Characterization of the consolidation coefficient behavior from piezocone and piezoball tests in a Brazilian soft soil

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ABSTRACT

The present paper aims to validate the applicability of a piezoball test equipped with pressure transducers at the probe's tip, middle, and equator faces to estimate the coefficient consolidation behavior of a soft soil deposit. The proposals of Mahmoodzadeh et al. (2015) and Liu et al. (2023), derived from numerical solutions, can be adopted to estimate horizontal coefficients of consolidation (c_h) through the piezoball dissipation measurements. The dissipations tests were performed at depths of 4, 6, 8, and 10 m and were conducted up to at least about 70% of dissipation of the excess pressure generated during the penetration, except for the test at a depth of 4m, done at 85%. Results were directly compared with piezocone, and the estimated values for the consolidation coefficient were similar for all methodologies applied, both at the face and equator positions.

Keywords: piezocone; piezoball; dissipation test; consolidation behavior.

1. Introduction

The consolidation characteristics, which are fundamental in soil-structure interactions, are influenced by whether the soil is drained, partially drained or undrained. Laboratory tests inferring the coefficient of consolidation (c_v or c_h) through oedometer tests are common, but their accuracy relies on sample quality. In situ dissipation tests, like the piezocone dissipation test, offer a field estimate of the consolidation coefficient (c_h) by allowing excess pore pressure to dissipate at pre-defined depths.

Complementary to piezocone tests, the development of full-flow penetrometers, especially those with a spherical tip (Ball), offers an alternative to traditional methods and demonstrates enhanced accuracy in determining undrained shear strength (Colreavy et al. 2012).

A noteworthy adaptation involves the Piezoball, a variant with pore pressure transducers, enabling the measurement of excess pore pressure during penetration. This modification enhances test versatility by facilitating dissipation tests and providing valuable data for determining consolidation coefficients and permeability parameters (DeJong et al. 2008). Attention must be given to the position of the pore pressure transducer to define the best theory application.

In this context, the proposals of Mahmoodzadeh et al. (2015), Colreavy et al. (2016) and Liu et al. (2023), derived from numerical solutions, which employed isotropic permeability tensor, can be adopted to estimate horizontal coefficients of consolidation (c_h) through the piezoball dissipation measurements considering the position at the probe's tip, middle and equator.

This study aims to evaluate proposals from the literature for estimating soil consolidation parameters. Dissipation tests were conducted at various depths, ranging from 4 to 10 meters, with dissipation levels reaching at least around 70% (85% for the 4m depth test) of the excess pressure generated during penetration. The results were systematically compared with piezocone data, indicating consistently similar estimated values for the consolidation coefficient for all methodologies, regardless of the face or equator positions. The best fit normalized dissipation curve was defined considering Liu et al. (2023) approach which considered equator (u_3) position.

2. Piezoball dissipation test

Incorporating pore pressure measurements in ball penetrometers is becoming a prevalent practice, as can be visualize in Figure 1. The primary focus has typically revolved around the equator position of the piezoball. Similar to the piezocone, the placement of the pore pressure sensor plays a crucial role in influencing the generated pore pressure and its subsequent dissipation, providing insights into stress changes around the ball (Colreavy et al. 2016).

Boylan et al. (2010) outlined the pore pressure response around a piezoball: at the tip, the soil experiences significant compressive stresses, resulting in positive excess pore pressures in a saturated soil; at the equator position, shear stresses occur, leading to either positive or negative excess pore pressures in a saturated soil, depending on the dilatancy and mobilized shear stress level; at the mid-face, the soil undergoes a combination of shear and compressive stresses, resulting in excess pore pressure levels between those observed at the tip and equator positions.

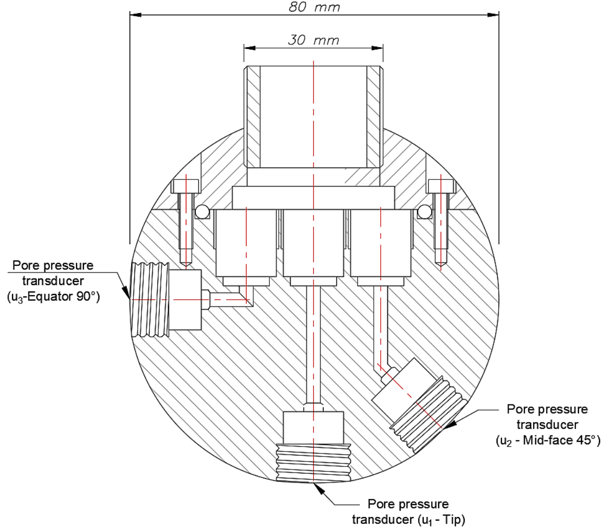


Figure 1. Piezoball penetrometer.

The piezoball dissipation test can be used to evaluate soft soils' hydraulic conductivity and consolidation coefficient (Low et al. 2007; DeJong et al. 2008). The recommendation for performing the dissipation test on soft soils is to dissipate at least 50% of the excess pore pressure generated (DeJong et al. 2010), independent of the position of the equipment's pore pressure transducer. In this sense, Kelleher and Randolph (2005) and Colreavy et al. (2010) used equipment with reading capacity in the equator (u_3) and middle faces (u_2) of the penetrometer. DeJong et al. (2008) show an equipment capable of measuring in these two positions and at the tip of the ball (u_1). There is still no consensus on the best position to interpret the measures of excess pressure generated in the test, although some research (e.g., Colreavy et al. 2016; Mahmoodzadeh et al. 2015) demonstrate consistent results for estimating c_h through readings at u_2. The present paper considers a Piezoball equipped with tree sensor positions.

The normalized excess pore pressure $\Delta u/\Delta u_{ini}$ evolution with a normalized time T can be considered for dissipation test interpretation. Where Δu is the excess pore pressure varying with time, and Δu_{ini} is the initial excess pore pressure. Normalized dissipation time T can follow the classical approach from Teh and Houlsby (1991) (Eq. (1)), from which a c_h value can be defined according to Eq. (2):

$$T = \frac{c_h\, t}{D^2\, {I_r}^{0.5}} \tag{1}$$

$$c_h = \frac{T_{50} D_c^2 I_r^{0.5}}{t_{50}} \tag{2}$$

where t_{50} is the time required for 50% dissipation of the excess pore pressure generated, D_c is the diameter of the piezocone, I_r is the rigidity index of the soil, and T_{50} in a normalized dissipation time considering the reading position – for piezocone tests and u_2 position, $T_{50} = 0.245$.

Inspired by the classical solution of Teh and Houlsby (1991), Mahmoodzadeh et al. (2015) (Eq. (3)) and Liu et al. (2023) (Eq. (4)) present similar proposals for establishing a unique curve in space $\Delta u/\Delta u_{ini} – T_b$, where T_b is the normalized time for the piezoball test.

$$\frac{\Delta u}{\Delta u_{ini}} \approx \frac{1}{1+\frac{T_b}{T_{b50}}} \qquad with \qquad T_{b50} = \frac{c_h t_{50}}{D_b d I_r^{0,25}} \tag{3}$$

$$\frac{\Delta u}{\Delta u_{ini}} \approx \frac{1}{\left(1+\frac{T_b}{T_{b50}}\right)^{0.9}} \qquad with \qquad T_{b50} = \frac{c_h t_{50}}{\left(\frac{D_b}{2}\right)^2 I_r^{0,25}} \tag{4}$$

where T_{b50} is the dimensionless time for 50% of dissipation to occur, with values of 0.12 and 0.18 for the positions u_2 and u_3 according to the proposal by Mahmoodzadeh et al. (2015) and 0.44 for the position u_3 according to Liu et al. (2023).

Equation (5) is proposed for estimating c_h through the dissipation of piezoball based on the normalization proposed by Mahmoodzadeh et al. (2015):

$$c_h = \frac{T_{b50} D_b d I_r^{0,25}}{t_{50}} \tag{5}$$

where D_b and d are the ball's and pushing rod's diameters just above the ball, respectively.

Liu et al. (2023) also propose an alternative for estimating c_h from readings in the position u_3 (Eq. (6)):

$$c_h = \frac{T_{b50}\left(\frac{D_b}{2}\right)^2 I_r^{0,25}}{t_{50}} \tag{6}$$

Colreavy et al. (2016) elaborated an empirical proposal for estimating c_h from readings taken at the equator position (u_3). In this case, a value of t_{max} is used, which indicates the time required to reach the highest value of excess pore pressure generated in the dissipation test, in addition to the dissipation time of 50% ($t_{50\%}$) according to Eq. (7):

$$c_h = 0.7\left(\frac{D_b d I_r^{0,25}}{t_{max}}\right)\left(\frac{t_{max}}{t_{50}}\right)^{1.2} T = \frac{c_h\, t}{D^2\, {I_r}^{0.5}} \tag{7}$$

3. Methods

3.1. Characterization Campaign

The experimental program took place in Tubarão, Santa Catarina, in the southern region of Brazil (Figure 2). The soft soil deposit is located within the Tubarão River delta, bordered by Precambrian crystalline rocks of the Atlantic Shield to the North and West and lagoon and aeolian deposition systems to the South and East. The soils in question display attributes such as organic content, significant compressibility, and reduced shear strength parameters, as established by a range of assessments, including piezocone-type field tests, vane tests, Marchetti dilatometers, and laboratory tests for characterization, as indicated by studies conducted by Mantaras et al. (2014), Schnaid et al. (2016), and Odebrecht and Schnaid (2018).

The conventional test campaign included standard piezocone tests, vane tests, and sample collection for characterization. Piezocone dissipation tests were carried out at three depths (4.8, 6.8, and 7.8 m). Laboratory characterization revealed that the site predominantly consists of silt (43% silt, 24% clay, and 33% sand) with a specific gravity of 2.71 g/cm3 and high plasticity (Plasticity Index - IP around 18%), aligning with the characteristics of Brazilian clay soils (Jannuzzi 2009; Schnaid 2009; Baroni 2010; Dienstmann et al. 2021).

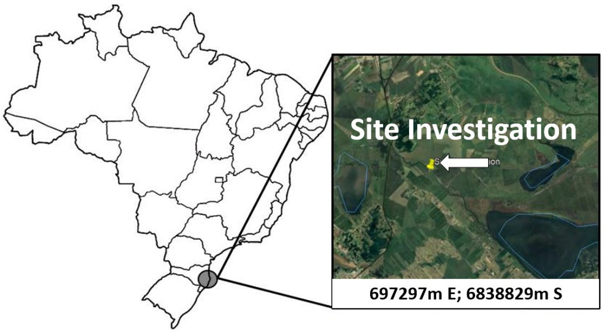
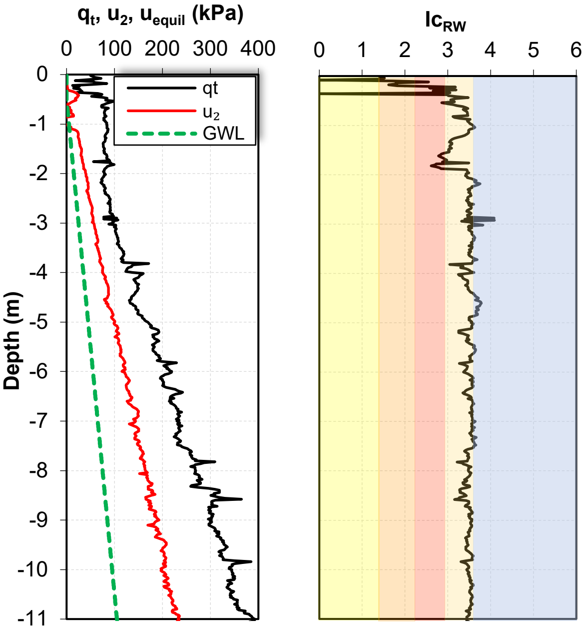


Figure 2. Location of investigation site.

The field test results, as depicted in Figure 3, include standard piezocone test outcomes showing tip penetration resistance (q_t), pore pressure (u_2), and Soil Index (Ic_{RW}). These results indicate clayey behavior with low tip strength (q_t from 10 to 400 kPa) and varying excess pore pressure generation (u_2 from 0 to 230 kPa).



(a) (b)

Figure 3. Typical soil profile from CPTu measurements.

3.2. Equipment

The piezoball test utilizes equipment with an 80 mm diameter (Figure 4), resulting in a cross-sectional area of 50 cm². The ratio between this area and the cross-section of the pushing rod just above the ball (A_s/A_p) is 7:1. Pore pressure measurements during the piezoball test are facilitated by three pressure transducers installed at the tip (u_1), middle face ($u_2 = 45°$), and along the equator line of the sphere ($u_3 = 90°$). A load cell is positioned immediately behind the probe and is equipped with four strain gauges and a sealing system through O-rings, to record penetration or extraction resistances. All equipment underwent laboratory calibration and met the minimum requirements outlined in ASTM D5778 (2020) before the commencement of field tests.

3.3. Procedures

The dissipation tests were performed at depths of 4, 6, 8, and 10 m. The equipment was inserted into the reference depth of each test following the standard rate (20 mm/s); the penetration was then stopped, the set of pushing rods was fixed to stabilize the probe, and the dissipation of excess pressure generated at the tip (u_1), intermediate (u_2) and equator (u_3) faces of the sphere was recorded. The tests were conducted up to at least about 70% of the dissipation of the excess pressure generated during the penetration. Table 1 summarizes the dissipation time for each test.

Figure 4. Piezoball and 10 cm² piezocone.

Table 1. Summary dissipation tests

Depth (m)	Dissipation time (s)
4*	33160
6	6870
8	6860
10	5900

* the test at 4 m was performed up to 85% dissipation - however, only the reading of u_1 was recorded due to a problem in data acquisition

4. Results and interpretation

Figure 5 shows the values of recorded pore pressure measurements in the three piezoball transducers. The reading obtained in the piezocone test (u_2 - CPTu) is also presented for comparative purposes. The pore pressure values at the tip position (u_1) reached the highest magnitude. In contrast, the pore pressure at the equator position (u_3) shows the smallest values.

These results corroborate research already carried out (e.g., Mahmoodzadeh et al. 2015; Colreavy et al. 2016), indicating that the excess pore pressure generated at the ball tip is high due to the dominance of compressive stresses. The excess pore pressure measurements at the middle face of the ball (u_2) are slightly higher than that obtained by the piezocone shoulder (u_2 - CPTu), also corroborating with research conducted in centrifuges tests in the works of Mahmoodzadeh and Randolph (2014), Colreavy et al. (2015, 2016), which showed similar results.

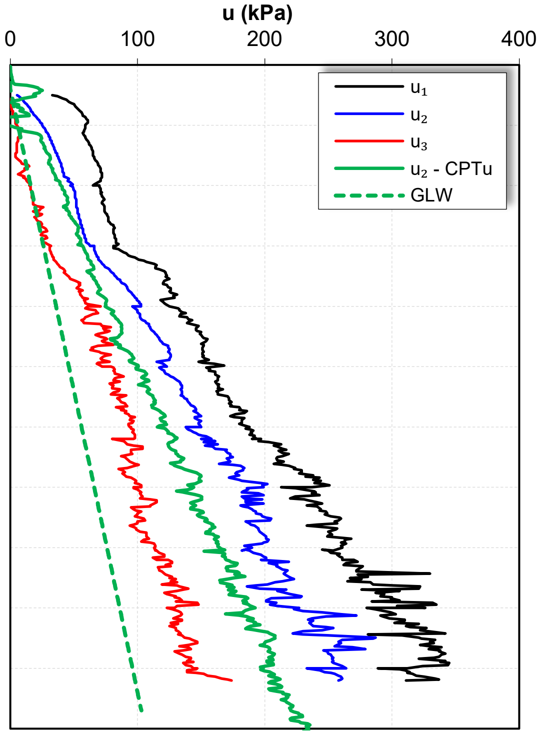


Figure 5. Profiles of pore-pressure

Piezocone and piezoball dissipation horizontal consolidation coefficient (c_h) were estimated using Teh and Houlsby (1991) (Eq. (2)) solution for piezocone, and Mahmoodzadeh et al. (2015) (Eq. (5)), Colreavy et al. (2016) (Eq. (7)), and Liu et al. (2023) (Eq. (6)) for piezoball. The resulting parameters are presented in Table 2. The value of *Ir* adopted is 108, obtained using the proposal by Schnaid et al. (1997) with triaxial test data. In general, the coefficient of consolidation estimated by different methodologies had the same magnitude of around 10^{-3} cm^2/s. The best approximation between estimated values considering piezocone and piezoball test was obtained by Liu et al. (2023) application.

To emphasize the applicability of normalized dissipation analysis and derived equation to c_h prediction, Figures 6 to 8 display dissipation tests interpretation considering Teh and Houlsby (1991), Mahmoodzadeh et al. (2015), and Liu et al. (2023) normalization. Dissipation curves at the three different sensor positions show, in general, contractive behavior. Comparing the piezocone test results with piezoball readings, Figure 6 presents the normalization of the dissipation time through Teh and Houlsby (1991), Eq. (1), with c_h estimated by the piezocone test. The diameter of each equipment was used for deriving *T* in this approach. In addition, the theoretical curves of Teh and Houlsby (1991) are plotted for the positions u_1 and u_2 of the piezocone.

Table 2. Summary dissipation tests

		c_h (cm²/s)		
Method	**Depth (m)**	**-6**	**-8**	**-10**
Teh and Houslby (1991)	u_2	9.99E-03*	5.89E-03*	-
Mahmoodzadeh et al. (2015)	u_2	4.77E-03	6.78E-03	1.23E-02
	u_3	4.62E-03	3.73E-03	4.34E-03
Colreavy et al. (2016)	u_2	6.12E-03	9.33E-03	1.92E-02
	u_3	3.62E-03	4.13E-03	5.32E-03
Liu et al. (2023)	u_3	7.53E-03	6.08E-03	7.07E-03

* interpolated values

Based on these considerations, it can be verified that the dissipation curves for the equator position (u_3) are the closest to the piezocone results. On the other hand, there is a similarity between the theoretical formulation of Teh and Houlsby (1991) for u_1 with the readings on the ball in the middle face position for the depth of 6 m. The migration mechanism of compressive and shear stresses, analogous between penetrometers for these positions, could cause the observed behavior.

Noting that Teh and Houlsby (1991) proposed normalization of T needs to be adapted for the ball test, Mahmoodzadeh et al. (2015) (Eq. (3)) and Liu et al. (2023) (Eq. (4)) solutions were also considered, resulting data are displayed in Figures 7 and 8. A good adaptation of the curves to position u_3 is noted with the corresponding theoretical curve of Mahmoodzadeh et al. (2015), Figure 7. However, the proposed solution does not seem to reflect the behavior of the Tubarão material for the position u_2. Considering Liu et al.'s (2023) adaptation, a good agreement was identified between the dissipation tests at the three depths and the theoretical curve.

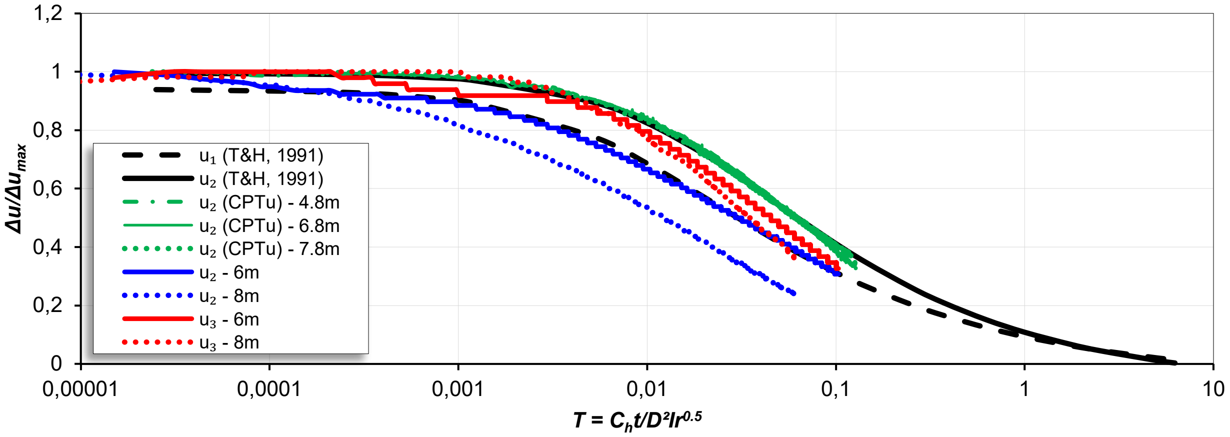


Figure 6. Excess pore pressure normalized *versus* time factor: Teh and Houlsby (1991) proposal.

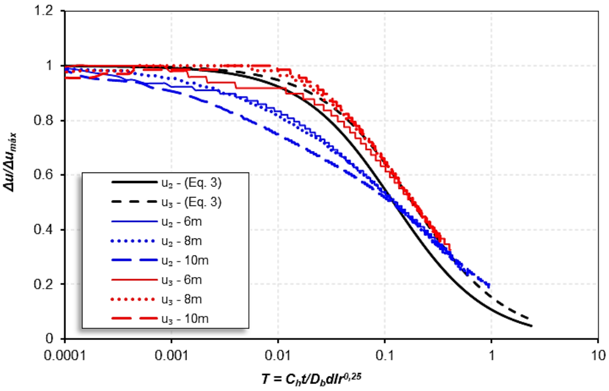


Figure 7. Excess pore pressure normalized *versus* time factor: Mahmoodzadeh et al. (2015) proposal.

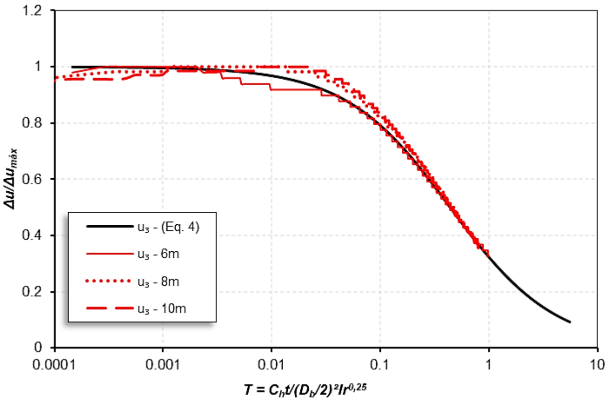


Figure 8. Excess pore pressure normalized *versus* time factor: Liu et al. (2023) proposal.

5. Conclusions

This study conducted investigations on a soft soil deposit in southern Brazil (Tubarão deposit) using piezocone, vane test, and piezoball tests. Dissipation tests were performed at four depths. When considering c_h estimative, all methodologies investigated resulted in coefficients of consolidation of the same order of magnitude. Considering Tubarão clay behavior, Liu et al. (2023) solution provided a better approximation between piezocone and piezoball dissipation-derived coefficients, and a good agreement between field test dissipations and theoretical curves.

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