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CPT-based correlations analysis to estimate shear wave velocity in tailings

Análisis de correlaciones basadas en ensayo CPT para estimar la velocidad de las ondas de corte en relaves

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ABSTRACT: Several correlations have been proposed to estimate shear wave velocity (Vs) using Cone Penetration Test (CPT) data. However, many of these methodologies are grounded in assumptions tailored to natural soils, such as clays and clean sands, which may yield unrealistic values when directly applied to tailings. This paper presents a comparison of various CPT-based correlations for estimating Vs using data obtained from Seismic Cone Penetrometer Testing (SCPTu) conducted on copper tailings. The key assumptions underlying each correlation are discussed to evaluate the factors influencing the estimates, including the depth (confinement pressure) and presence of the water table. Subsequently, deviations for each methodology relative to the downhole values are computed to ascertain which approach yields superior results compared to those obtained in the field. An optimization process is then employed to adjust the parameters of the different empirical equations, aiming to minimize errors in the estimates by proposing modifications to the original equations that better align with data from mining tailings.

KEYWORDS: cone penetration test (CPT), shear wave velocity, tailings characterization

1 INTRODUCTION

After the Maule MW8.8 earthquake (2010) in Chile, the cone penetration test (CPT) has become highly relevant for characterizing mining waste. Additionally, in recent years, with the decline in mineral grade in mining deposits, the characterization of abandoned tailings storage facilities through CPT soundings has become common to assess their behavior for potential re-mining plans.

Since the CPT provides a continuous profile in depth, there are no issues related to information gaps such as poor soil recovery from a borehole. Moreover, from the tip (qc) and sleeve (fs) resistance, as well as the dynamic pore water pressure (u2) measurement, several soil properties can be estimated to assess soil behavior (Robertson & Cabal, 2022).

One of the key parameters that can be derived from the CPT is the small strain shear modulus (G_0) by assessing the shear wave velocity (Vs) profile in depth. Based on elastic theory, G0 can be obtained by multiplying the mass density of the soil (ρ=γ/g) by the square of the soil shear wave velocity, as shown in Eq. (1):

$$G_0 = \rho V_s^2 \quad (1)$$

The shear wave velocity (or the small strain shear modulus) is an essential parameter for predicting deformations either through empirical expressions or numerical models, as well as for seismic amplification analysis. Additionally, it can be used to assess liquefaction potential (Kayen et al., 2013) as a preliminary assessment, considering that it is a small strain measurement while liquefaction is a large strain phenomenon. Although direct measurements of Vs are always preferred over correlations (Andrus et al., 2007), deriving Vs from CPT data could be faster and more economical for engineering projects.

Nonetheless, CPT-based correlations should be carefully assessed since there are soil conditions that could affect their results, such as microstructure (Robertson, 2009), for instance. Another relevant factor is soil saturation, where although water does not affect shear wave propagation, an unsaturated state of the soil increases both tip and sleeve resistance, which are the inputs for most of the correlations in the literature used to estimate shear wave velocity.

Most CPT-based correlations available in the literature for estimating shear wave velocity were calibrated for soils vastly different from mining tailings. Therefore, predictions are not always satisfactory, and in certain cases, there may be considerable dispersion between the estimate and the correct data collected from the field.

Shear wave velocity can also be obtained straightforwardly by using the downhole technique within the cone during pauses in the CPT penetration. By repeating this procedure several times during penetration, shear wave velocity can be continuously obtained.

The following article presents an analysis of four CPT-based methodologies for assessing shear wave velocity applied in 10 CPTu tests carried out on copper tailings. Additionally, results are compared with downhole tests performed in each of the SCPTu tests to assess which methodology fits the data better.

2 SHEAR WAVE VELOCITY CORRELATIONS BASED ON THE CPT DATA

Estimating the shear wave velocity through the results of CPT tests can seem paradoxical when considering that wave propagation occurs at strains less than 10^{-5}, while the cone penetration pushes the soil to large deformations associated with failure (Jefferies and Been, 2016; Mayne and Rix, 1995).

However, both Vs and qc exhibit dependencies on similar geotechnical parameters such as effective confining stress level (σ'_v), the geostatic stress ratio (K_0), mineralogy, aging, among others (Mayne and Rix, 1995).

Most of the expressions derived for estimating Vs from CPT data are for clayey soils. However, tailings typically classify as ML, especially for slimes, and sometimes as SM if there are whole tailings (Morales & Taborda, 2022; Morales & Sfriso, 2024).

Based on this, special emphasis was placed on studying expressions for sands and on authors who used tailings for their empirical correlation fitting.

Baldi et al. (1989) proposed a CPT-based correlation for V_s and G_0 in non-cohesive soils through tests carried out in calibration chambers and then compared to resonant column data. The expression was initially developed for silica sand from Ticino, Italy, and subsequently tested with SCPT on Po River sand and Gioia Tauro sandy gravel, yielding a good fit. The sandy soils at both sites were natural deposits with geological ages ranging from 3,000 to 20,000 years at a maximum depth of 30 m. The Baldi et al. (1989) expression is shown in Eq. (2), where qc is obtained directly from the CPT and σ'_v can be estimated from CPT dissipation tests and correlations for the unit weight or by directly measuring the unit weight in the field.

$$V_s^B = 277\, q_c^{0.13}\, {\sigma'_v}^{0.27} \tag{2}$$

Hegazy and Mayne (1995) analyzed data from 61 different locations, including clays, sands, and mine tailings. Based on this data, they suggested independent correlations for sands, clays, and all soil types in terms of qc and fs. They also concluded that qc is the most relevant variable for estimates, as the Mayne et al. (1994) correlation, based solely on sleeve resistance, did not fit the data. Eq. (3) shows the empirical equation proposed by Hegazy and Mayne (1995) for all soil types:

$$V_s^{H\&M} = (10.1 \log q_c - 11.4)^{1.67} \left(\frac{f_s}{q_c} 100\right)^{0.3} \tag{3}$$

Robertson (2009) studied 100 SCPTs from 22 sites in California, in addition to published information available in the literature. Most of the soils were coarse-grained, exhibiting drained behavior during penetration, and ranged predominantly from Holocene to Pleistocene uncemented soil deposits. Robertson (2009) found that Pleistocene soils have shear wave velocity values 25% higher than those of Holocene soils.

The empirical equation proposed by Robertson (2009) applies to all types of uncemented soils and incorporates q_c and f_s by considering the soil behavior index (I_c) as shown Eq (4) and (5).

$$V_s^R = \left(10^{0.55 I_c + 1.68} \left(\frac{q_t - \sigma_v}{P_a}\right)\right)^{0.5} \tag{4}$$

$$I_c = \sqrt{\left(3.47 - \log \frac{q_t - \sigma_v}{\sigma'_v}\right)^2 + \left(1.22 + \log \frac{f_s}{q_t - \sigma_v}\right)^2} \tag{5}$$

Since the effective confining stress level (σ'_v) is used in this correlation, it is recommended to include pore water pressure (pwp) dissipation tests to establish an accurate hydrostatic pwp profile (u_0) and provide a reliable estimation of the effective stresses.

Paredes and Illingworth (2022) analyzed more than 600 CPTs, 800 boreholes, and 45 downhole tests conducted at 45 different sites composed of Holocene estuarine, alluvial, and deltaic soils in Guayaquil, Ecuador. Their research found that while the Robertson (2009) empirical equation fits downhole results, it overestimates the results for soft clays by 20 to 30%. Therefore, they modified the Robertson (2009) equation by incorporating an age correction factor and using the end area corrected tip resistance (q_t) instead of the raw measured value (q_c). Eq. (6) presents the Paredes and Illingworth (2022) expression, which applies to clays and sands (q_t must be in MPa units).

$$V_s^{P\&I} = 112.82 (q_t)^{0.35} \tag{6}$$

3 DATA ANALYSIS

3.1 *Tailings characteristics*

Ten SCPTu tests conducted on different TSF impoundments were analyzed. Additionally, more than 100 samples were obtained using a MOSTAP sampler in twin boreholes, classifying the soil as ML with some layers of SM and ML-CL. Table 1 shows the main results obtained from the CPT and downhole tests performed in the field.

Table 1. Tailings characteristics.

Parameter (units)	q_t *(MPa)*	f_s *(MPa)*	u_2 *(MPa)*	*Vs (m/s)*
Min	0.1	0	0.08	102
Max	31.06	0.75	1.45	513
Average	4.64	0.07	0.17	254
P50	3.69	0.06	0.04	245
P30	1.66	0.03	0.00	207

It is important to note that the water table was highly variable for each CPT. Therefore, some data reflect partially saturated conditions, while others show saturation close to 100% (below the water table). Table 2 shows the water table location for each CPT, where CPT 3 and CPT 4 did not encounter a water table until the end of penetration.

Table 2. Water table depth for each CPT (nr=not reached).

CPT #	*Depth (m)*	CPT #	*Depth (m)*
CPT 1	37	CPT 6	12
CPT 2	40	CPT 7	4
CPT 3	nr	CPT 8	5
CPT 4	nr	CPT 9	5
CPT 5	10	CPT 10	5

3.2 *Microstructure Identification*

To assess the presence of cementation in tailings, the methodology proposed by Robertson (2016) was employed. This approach suggests using the normalized cone resistance (Q_{tn}) versus the small-strain rigidity index (I_G). This comparison is commonly used to identify the presence of microstructure in soils.

Figure 1 shows the relationship between Q_{tn} and I_G, where I_G corresponds to the ratio between G_0 (obtained from the downhole tests) and the net cone resistance (q_n). The 50th percentile (P_{50}) of Q_{tn} and qn was obtained by considering a soil column 50 cm above and below the depth of the downhole test. Figure 1 indicates that less than 20% of the data exhibits microstructure, as most of the data fall between the lines with the modified normalized small-strain rigidity index (K^*_G) equal to 100 and 330.

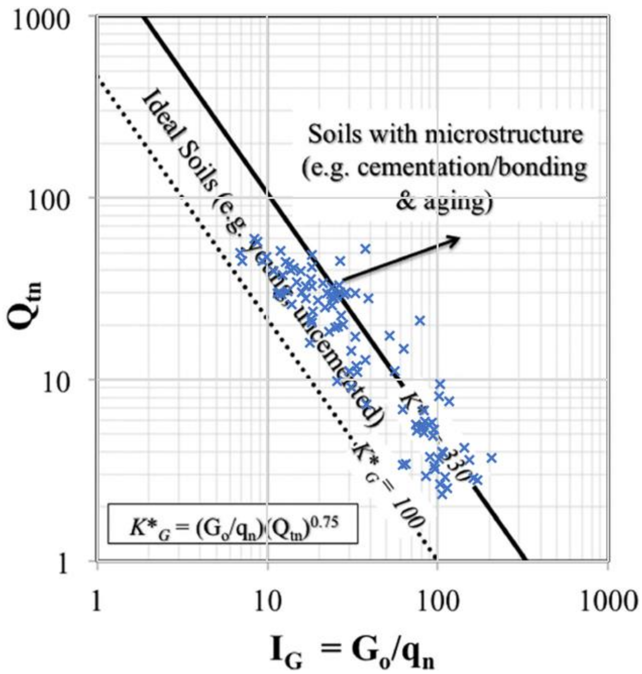

Figure 1. Q_{tn} vs I_G chart to identify soils with microstructure (modified from Robertson, 2016).

Indeed, most of the points that exhibit microstructure are close to the threshold $K^*_G = 330$, suggesting that microstructure does not play a significant role in the data interpretation. These results are consistent, as this manmade soil has a deposition time of less than 50 years and lacks the presence of salts or chemical compounds that could lead to cementation in tailings. Therefore, they can still be considered young and uncemented soils.

3.3 *Equations fitting*

The four empirical equations (Eqs. 2, 3, 4, and 6) were applied to the CPT results to estimate the shear wave velocity at depth. Figure 2 shows the results obtained from each methodology applied to one of the CPTs, along with the downhole results. The water table, located at a depth of 5 m, was included to distinguish between unsaturated and saturated zones.

To assess the error associated with each estimate, the variability of the parameters used in the equations was considered. The P50 of the parameters for each empirical equation was calculated, considering the soil 50 cm above and below the depth of the downhole test. This approach helps to discard anomalous peaks that could affect the representativeness of the estimates.

Using this method, the root-mean-square error (RMSE) (see Eq. 7) was calculated for the estimates from each of the ten CPTs, along with the downhole results. Figure 3 shows the RMSE for each CPT.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Vs_{predicted} - Vs_{downhole}\right)^2}{N}} \quad (7)$$

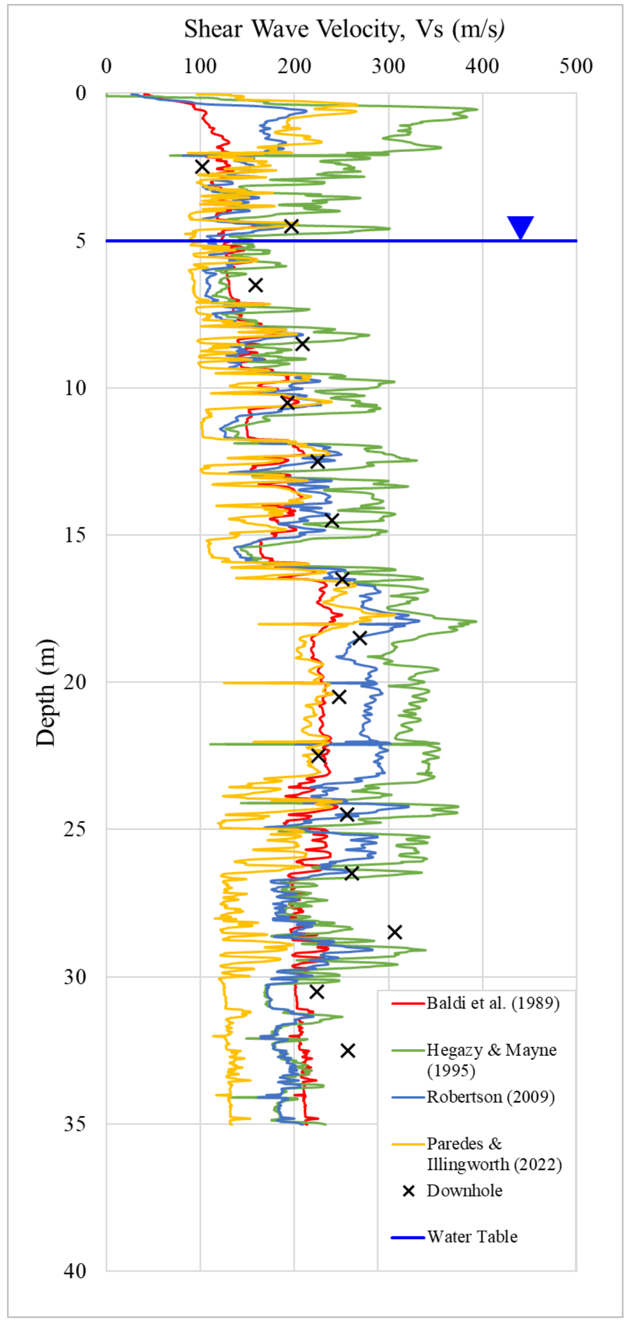

Figure 2. Comparison of the empirical equations for CPT 10.

As shown in Figure 3, all methodologies exhibit a similar trend in the estimated RMSE. However, the Paredes and Illingworth (2022) method shows the greatest difference compared to the downhole data, while the methods by Baldi et al. (1989), Hegazy and Mayne (1995), and Robertson (2009) show similar levels of accumulated error. It is noteworthy that the largest errors occur in CPT 3 and CPT 4, where there is no water table and unsaturated conditions prevail.

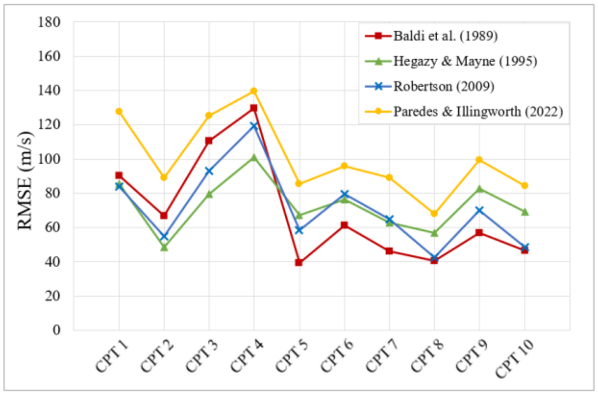

Figure 3. RMSE for all the CPTs.

Figure 4 shows the trend between the measured and predicted values according to the empirical equations. Generally, the empirical equations tend to underestimate the Vs values, as indicated by the slopes of the trend lines being below 1.0. Among the authors, Hegazy and Mayne (1995) have the best fit to the measured data (slope "m" closer to 1.0), followed by Robertson (2009) and Baldi et al. (1989). In contrast, the Paredes and Illingworth (2022) equation does not fit the data well, exhibiting considerable scatter.

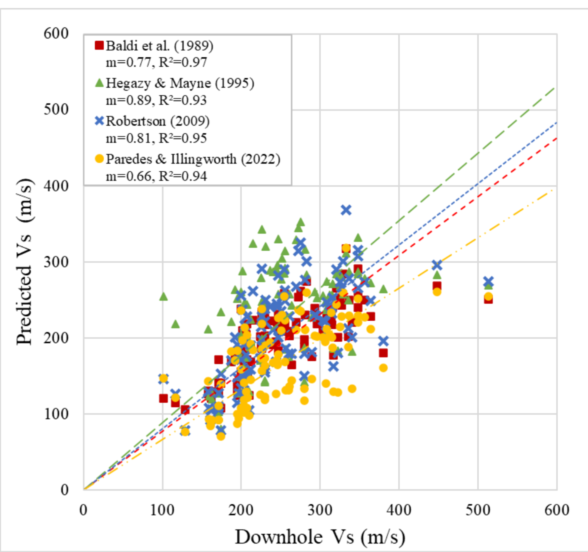

Figure 4. Comparison between measured and predicted Vs for all the CPT data.

3.4 *Saturation effect*

From Figure 3, the highest RMSE values are found in CPTs 1, 3, and 4, which have a large amount of data in unsaturated conditions (Vs measurements above the water table). Although water does not affect the propagation of shear waves, it does influence the tip and shaft resistance values measured by the cone (Russell et al., 2024).

To study the effect of saturation on the different equations analyzed, the data above the water table were separated from those below the water table, and separate analyses were performed on each dataset. Based on this, Figures 5 and 6 show the fit for the saturated and unsaturated data, respectively.

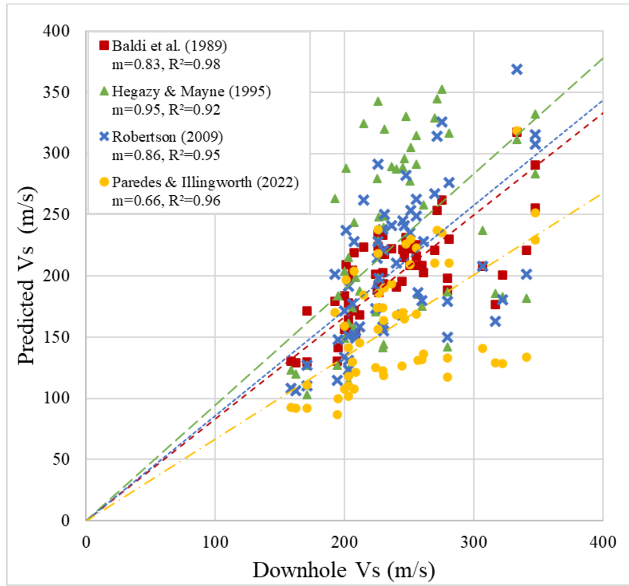

Figure 5. Comparison between measured and predicted Vs for the saturated data of all CPTs.

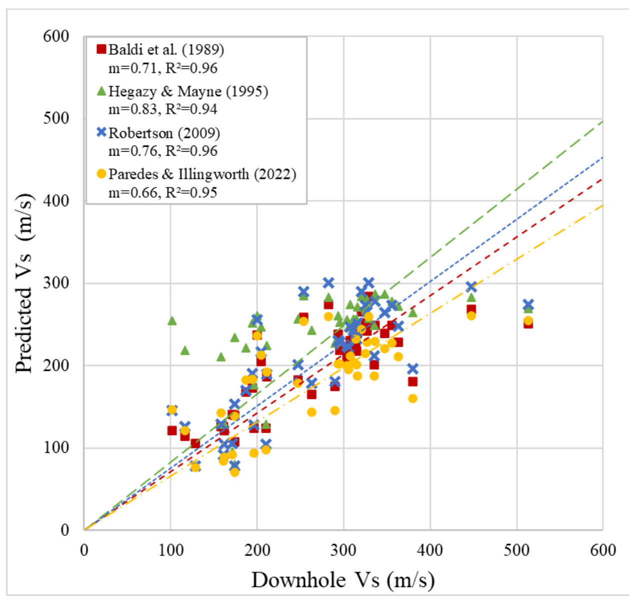

Figure 6. Comparison between measured and predicted Vs for the unsaturated data of all CPTs.

The results show an improved fit for the saturated data when using the methodologies of Baldi et al. (1989), Hegazy and Mayne (1995), and Robertson (2009). However, for Paredes and Illingworth (2022), the difference between the saturated and unsaturated fits is negligible, suggesting that moisture content does not affect the calculations for this method.

Regarding the trend lines, the Hegazy and Mayne (1995) method best fits the data (highest m value) for both saturated and unsaturated conditions, followed by Robertson (2009) and Baldi et al. (1989). However, Baldi et al. (1989) shows the least dispersion in the estimates for both saturated and unsaturated conditions, followed by Robertson (2009), Paredes and Illingworth (2022), and Hegazy and Mayne (1995).

3.5 *Depth effect*

Figure 7 shows the absolute difference between the measured and predicted values by depth for all the CPTs. The results suggest that depth has very little impact on the accuracy, with only a slight increase in data dispersion observed with increasing depth. This increase in data scattering is more pronounced for the Paredes and Illingworth (2022) method compared to the other methods.

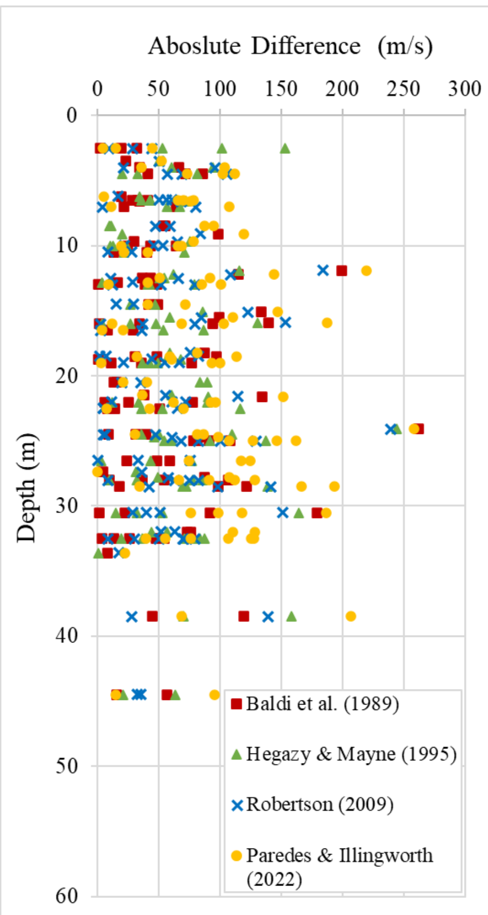

Figure 7. Comparison between measured and predicted Vs for the unsaturated data of all CPTs.

4 EQUATIONS OPTIMIZATION

The four methodologies presented in this paper were optimized to determine if changes to their fitting constants could improve the match between the predicted and measured Vs values. To achieve this, a genetic optimization algorithm was implemented to minimize the squared error for each empirical equation. The resulting fits are shown in Figure 8, and the optimized values for the empirical equations are presented in Table 3.

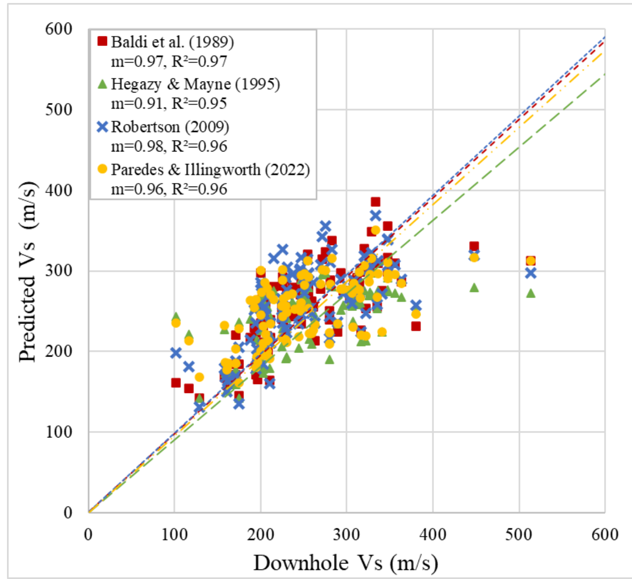

Figure 8. Comparison between measured and predicted Vs by the optimized equations for all the CPT data.

Table 3. Optimized equations

Author	*Algorithm optimization*
Baldi et al. (1989)	$337\, q_c^{0.12}\, \sigma'_v{}^{0.24}$
Hegazy and Mayne (1995)	$(49.3 \log q_c - 31.7)^{1.1} (f_s/q_c\, 100)^{0.11}$
Robertson (2009)	$\left(10^{0.67 I_c + 3.42} ((q_t - \sigma_v)/P_a)\right)^{0.36}$
Paredes & Illingworth (2022)	$205.74 (q_t)^{0.18}$

Similar to the analysis performed on the original empirical equations, the RMSE was estimated for the newly fitted equations. The results are shown in Figure 9, where the trend for each author is very similar to the results presented for the original equations in Figure 3. Nonetheless, the RMSE is significantly reduced for some CPTs. In particular, the optimized Paredes and Illingworth (2022) equation shows considerable improvement, minimizing the data scattering.

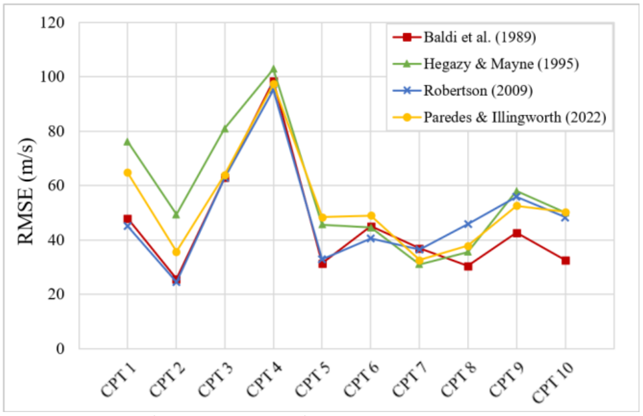

Figure 9. RMSE for all the CPTs after the optimization.

5 CONCLUSIONS

Four CPT-based methodologies for estimating the shear wave velocity were applied to CPT data from a tailings impoundment and compared to the Vs values obtained by the seismic piezocone. The results suggest that the methodology providing the best results is Hegazy and Mayne (1995), followed by Robertson (2009) and Baldi et al. (1989), while Paredes & Illingworth (2022) does not accurately fit the data since it considerably underestimates the Vs and shows significant scattering. Indeed, Paredes & Illingworth (2022) is the method that exhibits the highest RMSE value for each CPT, while Hegazy and Mayne (1995) show the lowest for four CPTs and Baldi et al. (1989) have the lowest RMSE for the other six CPTs.

If the Vs estimates are separated between saturated and unsaturated data, using the water table as the threshold, the trends between the methods remain unchanged, i.e., Hegazy and Mayne continue to be the equation that fits the best. However, the fit improves when only saturated data is considered, and it deteriorates if only unsaturated data is used.

The depth or confining pressure does not seem to have a significant effect on the estimates; however, for the Paredes and Illingworth (2022) methodology, the estimate tends to slightly increase its scattering with depth. This effect is very limited for the other methods and is hard to generalize.

If the considered equations are optimized by adjusting the constants of each equation, the results improve considerably, suggesting that the expressions could be adapted to tailings to provide good predictions in the absence of seismic piezocone data. However, the optimized equations have only been tested on these ten CPTs and need to be validated with more data from other impoundments to ascertain their accuracy and precision.

6 FUTURE WORK

The authors are currently working on testing the proposed expressions on a larger amount of data and different TSF.

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