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SITE CHARACTERIZATION AND SEISMIC ZONATION OF GUAYAQUIL CITY, ECUADOR

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ABSTRACT

Guayaquil is one of the most important cities in Ecuador and has a significant earthquake hazard arising from three complex tectonic environments. It is located in the estuarine zone of the lower Guayas River, and the soil stratigraphy consists of deep soft sediments over hard rocks from the Cretaceous period. These deltaic-estuarine sediments were deposited in a brackish environment, and they are unusually weak and highly compressible. Microtremor measurements have been performed to estimate site periods and indicate significant spatial variability. Shear wave velocity (V_s) measurements using the Spectral-Analysis-of-Surface-Waves (SASW) method were performed to better understand the variability of the site period map. Measurements were completed at 14 different sites to depths between 40 and 150 m, depending on spatial and source considerations. Additional site investigation, included cone penetration tests (CPT) and standard penetration tests (SPT) with energy measurements. This paper briefly describes the site characterization program and its implication on the seismic zonation of the city. The paper also presents preliminary correlations between the measured V_s and in situ soil parameters for these soft soil deposits.

Introduction

Guayaquil City is the main port of Ecuador and its productive activities represent over 20% of the country's global economy. The city is also the largest urban area with a population exceeding 2.1 million inhabitants, and it is heavily industrialized. The area is in a highly seismic region that is affected by three principal tectonic domains and has been impacted by several large earthquakes in the last century. The most important earthquake affecting Guayaquil occurred near the subducting Carnegie Ridge off the coast of Ecuador on May 14, 1942 with a magnitude of 7.8 and an epicentral distance of approximately 240 Km NW from the city. It caused significant damage in the central area of Guayaquil. The city lies on the right margin of the Guayas River where soft cohesive soils were deposited in a brackish deltaic-estuarine environment and due to the proximity of the river; the area has a high water table. These Holocene sediments are very soft, weak, and highly compressible. Moreover, the thickness of these soil deposits varies significantly with values between 15 and 60 m.

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The first settlements back in the 1600s were established in the hills, when the lowlands were mostly mangroves and wetlands. As the city grew, new portions of lowlands were gradually dredged. Up to the last century, some small estuary branches existed in what are now constructed/urbanized parts of the city. Over the last few decades, large areas of the city have been developed by placing fill over these estuarine deposits and new buildings have been constructed As a consequence of the large seismic hazard, there is a pressing need to estimate seismic performance of structures founded on these deep soft cohesive soils. Figure 1 shows a cross section of the North-South Viaduct on Machala Avenue which showcases typical ground conditions in Guayaquil.

An area of U.S. practice that is not well established is the seismic response of sites requiring site-specific evaluation, referred to as Soil Profile Type S_F (Uniform Building Code, UBC). At present, there is a lack of guidance regarding the performance of seismic site response analyses at these types of sites. Several specific cases (e.g., liquefiable soils, quick and highly sensitive clays) are included in this category, and this paper focuses on the particular cases of very thick soft/medium stiff clays where the depth of clay exceeds 36 m and very high plasticity clays with plasticity index, PI> 75, where the depth of clay exceeds 7 m (1997 UBC Section 1629.3.1).

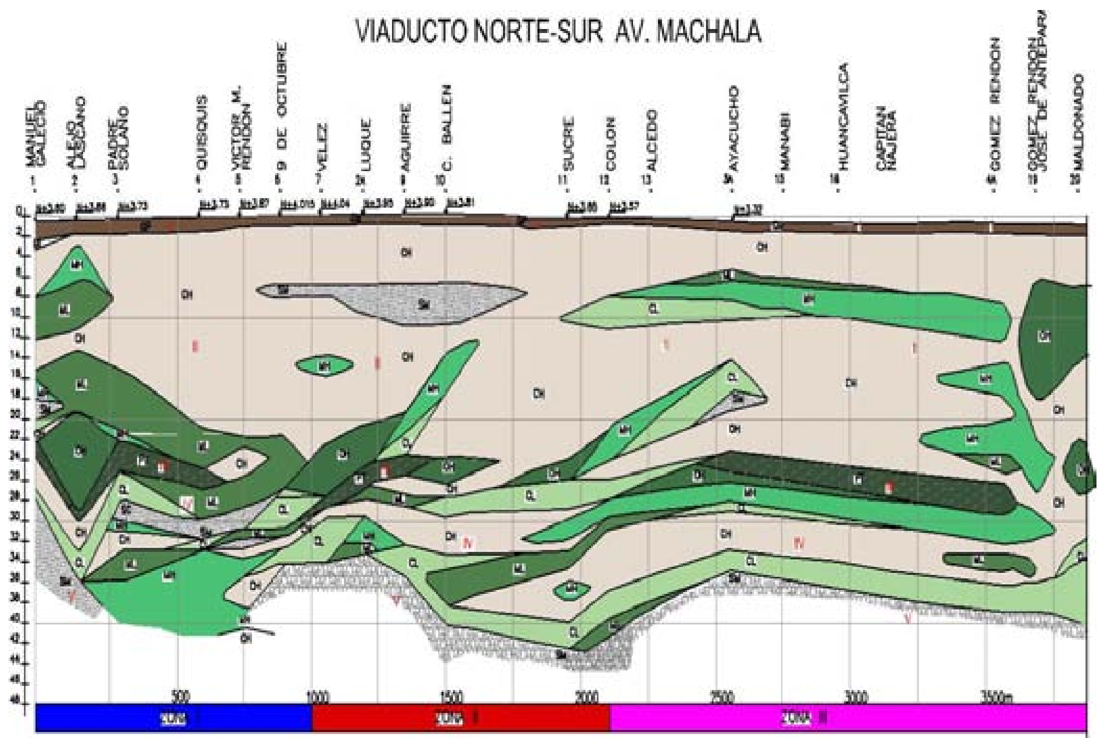


Figure 1. Cross section showing typical subsurface ground conditions in Guayaquil City showing the deep deposits of soft high plasticity clays (CH) underlying the city (depth at left is in meters).

Deep deposits of sediments exist in many urban areas within the United States, such as Boston, Charleston, Memphis, New York, and San Francisco, and as well in Guayaquil City, Ecuador. Studies of the seismic response of these soils through advanced cyclic testing and advanced numerical analysis will yield useful insights and advance the profession in the areas of code development and seismic zonation. Studying the seismic response of the deep soft clay deposits of Guayaquil has obvious benefits to the city and Ecuador, but it can also make a significant impact on the state of earthquake engineering practice in South America. The United Nations has already invested heavily in starting the characterization of the seismic hazard in Ecuador through the **R**isk **A**ssessment Tools for **Di**agnosis of **U**rban Areas against **S**eismic Disasters (RADIUS) project in Guayaquil. This paper briefly describes some of the work performed in Guayaquil as a part of the current seismic site characterization and zonation project that continues the earlier RADIUS effort.

Seismically and Geological settings of Guayaquil City

The city of Guayaquil is in a highly seismic region that is affected by three principal tectonic domains as shown in Fig. 2 (Alvarez, 2005):

1. *Seismogenic interplate contact:* It belongs to the subduction zone associated to the active Ecuadorian margin. In Northern Ecuador, a very strong earthquake with a rupture length of 500 km occurred in 1906.
2. *Guayaquil-Babahoyo strike-slip fault system*: This system is part of the Dolores-Megashear Zone. This complex fault system, which is mostly dextral near the city of Guayaquil, is actually recognized as a plate boundary, as along it, the North Andes Block moves towards the North-Northeast relative to the South American Plate (Pennington, 1981).
3. *Intraplate region*: Surrounding the city, numerous active faults located inside the plates are known to exist, such as the faults of the Chongón-Colonche Ridge to the west (e.g. Alvarez, 2003) and the Jubones, Portovelo, and Túmbez faults to the south (e.g. Benítez, 1987). This last group of faults could produce major earthquakes (Mw > 6.5), which could in turn generate significant ground motions in Guayaquil City.

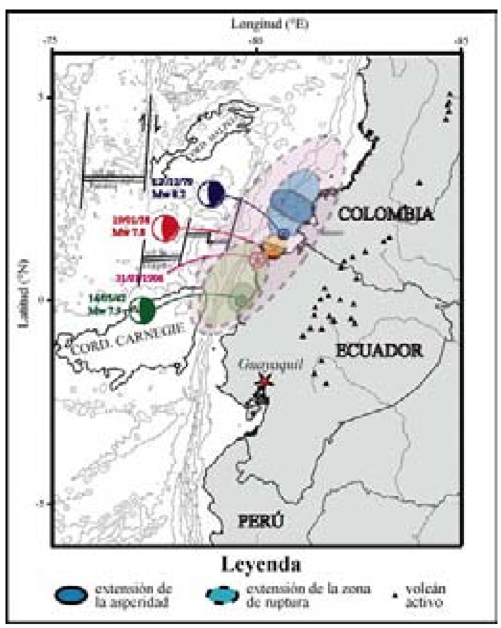
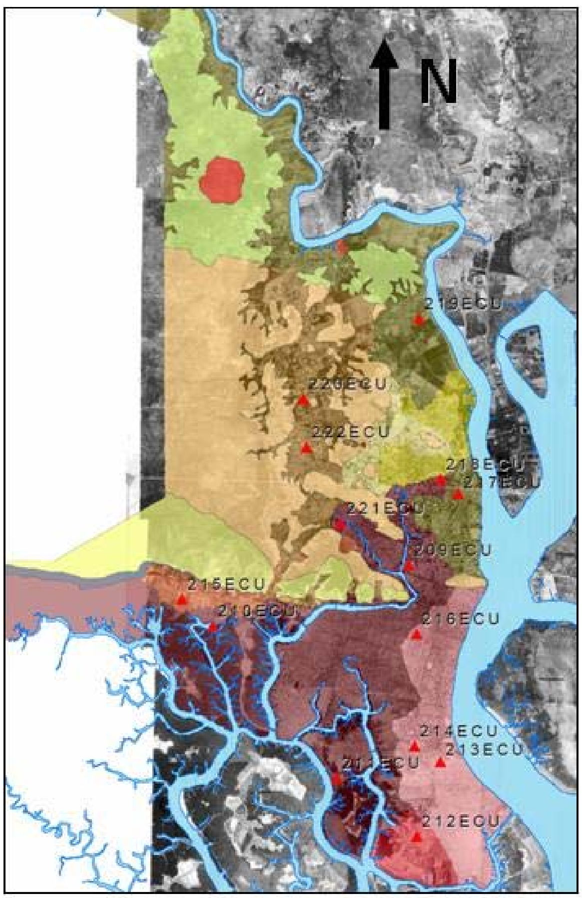


Figure. 2: Major earthquakes that affected the northwestern Ecuadorian coast during the last century.

Guayaquil is located at the convergence of three major geologic domains, each one of which presents their own geomorphologic characteristics, (Benitez, 2005): a) the Daule and Babahoyo rivers alluvial plain, b) the deltaic-estuarine complex of the Guayas estuary, and c) the hills of the Cordillera Chongón-Colonche. As in most of the cities located in the borders of navigable routes, the underlying soils of Guayaquil were deposited under water and are weak and compressible with shallow groundwater levels. Hard rocks of the Cretaceous period underlie these deep soft sediments (Reynaud et al., 1999). The deep soft sediments underlie all of the low, flat surfaces on which the city was built.

Geotechnical Subsoil Exploration Tests

Before the most recent program of additional subsurface investigation was carried out at the 14 selected sites, it was necessary to select a representative site, to integrate the geological study, the evaluation and characterization of the old estuary streams, and the analytical evaluation of the 590 borehole data collect and georeference each of them within a Geographic Information System Map. Each borehole has basic geotechnical parameters such as: plasticity index, liquid limit, Unified Soil Classification, undrained shear strength and fines content. Fig. 3 shows the location of the 14 test sites and the new geotechnical zonation of Guayaquil.



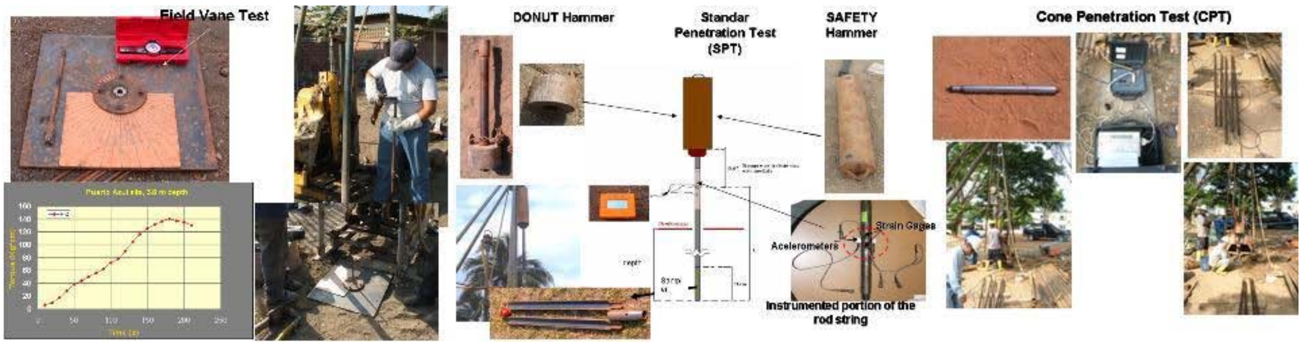
COLOR	ZONE	DESCRIPTION
	D1	Estuarine deltaic deposits (Este-Centro)
	D2	Estuarine deltaic deposits (Sur)
	D3	Estuarine deltaic deposits (Oeste-Norte-Trinitaria)
		Alluvial Valley Deposits (Norte)
	D4A	H < 10 m
	D4B	10 < H < 20 m
	D4C	H > 20 m
	D5	Alluvio-lacustrine deposits (Norte)
	D6	Colluvial deposits
	D7	Residual deposits and rock outcrop

D7

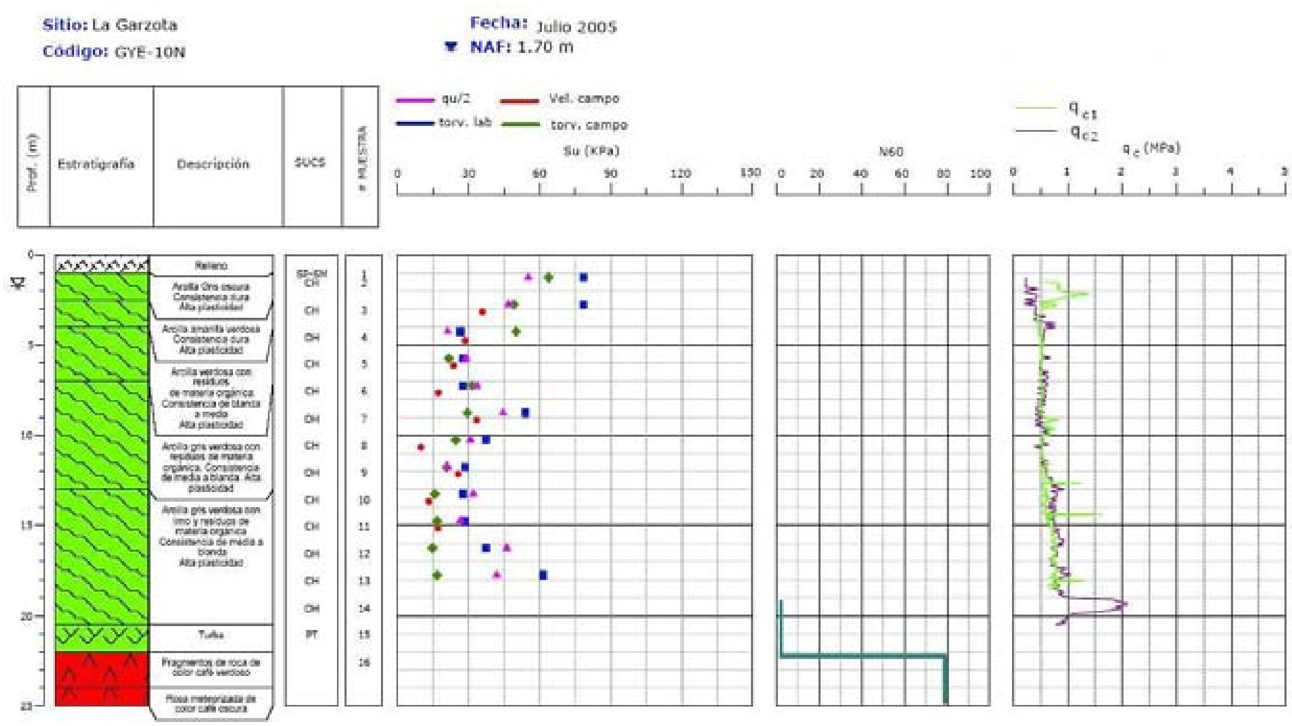
- Ancon Group
- San Eduardo Formation
- Guayaquil Formation
- Azucar Group
- Cayo Formation
- Undifferentiated granitic rocks
- Pinon Formation

Figure 3. New geotechnical zonation map for Guayaquil.

At each of the 14 sites, four in-situ tests were performed: CPT (Cone Penetration Test, ASTM D3441), SPT (Standard Penetration Test, ASTM D1586 and D6066), DCPT (Dynamic Cone Penetration Test) and VST (Vane Shear Test, ASTM D2573) as illustrated in Fig 4a. Both disturbed and undisturbed (using thin Shelby tube) soil samples were also taken in the borehole used for the SPT. Additional laboratory tests were performed on the samples collected, including: soil classification tests, undrained shear strength, oedometer, critical friction angle for sands (Santamarina & Cho, 2001) and specific surface measurements (Methylene blue absorption method, Santamarina, 2004) and some representative results are shown in Fig. 4b.



a)



b)

Figure 4: a) In situ test equipment used at each site; VST, SPT and CPT, respectively, b) Illustration of in-situ parameters for the site GYE-10N, La Garzota.

To evaluate the transmitted energy with two different hammer types, Donut and Safety, from the SPT test, an instrumented rod string was used. The setup included two diametrically opposite piezoresistive accelerometers mounted on metal blocks and bolted to the rod and two foil strain gages each consisting of two independent 350 –Ohm Wheatstone bridges bonded to a 60 cm-long AWJ rod section (i.e. identical to the rest of the rod string). The data was collected and processed with a SPT Analyzer TM (Pile Dynamics Inc.2000), which is similar to the Pile Driving Analyzer TM (PDA) PAL model but customized for SPT energy measurements. Measured SPT energies and hammer efficiency are provided in Table 1.

Table 1. Measured Energy Efficiency

Hammer Type	% ER	C_E
Donut	45-55	0.76-0.92
Safety	61-63	1.02-1.04

C_E= Hammer Efficiency, C_E= ER/60

A surface wave measurement system, consisting of 1-Hz Kinemetrics seismometers, was used to collect dispersion data for 14 sites. The random vibration dozer-source is centered in the SASW seismometer line and receives a broad spectrum of radiated waves from the dozer motion. The dozer is driven forward and backward several meters to produce low frequency ambient signals that are received by the sensors (Fig. 5). The receivers measure the waves and a Fast Fourier Transform (FFT) is performed on each of the four receiver signals. In near-real time, the linear spectra, cross power spectra, and coherence are computed. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test allowed the adjustment of various aspects of the test to optimize the capture of the phase data while still at the site. These aspects include the source-wave generation, total frequency range of all the steps, and receiver spacing. The inversion process was used to estimate the soil stiffness.

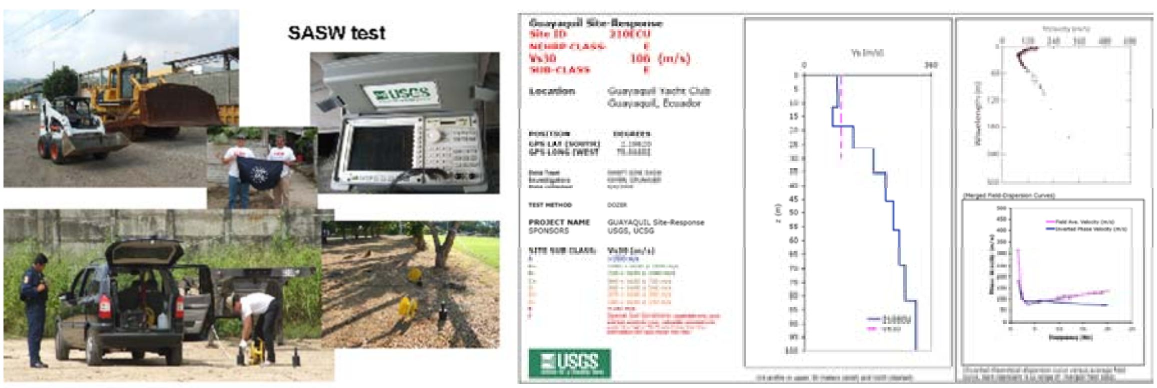


Figure 5. SASW field test equipment used and an example result of an inversion process

Spatial variation of the elastic-site period

One of the most important dynamic parameter for site response analysis and seismic zonation is the elastic site response period $T_s \approx 4H/V_s$. To estimate the site elastic period, 445 microtremor measurements have been taken using geophysics equipment and processed using the Nakamura (1989) method, (Vera-Grunauer, et. al. 2005). Figure 6 shows the elastic period map for the area of interest. The estimation of the spatial variability of the site elastic period was performed using the Ordinary Kriging with one neighbor's analysis. The value of the site elastic period estimated from the (H/V method) microtremor measurements is approximately 10% less than the value estimated from the SASW method as shown in Fig. 7.

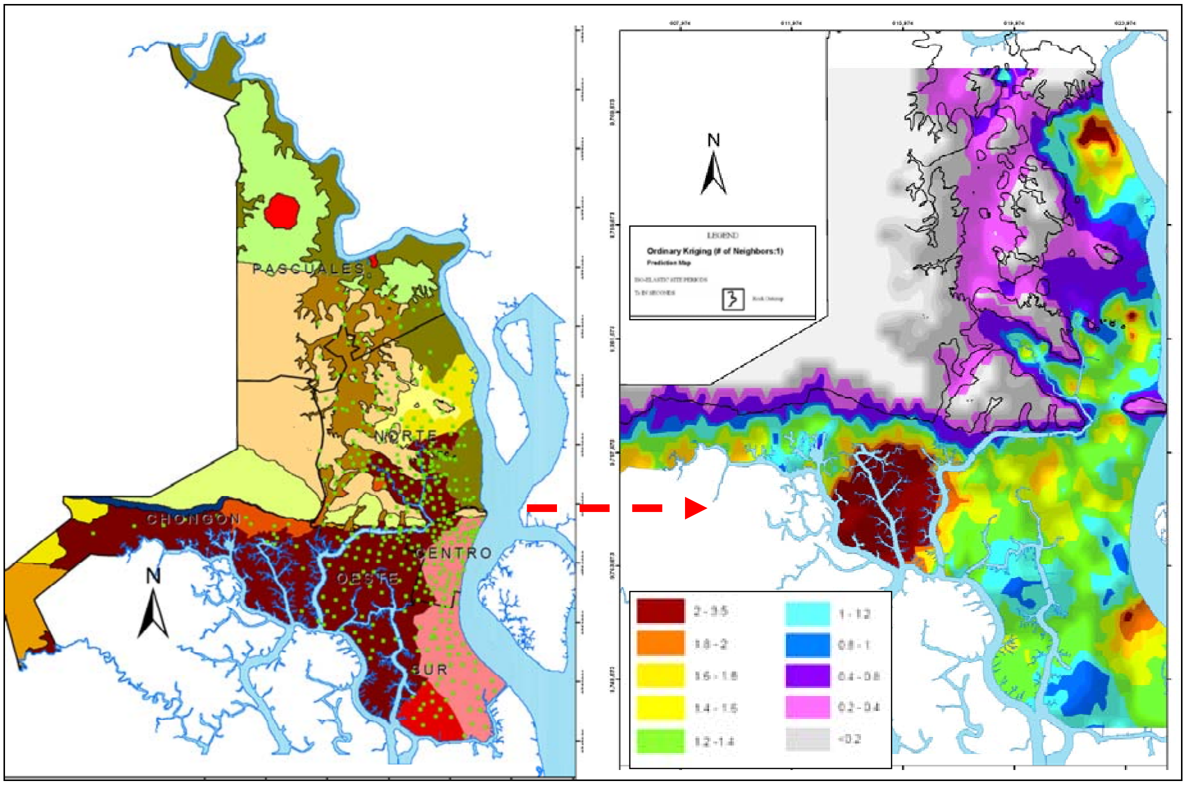


Figure 6. Spatial location of the microtremors measurement and the spatial variability of the site elastic period map. Colours indicate the range of site elastic period in seconds.

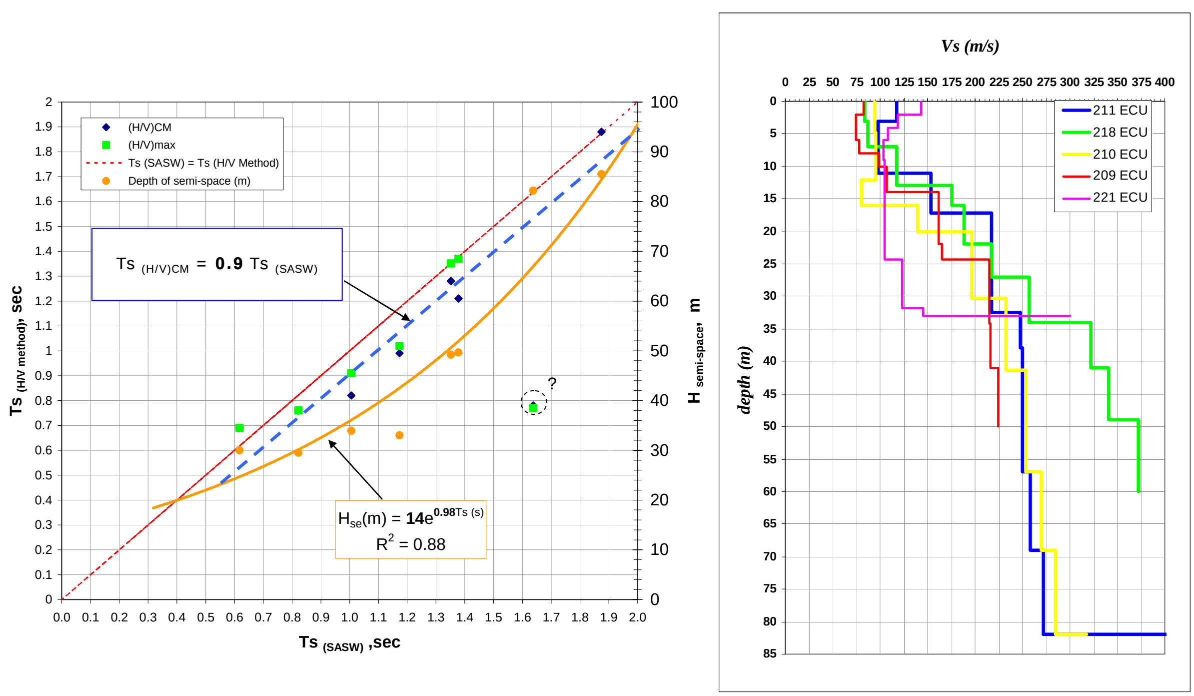


Figure 7. Relation of the site elastic period, estimated with microtremor measurements and SASW method, variation of the depth of the semi-space with the site elastic period, and the shear wave velocity profile for the geotechnical zone D3.

Empirical correlations between V_s and in situ parameters

One of the important dynamic parameters, required to perform an analysis of seismic soil response is the "small strain" ($\gamma < 1x10^{-4}$ %) dynamic shear modulus (G_{max}), which can be calculated from measurements of shear wave velocity (V_s), i.e. $G_{max} = \rho V_s^2$, where ρ = mass density of material. In many countries, as well as in the Grade-2 zonation method from the Manual for Zonation on Seismic Geotechnical Hazards (TC4, 1993), correlation studies of in-situ seismic wave velocities with other index tests or engineering properties of the soils have been shown to be useful for estimating shear wave velocity profiles at sites lacking geophysical data. In this project, several semi-empirical and empirical correlations have been developed for the SPT N-value, undrained shear strength, and CPT tip resistance for area of the city, for both clay and sand deposits.

For SPT based correlations, the overburden correction factor and the energy correction were considered to form $(N_1)_{60}$ values. The correlation equation has the form of $V_s = a\ N_{60}^b$, for clay and silt deposits and $V_s= a(N_1)_{60}^b$ for sand deposits, as shown in Figure 9. Shear wave velocity are in m/s, the value obtained for each soil deposit are shown at Table 2. For the geotechnical zone, D1, as well as others geotechnical zones, empirical correlation of V_s and the undrained shear strength were developed, as follow:

$$V_S = \left((2.5 \cdot S_U + 175) \cdot \frac{\sigma'_{vo} \cdot g}{\gamma} \right)^{1/2} \text{, for soils with OCR < 2} \qquad (1)$$

$$V_S = \left((2.5 \cdot S_U + 400) \cdot \frac{\sigma'_{vo} \cdot g}{\gamma} \right)^{1/2} \text{, for soils with OCR >2} \qquad (2)$$

Where σ'_{vo}= vertical in-situ effective stress (kPa), γ= total unit weight (kN/m^3), g = acceleration of gravity (m/sec^2), s_u = undrained shear strength (kPa), V_s = shear wave velocity (m/s).

Table 2. Values of a and b coefficients for V_s estimation

Type of Soil deposit	% Fine content	Depth (m)	a	b
Clay / Silt	> 50	< 30	130	0.145
Sand/ Silty Sand/ Clayey Sand	<40	< 20	105	0.23
		20 - 30	100	0.3
		>30	120	0.3
	20 - 40	<20	-	-
		20 - 30	93	0.28
		> 30	108	0.32
	10 - 20	<20	-	-
		20 - 30	60	0.4
		> 30	62	0.42
	< 10	< 20	105	0.22
		20 - 30	93	0.26
		> 30	100	0.25

Using the CPT tip resistance value, correlations with shear wave velocity can be derived using the cavity expansion theory and the hyperbolic stress-strain model,(Romo & Ovando, 1992). Results of field measurements are used to calibrate the semi-empirical correlations, as follows

$$V_s = \sqrt{\frac{3gq_c}{2N_{kc}\gamma_s(1+\upsilon)} e^{\frac{3N_{kc}-4}{4} - \frac{1}{2\beta}}} = \sqrt{\eta q_c e^{\alpha}} \qquad (3)$$

$$\alpha = \frac{3N_{kc} - 4}{4} - \frac{1}{2\beta}, \eta = \frac{3g}{2N_{kc}\gamma_s(1+\upsilon)} \quad (4)$$

where υ = Poisson coefficient of the soil, g = acceleration of gravity (m/s^2), γ_s = total unit weight of the soil (kN/m^3), β= ratio of su/p at each geotechnical zonation, N_{kc} = dynamic factor, q_c= tip resistance (kPa) and V_s = Shear wave velocity (m/s)

Geotechnical Zone	**Factor N_{kc} (min)**	**Factor N_{kc} (average)**	**Factor N_{kc} (max)**	**β**
D1, Estuarine-Deltaic (East-Downtown)	9.9	11	11.8	0.3
D2, Estuarine-Deltaic (South)	12	13	14	0.25
D3, Estuarine-Deltaic (West-North-Trinitaria)	11	12	12.6	0.22
D4, Alluvial Valley (North)	9.9	11	11.8	0.26

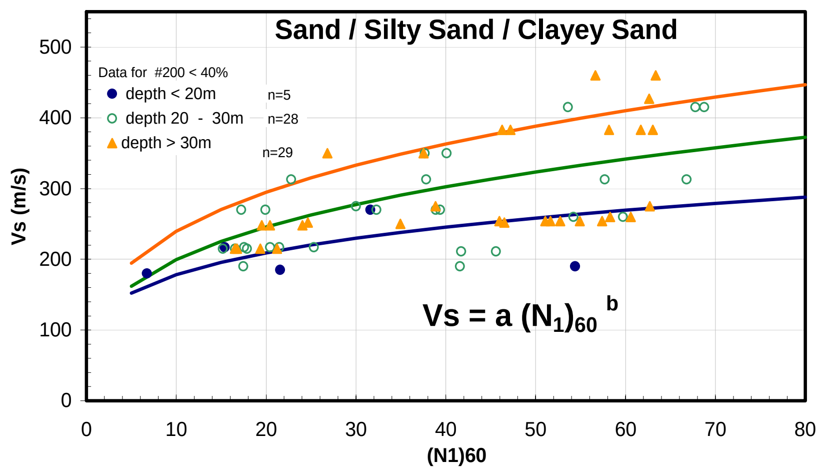


Figure 9. Relationship of SPT- N value with the in-situ shear wave velocity measured, for fine and coarse soil deposits

Summary

This paper briefly describes the seismic site characterization of the city of Guayaquil, Ecuador and focuses on the characterization of deep soft soil sites where there is a lack of guidance regarding the performance of seismic site response analyses. The findings will lead to practical guidelines for addressing the special concerns involved with analyzing the seismic response of these deposits, including correlations of dynamic soil properties with available in situ test results and simplified period-dependent site amplification factors for developing preliminary design spectra for these sites.

Acknowledgements

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