consolidation coefficient in this research, using the methodology proposed by de Pereira (2017), tended to be approximately 15% lower than the values calculated by Houlsby and Teh (1991) using the extrapolated approach (pore pressure versus square root of time); and tended to be approximately 30% higher than the values calculated also by Housby and Teh (1991) but using the translated approach (pore pressure versus time on a logarithmic scale). Therefore, it can be noticed in this research that the method proposed by Pereira (2017) proved to be an option to reduce the duration of excess pore pressure dissipation tests in CPTu tests. Still, it is essential to consider the potential differences in calculated horizontal consolidation coefficients when compared to the traditional methodology proposed by Houlsby & Teh (1991).

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