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Using Piezocone Dissipation Test to Estimate the Undrained Shear Strength (s_u), N_{kt} and $N_{\Delta u}$ Factors in Cohesive Soils

Dante René Bosch[1], Rubén Rafael Sotelo[1], Fernando María Mántaras[2]

[1]Center of Applied Geosciences, Faculty of Engineering, UNNE (National University of Northeast), Resistencia, Chaco, Argentina
[2]Geoforma Engenharia Ltda, Joinville, Brazil
Email: danterbosch@gmail.com

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Abstract

The current practice of geotechnical engineering commonly uses a combination of theoretical and empirical correlations to estimate the soil undrained shear strength in clays from the piezocone test. In order to complement the use of such correlations, the application of a method to estimate the soil undrained shear strength, using measures of the excess pore pressure in dissipation tests of piezocone is presented. In cohesive soils, excess pore pressure and undrained shear strength are dependent on the same variables (stress state, stress history, soil stiffness), which allows them to be related by the theoretical cavity expansion-critical state framework. This paper mentions the mathematical formulation that supports the theoretical framework used, its relationship with the N_{kt} and $N_{\Delta u}$ factors and their estimation in a case studied. The results obtained are consistent within the dispersion found in the international literature and encourage the use of the method in engineering practice.

Keywords

CPTu Piezocone, Overconsolidation Ratio, Undrained Shear Strength, Dissipation Test

1. Introduction

Prediction of soil properties from piezocone test (CPTu) data in cohesive soils is routinely carried out in geotechnical design. This is possible because there is a general recognition that analytical and numerical analysis techniques and constitutive models of soil behaviour are now sufficiently developed to produce good agreement between cone parameters and independently measured soil properties (e.g. Lunne et al., 1997; Yu, 2004; Schnaid, 2009). A theoretical frame is essential, because the CPTu cannot measure the undrained shear strength directly and therefore CPTu assessment of s_u relies on a combination of theory and empirical correlations.

Penetration tests in clay are generally undrained, and therefore the cone tip resistance q_c can be related to s_u as follows:

$$q_t = N_{kt} \cdot s_u + \sigma_0 \tag{1}$$

where N_{kt} is a theoretical cone factor and σ_0 is the *in situ* total stress. The cone factor may be determined using simple bearing capacity formulations, cavity expansion or strain path method (e.g. Terzaghi, 1943; Meyerhof, 1956; Caquot & Kerisel, 1953; Baligh, 1985; Teh & Houlsby, 1991; Yu & Whittle, 1999). Yu (2004) pointed out that while each theory may be used alone for cone penetration analysis, better predictions of cone penetration mechanisms may be achieved if some of the methods are used in combination. A combination of strain path analysis and finite element calculations was used by Teh & Houlsby (1991) to model cone penetration in a Von Mises soil. Yu & Whittle (1999) proposed a cone factor estimated from both strain path analysis and cavity expansion methods. In this approach, the strain path solution developed by Baligh (1985) was used to estimate the size of the plastic zone produced by penetration. Once the plastic zone is established, spherical cavity expansion was used to determine the stress distribution and therefore cone resistance. Burns & Mayne (1998) use cavity expansion-critical state framework to model monotonic and dilatory response with regard to time.

Whereas theoretical solutions have been contributing in the understanding of the fundamental mechanics of cone penetration, empirical correlations are still widely used in practice to estimate s_u from cone resistance. Values of cone factor (N_{kt}) often fall in the range from 10 to 20 and are influenced by soil plasticity, overconsolidation ratio, sample disturbance, strain rate and scale effects, as well as the reference test from which s_u has been established (e.g. Aas et al., 1986; Mesri, 1975; Lunne et al., 1997). However in overconsolidated clays the values of N_k often fall outside the predicted range and there are no constitutive modes to support empirical evidences.

A potential alternative to overcome the existing uncertainty related to N_{kt} is to use the excess pore pressure to estimate s_u. Several relationships have been proposed based on theoretical or semi-theoretical approaches using cavity expansion theory (Battaglio et al., 1986; Campanella et al., 1985; Randolph & Wroth, 1979; Vesic, 1972):

$$s_u = \frac{u_2 - u_o}{N_{\Delta u}} \tag{2}$$

where $N_{\Delta u}$ is shown from cavity expansion to vary in the range of 2 to 20. Lunne et al. (1997) recommend using a value of $N_{\Delta u}$ of between 7 and 10. It has been advocated that these methods have the advantage of increased accuracy in the measurement of Δu, mainly in soft clays where Δu can be very large (e.g. Campanella et al., 1985).

The rationality in using Equation (2) is that cone resistance and excess pore pressures generated during cone penetration into fine grained soils will be dependent on the same parameters—stress state, stress history, soil stiffness—and can therefore be associated in CPTu predictions. Proposed semi-empirical solutions (Massarch & Broms, 1981; Campanella et al., 1985) attempt to capture the reduction in excess pore pressures with increasing overconsolidation ratio. In addition, there has been some research work suggesting that N_{kt} and $N_{\Delta u}$ is related to the B_q parameter but while this appears to hold on a site specific basis, no global correlation has been identified.

A new method proposed by Mántaras et al. (2014) is applied here. This analysis advocates a different approach using dissipation tests and linking the measured piezocone maximum dissipation excess pore-water pressure ($\Delta u_{\max}$) to the undrained shear strength (s_u). The mathematical solution proposed by Burns & Mayne (1998) is used as reference given the fact that excess pore water pressures are computed through a combination of the octahedral and the shear-induced components, allowing both normally and overconsolidated clays to be modeled from pore pressures measured immediately behind the cone shoulder (u_2).

The verification of the aforementioned method requires well-documented cases, which are not always available in engineering practice. This work aims to expand the database on which the method is based, and to verify the consistency of results within the empirical framework that relates cone factors and normalized excess pore pressure.

2. Mathematical Formulation (Mántaras et al., 2014)

The mathematical solution proposed by Burns & Mayne (1998) is based on the cavity expansion-critical state framework for the monotonic and dilatory response with regard to time. The excess pore water pressures, Δu, at any time can be compared with the initial values during penetration, $\Delta u_i = u_{2i} - u_0$, represented as:

$$\Delta u_i = \left(\Delta u_{oc}\right)_i + \left(\Delta u_\tau\right)_i$$

where: $\left(\Delta u_{oc}\right)_i = (2/3) M \sigma'_{vo} \left(OCR/2\right)^{\Lambda} \ln I_r$ is the octahedral component during penetration and $\left(\Delta u_\tau\right)_i = \sigma'_{vo}\left[1-\left(OCR/2\right)\right]^{\Lambda}$ is the shear-induced component during penetration, with OCR (the overconsolidation ratio), ϕ' the effective friction angle, $M = (6\sin\phi')/(3-\sin\phi')$ and Λ the compressibility ratio (1 − C_C/C_R). Departing from this concept, Burns & Mayne (1998) derived the following equation for the normalized excess pore pressure:

$$\frac{\Delta u}{\sigma'_v} = \frac{\frac{2}{3} M \cdot \ln\left(I_r\right)\left[\frac{OCR}{2}\right]^{\Lambda}}{1+50\cdot T} + \frac{1-\left[\frac{OCR}{2}\right]^{\Lambda}}{1+5000\cdot T} \tag{3}$$

where: I_r is the rigidity index and T a dimensionless time factor.

Being $T_{\max}$ the value of T where the excess pore pressures reaches its maximum value, it is possible to found it analitically from the equation: $\partial\left(\Delta u/\sigma_v'\right)/\partial T = 0$ resulting the expression:

The maximum value of T could be obtained

$$T_{\max} = -\frac{1}{50}\frac{\left[\alpha\left(\frac{OCR}{2}\right)^{\Lambda} + 1 - \left(\frac{OCR}{2}\right)^{\Lambda} - 9.9\sqrt{\alpha\cdot\left(\frac{OCR}{2}\right)^{\Lambda}\cdot\left[\left(\frac{OCR}{2}\right)^{\Lambda} - 1\right]}\right]}{100\cdot\alpha\cdot\left(\frac{OCR}{2}\right)^{\Lambda} + 1 - \left(\frac{OCR}{2}\right)^{\Lambda}} \quad (4)$$

Note that $T_{\max}$ is the value of T where the excess pore pressure reaches its maximum value taking the first derivative of Equation (3) and setting the gradient of the function equal to zero, it is possible to determine the maximum value of the normalized excess pore pressure in relation to time factor T.

($T_{\max}$) combined with $\Delta u_{\max}$ and related to the normalized undrained shear strength from direct shear undrained test (Wroth, 1984) yields the undrained pore pressure ratio $N_{\Delta u_{\max}}\left(=\Delta u_{\max}/s_u\right)$ defined as the ratio of the maximum excess pore pressure and the undrained shear strength:

$$N_{\Delta u_{\max}} = \left(\frac{\Delta u_{\max}}{s_u}\right) = \frac{\dfrac{\frac{2}{3}M\cdot\ln\left(I_r\right)\left[\frac{OCR}{2}\right]^{\Lambda}}{1+50\cdot T_{\max}} + \dfrac{1-\left[\frac{OCR}{2}\right]^{\Lambda}}{1+5000\cdot T_{\max}}}{\frac{1}{2}\sin\left(\phi\right)\cdot OCR^{\Lambda}\cdot\log\left(I_r\right)} \quad (5)$$

Based on Equation (5), the derived formulation shows little sensitivity to variations on OCR and ϕ', and for typical soil parameters can be reduced to a relatively simple expression of a constant times the logarithm of the rigidity index, I_r (as illustrated on Figure 1 for OCR).

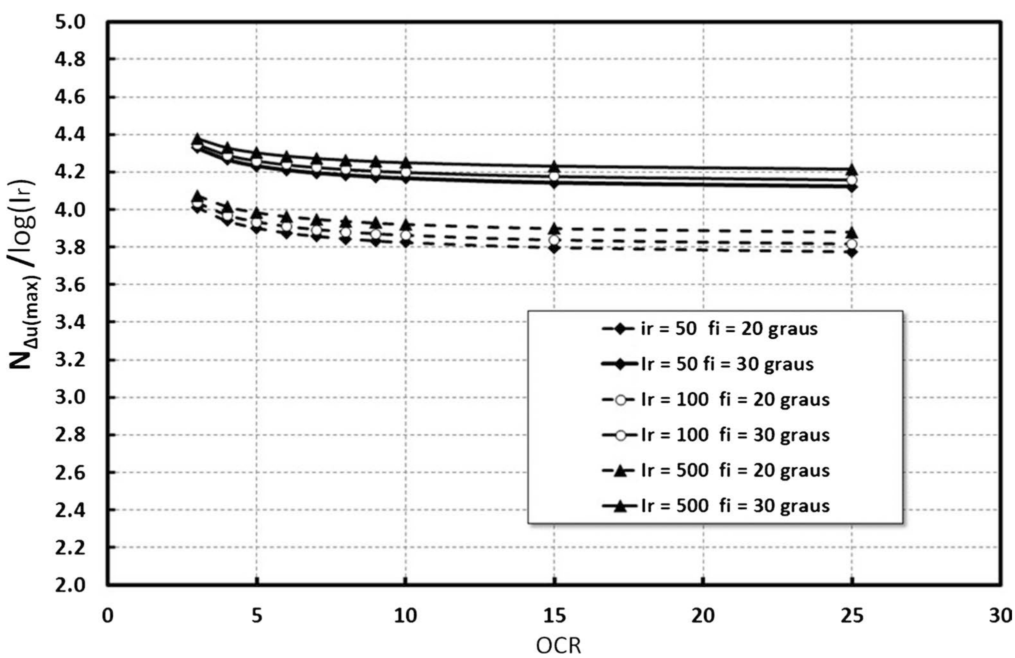


Figure 1. Undrained pore pressure ratio $N_{\Delta u_{\max}}$ (Mántaras et al.., 2014).

Advantages of interpreting pore pressures measurements compared to the more conventional piezocone penetration data are: (a) the cone factor $N_{\Delta u_{\max}}$ is less affected by soil rigidity and stress history because measurements result from pore pressure flow around the probe rather than of complete soil displacement caused by the cone penetration test and (b) well-defined failure mechanisms of flow around the probe allow for sound theoretical analysis of pore pressure dissipation and shear strength.

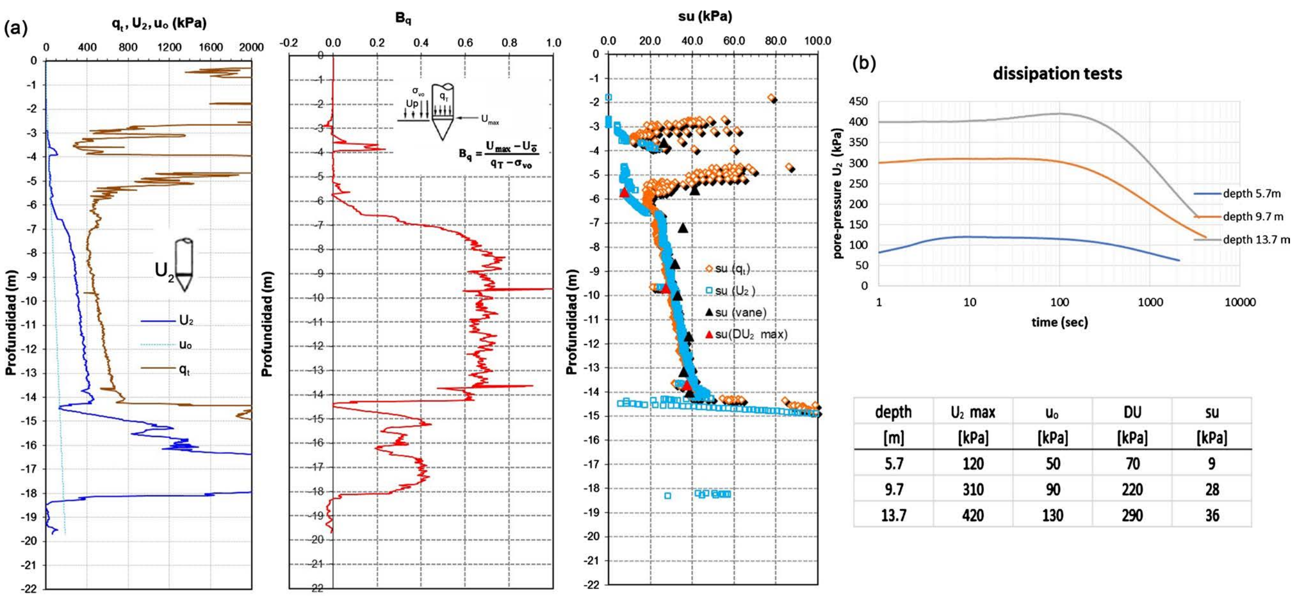
From the mathematical viewpoint the above expression is rigorously consistent; expressing the ratio between values of pore pressure measured during piezocone dissipation and the undrained shear strength in Direct Simple Shear conditions.

3. Case Studied

To illustrate the possibilities offered by the approach proposed by Mántaras et al. (2014), it will be applied to data from a well-documented site research program of a soft clay deposit in the metropolitan area of Porto Alegre, Rio Grande do Sul, Brazil. The complete research program consists of eleven study points using different types of tests in each one.

In order to visualize the results of the different tests and the application of the method, two points of very different characteristics were chosen to be presented in this work. In both cases, undrained shear strength values predicted from classical approaches are consistent between them (s_u obtained from Vane test, N_{kt} and $N_{\Delta u}$).

The first boring is illustrated in Figure 2, showing a homogeneous clay profile deposit. Undrained strength, s_u, obtained from the dissipation test method proposed by Mántaras et al. (2014) using $N_{\Delta u_{\max}} = 8$ ($N_{\Delta u_{\max}} = 4 * \log I_r$, with I_r equal to 100 = 8) are of the same order of magnitude as those calculated from other methods.



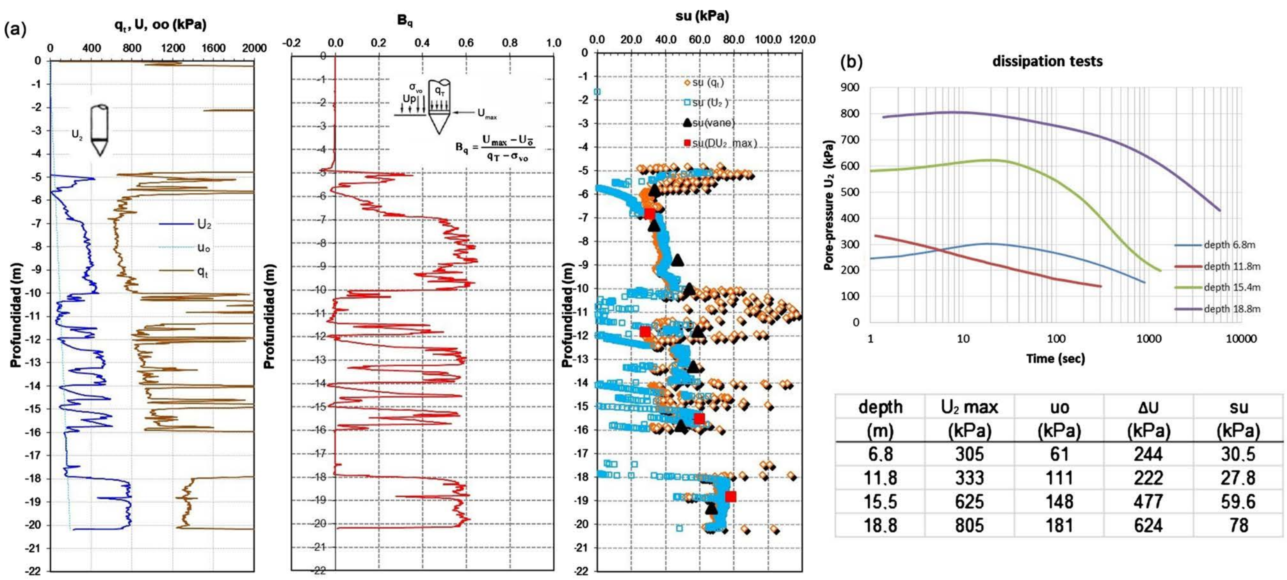
depth [m]	U2 max [kPa]	uo [kPa]	DU [kPa]	su [kPa]
5.7	120	50	70	9
9.7	310	90	220	28
13.7	420	130	290	36

Figure 2. Metropolitan Region Porto Alegre, Brazil. (a) Homogeneous geotechnical profile. (b) Dissipation tests.

The second boring is illustrated in **Figure 3**, showing a layered deposit. The different grain size of layers could also be estimated from assessment of horizontal coefficient of consolidation, C_h, from dissipation tests. Once again, dissipation test results yielded s_u values of the same order of magnitude as those calculated from other methods.

Table 1 summarized the results for the whole campaign. Aiming to verify the consistency of assessed undrained strength with this novel approach, the cones factor N_{kt} and $N_{\Delta u}$ values were back calculated in **Table 1** and presented in **Figure 4** and **Figure 5** in the same framework proposed by Lunne et al. (1997).

Despite the dispersion of the results, it is clear the trends of N_{kt} vs. B_q and $N_{\Delta u}$ vs. B_q values and are consistent with those found in international literature.



depth (m)	U₂ max (kPa)	uo (kPa)	ΔU (kPa)	su (kPa)
6.8	305	61	244	30.5
11.8	333	111	222	27.8
15.5	625	148	477	59.6
18.8	805	181	624	78

Figure 3. Metropolitan Region Porto Alegre, Brazil. (a) Erratic geotechnical profile. (b) Dissipation tests.

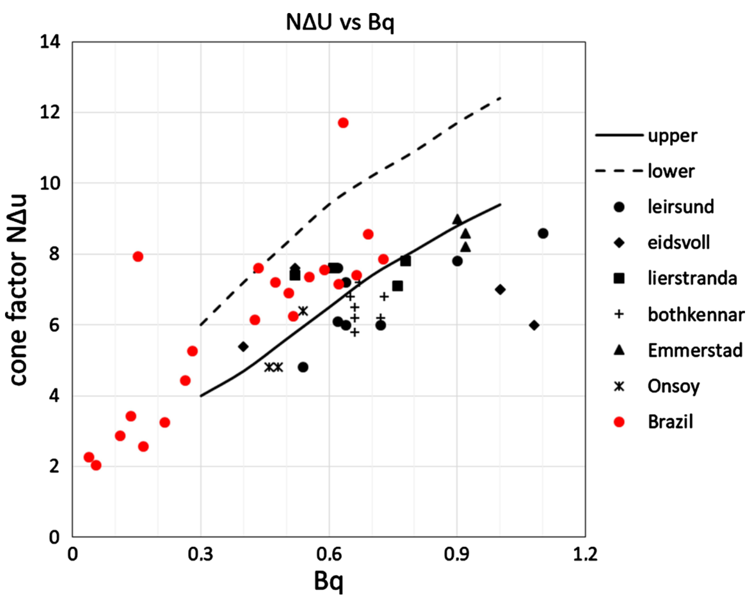


Figure 4. Back calculated cone factors $N_{\Delta u}$ vs. B_q using s_u ($\Delta u_{\max}$ method).

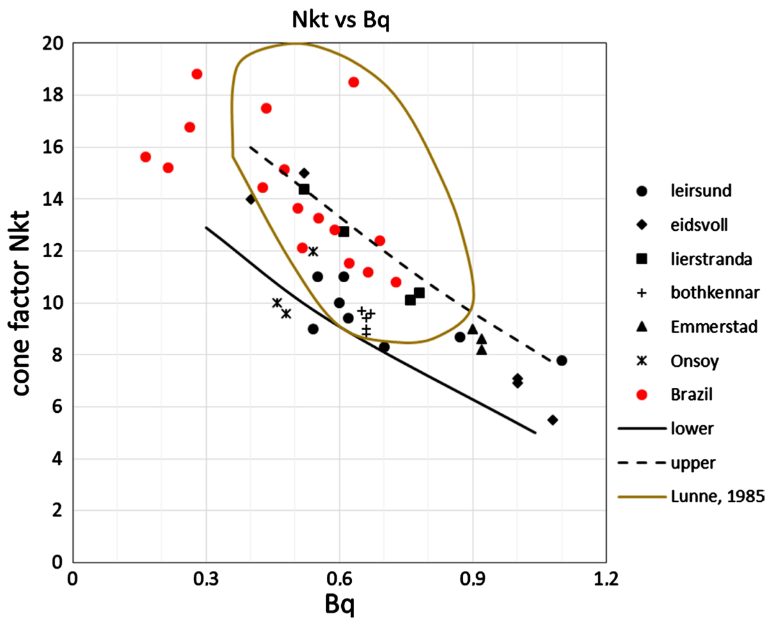


Figure 5. Back calculated cone factors N_{kt} vs. B_q using s_u (Δu_{max} method).

Table 1. All the results obtained in the complete study.

Boring	NA m	prof m	u eq kPa	u_{2max} (ddp) kPa	Δu_{2max} (ddp) kPa	s_u (Δu_{2max}) kPa	q_t (medio) kPa	σ_v total kPa	u_2 (medio) kPa	B_q	N_{kt}	$N_{\Delta u}$
		5.3	46	160	114	14	359	91	121	0.28	18.8	5.3
A	0.7	8.3	76	255	179	22	403	132	216	0.52	12.1	6.3
		11.3	106	205	99	12	881	177	104	0.00	56.9	−0.2
		5.5	35	110	75	9	446	95	54	0.05	37.4	2.0
B	2.0	8.0	60	260	200	25	424	136	239	0.62	11.5	7.2
		11.0	90	320	230	29	684	181	309	0.44	17.5	7.6
		5.7	50	110	60	8	541	100	67	0.04	58.8	2.3
C (Figure 2)	0.7	9.7	90	310	220	28	457	160	306	0.73	10.8	7.9
		13.7	130	430	300	38	640	221	408	0.66	11.2	7.4
		6.8	61	305	244	31	632	120	196	0.26	16.8	4.4
D (Figure 3)	0.7	15.5	148	625	477	60	1113	252	515	0.43	14.4	6.2
		18.8	181	805	624	78	1308	308	770	0.59	12.8	7.6
		5.8	41	150	109	14	571	97	37	−0.01	34.8	−0.3
E	1.7	8.0	63	195	132	17	994	131	194	0.15	52.3	7.9
		22.0	203	2300	2097	262	6942	373	1099	0.14	25.1	3.4
F	1.0	6.0	50	190	140	18	359	93	107	0.21	15.2	3.3
		9.0	80	255	175	22	540	135	336	0.63	18.5	11.7
G	1.9	7.0	51	285	234	29	562	105	126	0.16	15.6	2.6
		9.0	71	370	299	37	700	134	340	0.48	15.1	7.2
H	1.5	10.0	85	210	125	16	551	148	130	0.11	25.8	2.9
I	2.9	9.0	61	330	269	34	584	138	308	0.55	13.3	7.3
J	1.6	7.5	59	255	196	25	455	121	228	0.51	13.6	6.9
K	2.8	7.0	42	280	238	30	483	114	297	0.69	12.4	8.6

4. Closing Remarks

The paper applies a new method proposed by Mántaras et al. (2014) to estimate the undrained shear strength from piezocone dissipation tests. Stress history, shear strength and compressibility are the critical factors affecting the accuracy of predictions and are properly taken into account.

The method yields an undrained pore pressure ratio $N_{\Delta u_{\max}}$ of about 8 which is within the range of early recommended values.

Also the N_{kt} and $N_{\Delta u}$ factors calculated from the results of undrained resistance obtained from dissipation tests applying this new mathematical formulation are consistent with those referenced in the international literature and encourage its use in the engineering practice.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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