Shear wave velocity prediction using different in situ tests at a soft clayey site in Guayaquil (Ecuador)

B.Intriago[1], H. Bazurto[2], D. Besenzon[3]
Facultad de Ingeniería en Ciencias de la Tierra,Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador, baintria@espol.edu.ec1, hbazurto@espol.edu.ec[2], besenzon@espol.edu.ec [3]

X. Vera-Grunauer
Geoestudios S.A., Guayaquil, Ecuador, xvg@geoestudios.com.ec

S. Amoroso
Dept. ofEngineering and Geology, Universityof Chieti-Pescara, Pescara, Italy, sara.amoroso@unich.itIstitutoNazionale di Geofisica e Vulcanologia, L'Aquila Italy

ABSTRACT: Guayaquil city is located on the West margin of the Guayas River along the Pacific coast of South America. According to research and zoning from previous studies a large area of the city sits on estuarine deltaic deposits which consist of weak and highly compressible clays with diatoms. The nature of these soft clays may determine difficulties in the use of some methods or equations, and consequently in the reliability of the obtained interpretation of the results. The paper examines the correlations to obtain rough estimates of the shear wave velocity from flat dilatometer tests (DMT), standard penetration test (SPT) and cone penetration tests (CPT). While the direct measurement of S-wave is obviously preferable, these correlations may turn out useful in various circumstances. The experimental results at the site suggest that the DMT predictions more reliable and consistent than the SPT and CPT predictions, presumably because of the availability, by DMT, of the stress history index.

Keywords:flat dilatometer test (DMT); piezocone test (CPTu);standard penetration test (SPT); shear wave velocity prediction; soft clays.

1. Introduction

In the last decades, Guayaquil soils have been widely studied because of an increasing urban process that the Ecuadorian city has experienced. Nevertheless, limited information is available in the literature about estimation of geotechnical parameters related to this area.

The estuarine zone of the Guayas River deposits is highly heterogeneous. The soil stratigraphy consists of very soft, weak, and highly compressible sediment over hard rocks of Piñon and Cayo Fm. These soils, once analyzed microscopically, show in their matrix clay minerals of heterogeneous composition. One of these components are diatoms[1].

The considerable presence of diatoms in Guayaquil deposits, mainly in the first 15 m [2] assumes importance considering that the majority of the methods or geotechnical correlations are calibrated on datasets that do not consider the diatom content in soft clays.

In Ecuador, the standard penetration test (SPT) is overused for the geotechnical design. This practice is attributed to its widespread use worldwide during the last decades, which has led to the collection of a considerable number of data and correlations, considering the limited cost of execution during the cores, the usual availability of the SPT equipment, and the easy execution. However, its use should not be generalized in all soils, especially in soft clays.

The results are difficult to interpret in cohesive deposits and, consequently, not conclusive due to the low number of blows. Besides, the samples obtained are highly altered, and therefore they are not representative of the in situ conditions [3]. In this respect, it is advisable to use other in situ tests, such as the piezocone test (CPTu) and the seismic dilatometer test (SDMT), to better capture the undrained and drained behavior of cohesive and incoherent soils, respectively. These in situ tests have also the advantage (1) to be easy to execute, (2) to be a good cost-benefit compromise, (3) to reduce the alteration of the soil by evaluating its natural state, and the possibility of investigating in greater detail the spatial variability of the subsoil [4].

The paper examines the correlations to obtain rough estimates of the shear wave velocity from flat dilatometer tests (DMT), standard penetration test (SPT) and cone penetration tests (CPT) at the soft clay site of Guayaquil. While the direct measurement of S-wave is obviouslypreferable, these correlations may turn out useful in various circumstances when geophysical surveys are not available. In this respect, previous research studies are also available on various soil deposits and using different in situ tests (e.g. [5, 6, 7, 8]).

2. Site investigation

The study area, namely Murano, is located in Kennedy Norte sector (North-East of the city), along two estuarine branches and characterized by soft unconsolidated sediments. According to Vera-Grunauer [1], the site corresponds to the lithological unit D3. This zone is defined as Holocene estuarine deltaic deposits.

The site invesigation at the Murano site (Fig. 1.) included multiple geotechnical and geophysical surveys, n. 2 boreholes (P-1 and P-2) at depths of 46 and 45 m respectively, with the execution of SPTs. In situ tests

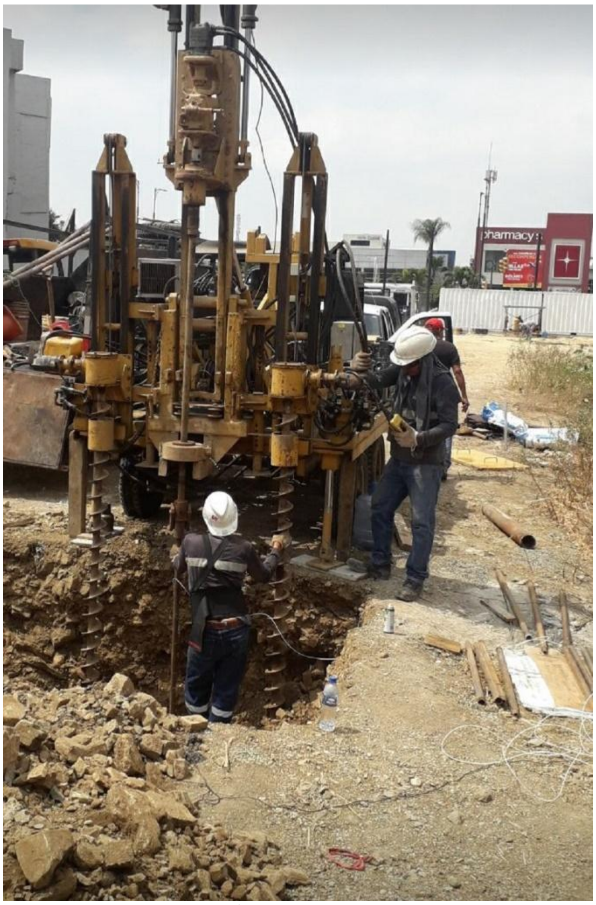

Figure 1. Execution of in situ tests at the Murano site.

included n. 2 piezocone tests, namely CPTu1 and CPTu2, at 41 and 30 m of depth respectively, and n. 1 seismic dilatometer (SDMT1) test at 31 m of depth. Due to the irregular topography of the area for the presence of a non-penetrable fill, in situ tests needed a predrilled hole up to 2 m depth. With reference to geophysical measurements a multichannel analysis of surface waves (MASW) survey was performed with a microtremor array measurement (MAM) test for a total length of 80.5 m.Further details on the geotechnical and geophysical campaign can be found in [9].

Fig. 2. summarizes the results of the direct measurements obtained from (1) SPT through the blow counts (N_{SPT}), necessary to penetrate the sampler 300 mm into the ground, after advanced first penetration of 150 m; (2) CPTu through the readings of the corrected cone resistance (q_t), sleeve friction (f_s), and pore water pressure (u_2); DMT though the two corrected pressure readings, namely p_0 (1st reading) and p_1 (2nd reading); (4) SDMT and MASW+MAM throgh the shear wave velocity (V_s).

The low N_{SPT} and q_t measurements and the high f_s and u_2 values in the upper 30 m of depth, together with the proximity of p_0 and p_1 pressures depth by depths, agree to identify the profile of a soft and clayey soil. Moreover, the two independent V_s profiles highlight a good agreement between the geophysical and geotechnical methods, thus strengthening the reliability of the acquisitions at the test site. In depth considerations on the geotechnical characterization of the Murano site can be found in [9].

3. Shear wave velocity at the test site using geotechnical and geophysicalmeasurements

The estimation of the shear wave velocity (V_s) is fundamental in geotechnical engineering design, not only for site classification and soil-structure interaction, but also for earthquake analysis and site response. Penetration tests can be used for predicting V_s through some measured parameters. In particular, DMT allows to estimate the small strain shear modulus (G_0), based on the material index I_D, the horizontal stress index K_D and the constrained modulus M according to [10]and hence V_s, through the theory of elasticity, as follow:

$$V_s = \sqrt{G_0/\rho} \tag{1}$$

where ρ is soil density. The equations to predict G_0 are listed in Table 1.

Table 1. Equations to estimate V_s from DMT according to [10]

Soil type	G_0 correlation
Silts: $0.6<I_D< 1.8$	$G_0=M\cdot 15.686\cdot K_D^{-0.921}$
Clays: $I_D< 0.6$	$G_0=M\cdot 26.177\cdot K_D^{-1.0066}$
Sands: $I_D> 1.8$	$G_0=M\cdot 4.5613\cdot K_D^{-0.7967}$

The experimental equations presented in Table 1 were developed using same-depth G_0, I_D, K_D and M values determined by SDMT at 34 international research sites, in a wide array of soil types. Ofthe over 2000 data points available, only 800 high qualitydata points were considered, relative to uniform one-metersoil intervals where log G_0, I_D, K_D and M values all differ less than 30% from their average to ensure a proper match of the data [11]. The DMT parameters have been calculated with the usual DMT interpretation formulae [12,13].

With reference to SPT, several authors developed and recommended correlations, expressed as a function of N_{SPT}, N_{60}, depth (Z) or effective vertical stress (σ_{vo}'), soil type and geological age, as reported in Table 2. Moreover, for CPT numerous equations were also estimated to predict V_s using tip resistance (cone tip resistance q_c or corrected cone tip resistance q_t), sleeve friction (f_s), depth (Z) or effective vertical stress (σ_{vo}'), soil type, and geologic age (Table 3).

Fig. 3a provides the comparison between V_s measured and V_s predicted by DMT, that shows a reasonable agreement. There is a slight overestimation of DMT values, more pronounced in the upper 15 m that could be related to the higher concentration of the diatoms to which K_D could be noticeable more reactive, due to its sensitivity to stress history, structure and prestraining/aging, scarcely felt by q_c (or q_t) from CPT and from N_{SPT} from SPT [6, 14].

The large number of correlations developed for SPT, involving a relevant number of parameters, determined a wide variability within the V_s profiles (Fig. 3b), as previously noted also by other authors in other sites (e.g. [7], [8]), and confirmed for the soft clay deposits of the Murano test site (e.g. [20] estimates values up to two times the measured ones).A similar behaviouris observed with the V_s correlations developed for CPT test (Fig. 3c.) (e.g.[22] estimates values up to four times the measured ones).

Table 2. Main available equations to estimate V_s from SPT.

Author	**Soil Type**	**V_s correlation**	**Geological description**
Wair et al. [15]	All soils	$V_s= 26\cdot N_{60}^{0.215}\cdot \sigma'_{v0}{}^{0.275}$	Holocene
	All soils	$V_s= 34\cdot N_{60}^{0.215}\cdot \sigma'_{v0}{}^{0.275}$	Pleistocene
	Clays and silts	$V_s= 23\cdot N_{60}^{0.17}\cdot \sigma'_{v0}{}^{0.32}$	Holocene
	Clays and silts	$V_s= 29\cdot N_{60}^{0.17}\cdot \sigma'_{v0}{}^{0.32}$	Pleistocene
	Sands	$V_s= 27\cdot N_{60}^{0.23}\cdot \sigma'_{v0}{}^{0.23}$	Holocene
	Sands	$V_s= 35\cdot N_{60}^{0.23}\cdot \sigma'_{v0}{}^{0.25}$	Pleistocene
Imai and Yoshimura [16]	All soils	$V_s=76\cdot N_{SPT}^{0.33}$	-
Kalteziotis et al. [17]	All soils	$V_s =76.2\cdot N_{SPT}^{0.24}$	-
	Sands and silts	$V_s = 49.1\cdot N_{SPT}^{0.502}$	
	Clays	$V_s = 76.55\cdot N_{SPT}^{0.445}$	
Ohsaki and Iwasaki [18]	All soils	$V_s=81.4\cdot N_{SPT}^{0.39}$	-
	Sands	$V_s = 59.4\cdot N_{SPT}^{0.47}$	
Iyisan [19]	All soils	$V_s= 51.5\cdot N_{SPT}^{0.516}$	Deep alluvial deposits
Jinan [20]	All soils	$V_s=116.10\cdot (N_{SPT}+0.32)^{0.202}$	Soft Holocene deposits
Dikmen [21]	All soils	$V_s=58\cdot N_{SPT}^{0.39}$	Quaternary alluvium
	Sands	$V_s = 73\cdot N_{SPT}^{0.33}$	Quaternary alluvium
	Clays	$V_s = 44\cdot N_{SPT}^{0.48}$	Quaternary alluvium
	Silt	$V_s = 60\cdot N_{SPT}^{0.36}$	Quaternary alluvium

Table 3. Main available equations to estimate V_s from CPT.

Author	V_s(or G_0) correlation	Geological description
Robertson [22]	$V_s=\alpha_{vs}\cdot\left(q_t-\sigma'_{v0}\right)^{0.5}/p_a$; $\alpha_{vs}=10^{0.55\cdot I_c+1.68}$	Holocene and Pleistocene soils, mostly uncemented
Hegazy and Mayne [23]	$V_s=[10.1\log\left(q_t\right)-11.4]^{1.67}\cdot f_s/q_t\cdot 100$	All types of soils
Simonini and Cola [24]	$G_0=49.2\cdot q_c^{0.51}$	Sand, silt and silty clay of Venice Lagoon
Andrus et al. [25]	$V_s=2.27\cdot q_t^{0.412}\cdot I_c^{0.989}Z^{0.033}\cdot ASF$; ASF = 1.00	Holocene soils
	$V_s=2.62\cdot q_t^{0.395}\cdot I_c^{0.912}Z^{0.124}\cdot SF$; SF =1.12	Pleistocene soils
Madiai and Simoni [26]	$V_s = 140\cdot q_c^{0.30}\cdot f_s^{-0.13}$	Holocene cohesive soils
	$V_s = 268\cdot q_c^{0.21}\cdot f_s^{0.02}$	Holocene incoherent soils
	$V_s = 182\cdot q_c^{0.33}\cdot f_s^{-0.02}$	Pleistocene cohesive soils
	$V_s = 172\cdot q_c^{0.35}\cdot f_s^{-0.05}$	Pleistocene incoherent soils
Bouchovalas et al. [27]	$G_0=28.0\cdot q_c^{1.40}$	Very soft clays
Vera-Grunauer [1]	$V_s=\sqrt{\eta\cdot q_c e^{\alpha}}$; $\alpha = [(3N_{kc} - 4) / 4]-[1 / (2\beta)]$; $\eta = 3g / [2N_{kc}\cdot\gamma_s\cdot(1+\nu)]$	Clays with diatoms

p_a = atmospheric pressure; ASF = Age scaling factor; SF = Scaling factor; γ_s= volumetric weight; g = gravity; N_{kc}=correlation factor; β = ratio between undrained shear strength and effective vertical stress; ν = Poisson's constant.

test (Fig. 3c) (e.g.[22] estimates values up to four times the measured ones). The arisen uncertainty could be due to the dependency to numerous and different parameters mentioned above that CPT and SPT parameters may not capture correctly. However, it is possible to select the best SPT-V_s and CPT-V_s predictions for soft clay deposits using the formulas proposed by [15], [17] and [21] for SPT test. Interestingly, the last two equations developed for all types of soils are in better agreement with the measured V_s profile than those made exclusively for clays. The selected equation [15] is valid for Holocene clays and silts. For CPT test, [27] and [1] resulted to fit better with V_s measurements, and they are valid for very soft clays and for clays with diatoms. In particular, Vera- Grunauer [1] proposed a site-specific correlation calibrated using Guayaquil dataset, that for D3 zone it established the following input parameters: β=0.22; N_{kc}=12; γ_s=15 kN/m^3; ν=0.3. All together the measured (SDMT, MASW+MAM) and selected-predicted [1,10,15,17,21,27]$V_s$data presented reasonable agreement identifying V_s values increasing in the 30 m depth in range of 50-180 m/s (Fig. 3d).

Further considerations can justify the better and univocal V_s prediction from DMT in comparison to CPT and SPT estimations. The equations listed in Table 1. were developed by [10] with reference to the diagram of Fig. 4. for which the followimg considerations can be reported [11]:

- the ratio G_0/M varies in a wide range (≈ 0.5 to 20 for all soils), hence it is far from being a

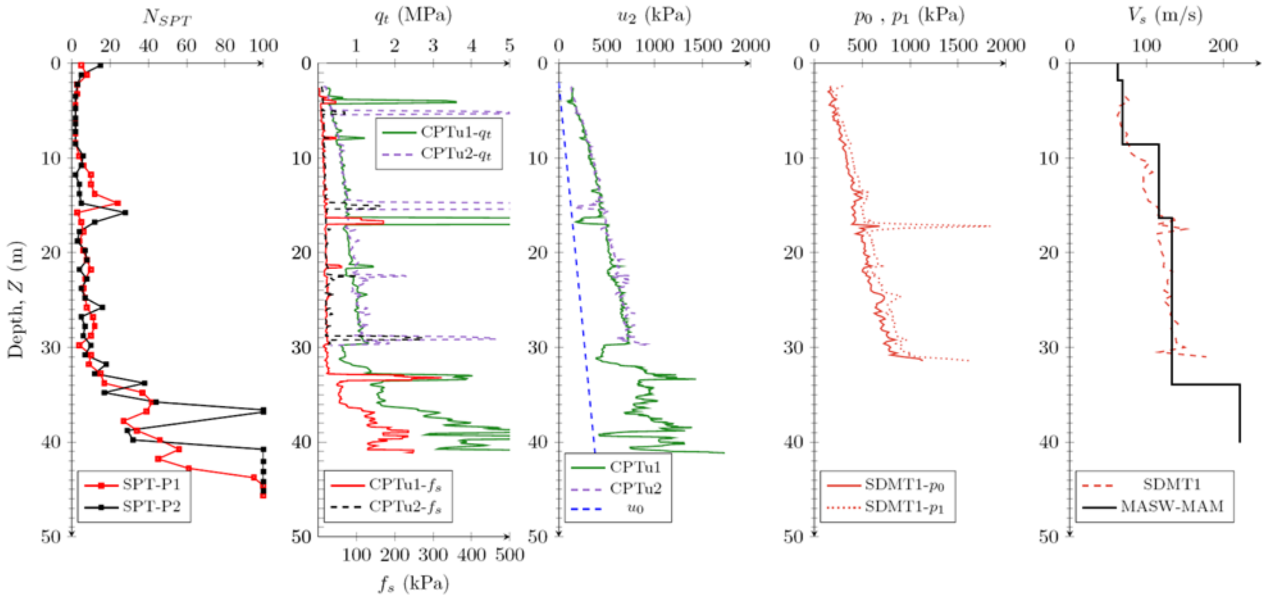

Figure 2. Measured parameters for geotechnical and geophysical tests at Murano site: SPT blow counts (N_{SPT}), corrected cone resistance (q_t), sleeve friction (f_s), pore water pressure (u_2), corrected DMT readings (p_0, p_1), shear wave velocity (V_s)

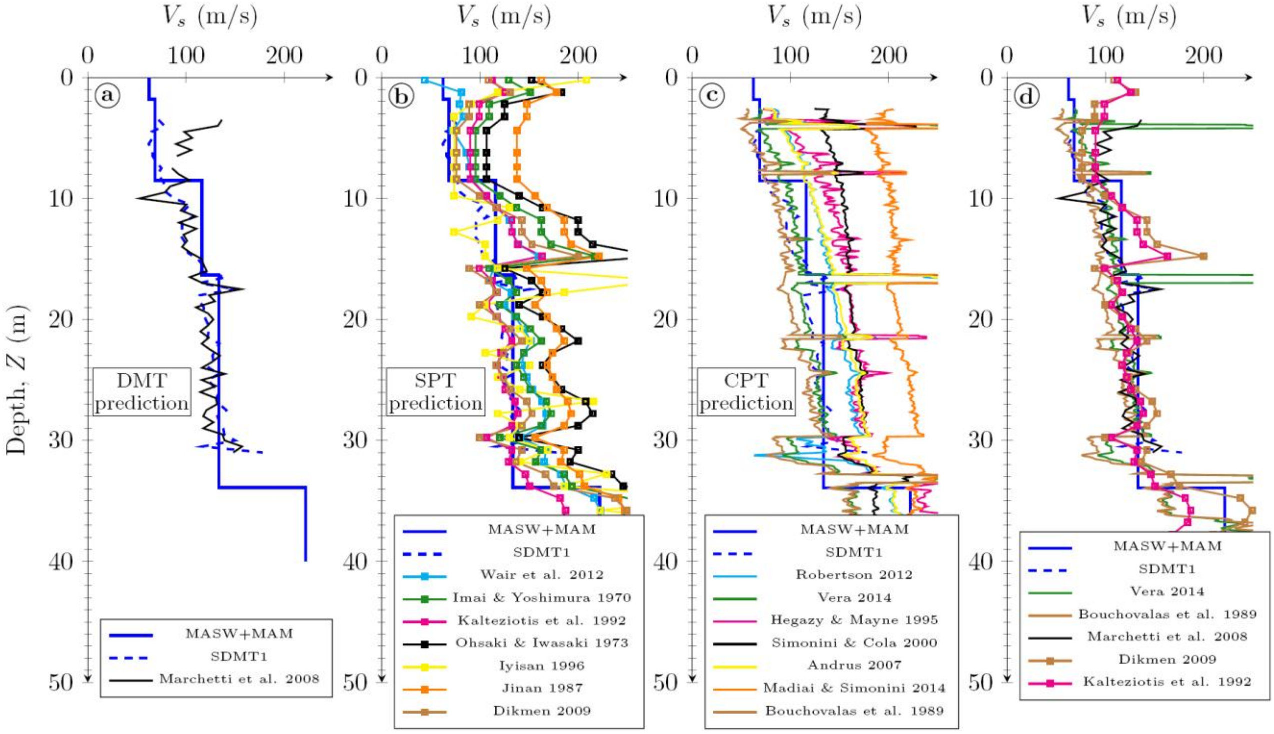

Figure 3. Comparison of V_s measured and $V_s$predicted by DMT (a), SPT (b), and CPTu (c); comparison of V_s measured and V_s predicted using the best correlations. The plots correspond to borehole P1, CPTu1 and SDMT1 tests.

constant. Its value is strongly dependent on multiple information, e.g., (at least) soil type and stress history. Therefore, it appears next to impossible to estimate the operative modulus M by dividing G_0 by a constant, as suggested by various Authors;

- the diagram highlights the dominant influence of K_D on the ratio G_0/M. In case of non availability of K_D (which reflects the stress history) all the experimental data points would cluster on the vertical axis, making the selection of the ratio G_0/M hopelessly uncertain. Hence as many as three information, i.e., I_D, K_D and M (though only two independent), are needed to formulate rough estimates of G_0 (and hence V_s). On the other hand the poor direct correlability of M to G_0, in absence of additional information, was expectable. M to G_0 are inherently different parameters, since at small strains the soil tendency to dilate or contract is not active yet. Such tendency substantially affects the operative modulus M, but does not affect G_0. Said in a different way, M includes some stress history information, G_0 does not [28];
- based on the latest consideration, the use of N_{SPT} or q_c (or q_t) alone as a substitute of V_s (when not measured) does not appear to be founded on a firm basis. In fact, if V_s is assumed to be the primary parameter for the

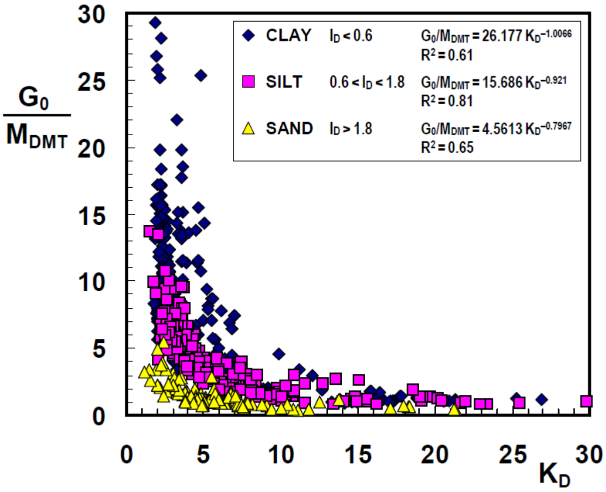

Figure 4. Ratio G_0 /M vs. K_D for various soil types[11]

classification of the site, then the possible substitute of V_s must be reasonably correlated to V_s. If three parameters (I_D, K_D and M) are barely sufficient to obtain rough estimates of V_s, then the possibility to estimate Vsfrom only one parameter appears remote.

4. Conclusions

The comparison between predicted and measured $V_s$values at the trial site of Murano (Guayaquil, Ecuador) suggested that DMT prediction is more reliable than CPT and SPT predictions. The high number of V_s correlations developed for CPT and SPT test detected a wide variability within the V_s profile of the soft clays, resulting in contrast with the single approach available for DMT[10]. The arisen uncertainty could be due to the dependency to numerous and different parameters related to the geological age, soil type and in situ stress state that CPT and SPT parameters may not capture correctly. At the same time, DMT (through K_D) is well correlated to stress history, prestraining/aging and structure scarcely felt by q_c (or q_t) and N_{SPT}.

Acknowledgement

Special thanks to Studio Prof. Marchetti (Italy) for kindly providing the SDMT apparatus and to Prof. Maurizio Mulas (Escuela Superior Politécnica del Litoral, Ecuador) for sharing scientific geological information of the studied area.

References

[1] Vera-Grunauer, X. “Seismic response of a soft, high plasticity, diatomaceous naturally cemented clay deposit”, PhD thesis, University of California, Berkeley, 2014.

[2] Torres, G., Recalde, S., Narea, R., Troccoli, L., Rentería, W. “Variabilidad espacio-temporal del fitoplancton y variables oceanográficas en El Golfo de Guayaquil durante el 2013-15” (Spatio-temporal variabilityofphytoplankton and oceanographic variables in El Golfo de Guayaquil during 2013-15)Revista del Instituto de Investigación FIGMMG-UNMSM, Volume(20), pp. 70–79, 2018. (in [Spanish]).

[3] Mayne, P.W., Coop, M.R., Springman, S., Huang, A.-B., Zornberg, J. “Geomaterial behavior and testing”, In: Proceedings 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, 2009, pp. 2777–2872.

[4] Devincenzi, M., Powell, J.J.M., Cruz, N., De Toledo, M.A.Á. “Actualidad en el uso de los ensayos geotécnicos in situ” (Present use ofgeotechnical in situ tests) Revista Digital del Cedex,Volume (31), 2007. (in [Spanish]).

[5] Ferreira, C., Viana da Fonseca, A., Saldanha, S., Ramos, C., Amoroso, S., Minarelli, L. “Estimated versus measured vs profiles and Vs30 at a pilot site in the Lower Tagus Valley, Portugal”, In 16th European Conference on Earthquake Engineering, Teshaloniki, Greece, 2018, pp. 18-21.

[6] Amoroso, S. “Prediction of the shear wave velocity Vs from CPT and DMT at research sites”, The Frontiers of Structural and Civil Engineering, Volume (8), pp. 83–92, 2014. https://doi.org/10.1007/s11709-013-0234-6.

[7] Fabbrocino, S., Lanzano, G., Forte, G., de Magistris, F.S., Fabbrocino, G. “SPT blow count Vs. shear wave velocity relationship in the structurally complex formations of the Molise Region (Italy)”,Engineering Geology, Volume (187), pp. 84–97, 2015.

[8] Akin, M.K., Kramer, S.L., Topal, T. “Empirical correlations of shear wave velocity (Vs) and penetration resistance (SPT-N) for different soils in an earthquake-prone area (Erbaa-Turkey)”,Engineering Geology, Volume (119), pp. 1–17, 2011. https://doi.org/10.1016/j.enggeo.2011.01.007.

[9] Intriago, B. Bazurto, H. Besenzon, D., Vera-Grunauer, X. Amoroso, S. “Geotechnical characterization of the estuarine deltaic deposits in the Guayaquil City through in situ and laboratory tests”, Engineering Geology, submitted.

[10] Marchetti, S., Monaco, P., Totani, G., Marchetti, D. “In situ tests by seismic dilatometer (SDMT)”, In: Proceedings of the From Research to Practice in Geotechnical Engineering, USA, 2008, pp. 292–311. https://doi.org/10.1061/40962(325)7

[11] Monaco, P., De Magistris, F. S., Grasso, S., Marchetti, S., Maugeri, M., & Totani, G. “Analysis of the liquefaction phenomena in the village of Vittorito (L’Aquila)”, Bulletin of Earthquake Engineering, Volume(9), pp. 231-261, 2011.https://doi.org/10.1007/s10518-010-9228-0

[12] Marchetti, S. “In Situ Tests by Flat Dilatometer”, Journal of the Geotechnical Engineering Division, Volume (106), pp. 299-321, 1980.

[13] Marchetti, S., Monaco, P., Totani, G., Calabrese, M. "The Flat Dilatometer Test (DMT) in Soil Investigations – A Report by the ISSMGE Committee TC16", In: Proc. International Conference on In situ Measurement of Soil Properties and Case Histories, Bandung, Indonesia, 2001, pp. 95–131. Official version approved by TC16 reprinted Proc. 2nd International Conference on the Flat Dilatometer, Washington D.C., USA, 2006, pp. 7–48.

[14] Marchetti S. “Sensitivity of CPT and DMT to stress history and aging in sands for liquefaction assessment”, In: Proceedings of the CPT 2010 International Symposium, Huntington Beach, California, 2010.

[15] Wair, B.R., DeJong, J.T., Shantz, T. “Guidelines for Estimation of Shear Wave Velocity Profiles, Pacific Earthquake Engineering Research Center, Sacramento, California, 2012.

[16] Imai, T., Yoshimura, Y. “Elastic wave velocity and soil properties in soft soil”, Tsuchito-Kiso, Volume(18), pp. 17–22, 1970. (in [Japanese])

[17] Kalteziotis, N., Sabatakakis, N., Vassiliou, J. “Evaluation of dynamic characteristics of Greek soil formations”, In: Second Hellenic Conference on Geotechnical Engineering, Teshaloniki, Greece, 1992, pp. 239–246. (in [Greek])

[18] Ohsaki, Y., Iwasaki, R., 1973. “On dynamic shear moduli and Poisson’s ratios of soil deposits”, Soils and Foundations, Volume (13), pp. 61–73, 1973.

[19] Iyisan, R. “Correlations between shear wave velocity and in-situ penetration test results”, Teknik Dergi, Volume (7), pp. 371–374, 1996. (in [Turkish])

[20] Jinan, Z. “Correlation between seismic wave velocity and the number of blow of SPT and depth”,Chinese Journal of Geotechnical Engineering, pp. 92–100, 1987.

[21] Dikmen, Ü. “Statistical correlations of shear wave velocity and penetration resistance for soils”, Journal of Geophysics and Engineering, Volume (6), pp. 61–72, 2009.

[22] Robertson, P.K. “Discussion of Influence of particle size on the correlation between shear wave velocity and cone tip resistance”, Canadian Geotechnical Journal, Volume (49), pp. 121–123, 2012.

[23] Hegazy, Ya., Mayne, P. “Statistical correlations between vs and cone penetration data for different soil types”, In: Proceedings of the International Symposium on Cone Penetration Testing, CPT. Linkoping, Sweden, 1995, pp. 173–178.

[24] Simonini, P., Cola, S. "Use of piezocone to predict maximum stiffness of Venetian soils", Journal of Geotechnical and Geoenvironmental Engineering, Volume (126), pp. 378–382, 2000.

[25] Andrus, R.D., Mohanan, N.P., Piratheepan, P., Ellis, B.S., Holzer, T.L. "Predicting shear-wave velocity from cone penetration resistance", In: Proceedings of the 4th International Conference on Earthquake Geotechnical Engineering, Thessaloniki, Greece, 2007.

[26] Madiai, C., Simoni, G."Shear wave velocity-penetration resistance correlation for Holocene and Pleistocene soils of an area in central Italy", In: Proceedings 2nd International Conference on-Geotechnical Site Characterization (ISC'2)", Porto, Portugal, 2004 pp.1687–1694.

[27] Bouckovalas G., Kalteziotis N., Sabatakakis N., Z.H. "Shear wave velocity in a very soft clay-measurements and correlations", In: Proceedings of the 12th International Conference Soil Mechanics Foundation Engineering (ICSMFE), Rio de Janeiro, Brazil, 1989, pp. 191–194.

[28] Powell J J M, Butcher A P. "Small strain stiffness assessments from in situ tests", In: Proceedings of the 2nd International Conference on Geotechnical Site Characterization (ISC'2)". Porto, Portugal, 2004, pp. 1717–1722.