

## GEOTECHNICAL SEISMIC CHARACTERIZATION FOR THE MICROZONATION OF BOGOTÁ

Jorge A. RODRIGUEZ<sup>1</sup>, Fernando RAMIREZ<sup>2</sup>, Juan P. ESCALLON<sup>3</sup>

### ABSTRACT

The seismic microzonation study for Bogotá was initially completed in 1997. This study was based on a small number of soil borings and seismic geotechnical tests. Limitations in the design parameters from this study have been identified, and an effort is being made to produce a revised microzonation and design parameters.

To date some 100 local site response studies including down hole tests to at least 50 m deep, and dynamic lab tests have been completed. The paper present results of a regional analysis of this data in order to formulate a revised seismic geotechnical model for the city.

The analysis included the evaluation of shear wave velocity ( $V_s$ ) profiles in the soil formations found in the city including ranges of variation and identification of correlation with soil properties and soil state variables such as the confining pressure and void ratio. The analysis shows good correlation of  $V_s$  field values with soil properties and origin. The information from laboratory soil tests including bender elements, and cyclic triaxial was also analyzed in order to define general trends for the local soils. This information was compared with internationally reported data and compared with the shear wave velocity data trends from field tests in order to evaluate the reliability and ranges of variation of dynamic soil properties to be used in site response analysis. Dynamic soil properties were defined for soils in the city based on type, soil state and confining pressure.

Keywords: Microzonation, dynamic soil properties, soft soil, Bogotá soils, geostatistics

### INTRODUCTION

The city of Bogotá is located in an area some 60 km long by 10 km wide in a high plain known as the Bogotá Sabana and is home to some eight million people. It is located in the higher part of the western cordillera in the Colombian Andes, and is a sedimentary basin formed by tectonic processes. The deposits reach over 450 m deep formed trough all the Pleistocene and Holocene, in the lower part of the sequence the soils are mainly alluvial of the Subachoque formation, and in the upper part the soils are made of very soft lacustrine silts and clays of the Sabana Formation (Torres et al, 2005). The underlying bedrock is formed of claystones and sandstones of tertiary to cretaceous age. The Sabana Formation may reach 250 m depth, and are very soft and compressible, nearly normally consolidated soils.

The seismic microzonation study for Bogotá was initially completed in 1997. This study was based on a small number of soil borings and seismic geotechnical tests. Also limited seismological data was available at the time. Limitations in the design parameters from this study have been identified, and an effort is being made to produce a revised microzonation and design parameters.

To date some 100 local seismic site response studies including down hole tests to at least 50 m deep, and dynamic lab tests have been completed. The paper present results of a regional analysis of this data in order to

---

<sup>1</sup>Professor, Head Department of Civil Engineering, Javeriana University, Bogotá, Colombia, Email: rodriguezja@javeriana.edu.co

<sup>2</sup>Disaster Prevention Office, Bogotá, Colombia.

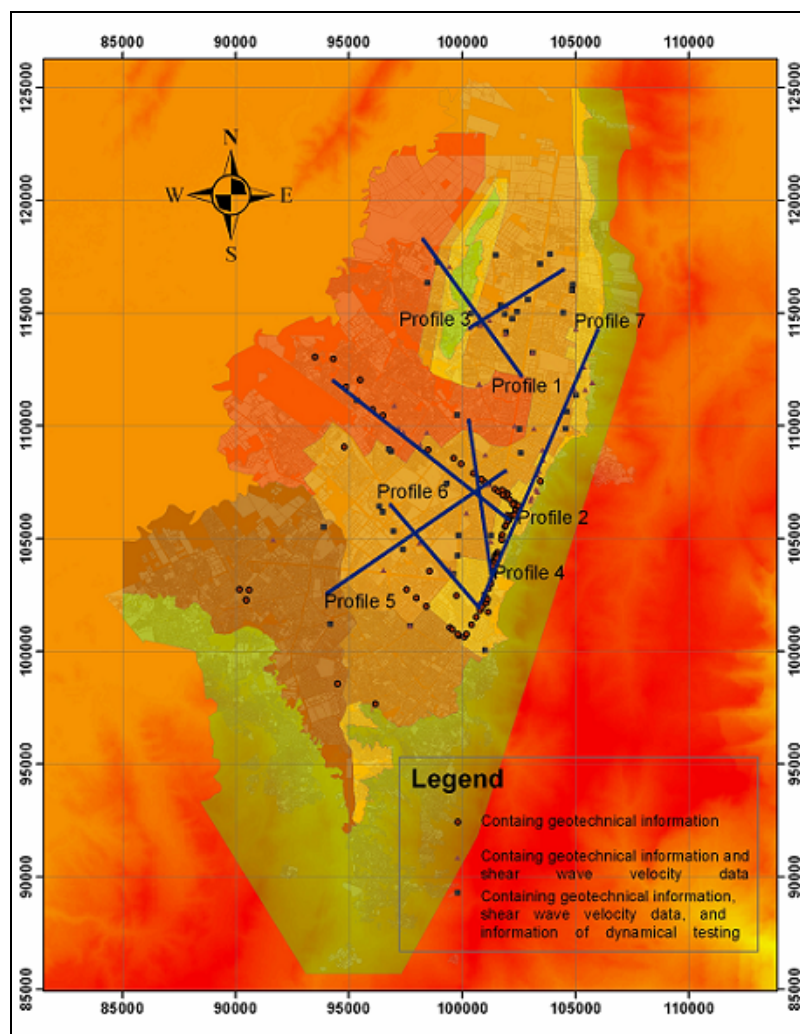
<sup>3</sup>Jeoprobe Ltda. Bogotá, Colombia, Email: jpescallono@unal.edu.co.

formulate a revised seismic geotechnical model for the city. This model will be used as an input for site response analysis to be conducted for the revision of the microzonation design parameters for the city.

The analysis included the evaluation of shear wave velocity ( $V_s$ ) profiles in the different soil formations found in the city including ranges of variation and identification of correlation with soil properties and soil state variables such as the confining pressure and void ratio. The analysis show good correlation of  $V_s$  field values with soil properties and origin.  $V_s$  values and ranges of variation were defined for the different soil formations in the city.

The information from lab soil tests including bender elements, resonant column and cyclic triaxial was also analyzed in order to define general trends for the local soils. This information was compared with internationally reported data and also compared with the shear wave velocity data trends from field tests in order to evaluate the reliability and ranges of variation of dynamic soil properties to be used in site response analysis. Dynamic soil properties ( $G/G_0$  and damping ratio) were defined for soils in the city based on type, soil state and confining pressure.

A revision of the soil zones defined in the 1997 study was completed, and geostatistics analyses to evaluate the reliability of the spatially correlated model are also under way. The zones established in the microzonation are shown in Figure 1.



**Figure 1 – Sections traced to study the transitional behavior of the  $V_s$  from the east hills to the central part of the intermountain valley (sections 1 and 3), from the east hills towards the deeper part of the soil deposit in the city (sections 2, 4 and 5), through the intermountain valley (section 6) and through the east hills (section 7).**

This figure is based on a rendering from a digital terrain model of the area of the city. Each area has a different color as follows: zone 1 (green), zone 2 (light yellow), zone 3 (dark yellow), zone 4 (orange) and zone 5

(brown). The darker areas correspond to higher elevations. The different zones correspond to the following characteristics: zone 1 is formed by the surrounding hills, zone 2 is formed by the piedmont areas, zones 3 and 4 are constituted by lacustrine clayey soft soils lying over aluvial older soils. The deeper deposits are found in zone 4, and finally zone 5 is formed by mostly aluvial and lacustrine soil deposits.

## 1 – TYPE OF INFORMATION GATHERED

The study began with collection of all the information from local seismic site response studies and other geotechnical studies available in the city. This information included description of the strata, soil classification test, shear wave velocity data mostly obtained from down hole tests, and dynamical laboratory tests results. The sites were classified according to the type of information available as follows:

- A type sites: Containing geotechnical information
- B type sites: Containing geotechnical information plus shear wave velocity profiling
- C type sites: Containing geotechnical information, shear wave velocity profiling, and curves of stiffness reduction and damping from dynamic lab tests

Sites with shear wave velocity data had an additional classification according to whether the  $V_s$  data was obtained from down hole tests or from correlations obtained from other geotechnical data. This classification was used for every zone identified by the seismic microzonation study. Table 1 shows the summary of sites A, B and C distributed by zone, and Table 2 shows the summary of points A, B and C as well as the total of sites points analyzed.

**Table 1. Type A, B and C Points of Analysis distinguished for Zones.**

ZONES	TYPES OF POINTS OF ANALYSIS		
	A	B	C
Zone 1	1	3	0
Zone 2	48	16	4
Zone 3	10	17	24
Zone 4	6	10	3
Zone 5	5	2	2
Transition zones 1 and 2	1	6	1
Transition zones 2 and 3	7	6	6
Transition zones 3 and 4	1	5	3
Transition zones 2 and 5	10	0	0

**Table 2. Total of Points of Analysis**

TOTAL OF POINTS OF ANALYSIS		
A	B	C
89	65	43
Total = 197		

## 2 – DATA PROCESSING AND ANALYSIS

The shear wave velocity data available from measurements in the city was correlated with basic soil type and state parameters following the work by Kokoshu, (1980); Humphries and Wahls, (1968); Hardin and Black, (1968, 1969), and others, who have studied the relationships between these parameters. These correlations are based on the evidence that show the dependency of low strain shear stiffness of soils ( $G_0$ ) on the void ratio ( $e$ ), over consolidation ratio (OCR) and the stress state in the following general way:

$$G_0 = KF(e) \left( \frac{\sigma'_c}{\sigma_{ref}} \right)^m OCR^k \quad (1)$$

Where:

$K$  = Depends on the type of material  
 $\sigma'_c$  = Effective confining pressure  
 $\sigma_{ref}$  = reference stress (commonly 100 KPa)  
 $m$  = Power of the stress ratio  
 $OCR$  = Over consolidation ratio  
 $k$  = Power of the over consolidation ratio

$F(e)$  is a function of void ratio. Hardin, (1978) suggests the following form:

$$F(e) = \frac{1}{(0.3 + 0.7e^2)} \quad (2)$$

Considering that the soil behavior should respond in the basic same form, but that the coefficients in the correlations, and particularly the factor  $K$ , should be dependent on the particular soil formations found in the city, and attempt was made to obtain a specific correlation of the parameter  $K$  with plasticity index for the Bogotá soils. In order to do this, the Young's modulus at low strain data obtained from Vs measured in the down hole tests was normalized using equations (1) and (2). Values obtained from P wave velocity and Vs measurements in the down hole tests were used to define the poisson ratio used to obtain the Young modulus from S-wave velocity values. After the normalization by all the known parameters at each site and depth, a correlation was obtained of the normalized values with the plasticity index as seen in figure 2. The soils in Bogotá are mostly normally consolidated, although there is a crust some 5 m deep that is lightly overconsolidated. The measurements in these over consolidated soils have been considered apart. Both the overconsolidated clays, and the normally consolidated clays and silts of zones 3 and 4 formed in a lacustrine environment exhibit a clear correlation of the normalized values ( $K$ ) with the plasticity index.

It was found that all of the data fall in the range of  $K$  shown in figure 2 exhibiting a linear correlation with the plasticity index as follows (Rodríguez J., Escallón J. (2006)):

$$K = 3056.4 * IP + 31031 \pm \bar{\sigma} \quad (3)$$

Where:

$$\bar{\sigma} = \text{the standard deviation of the data} = 85638$$

For overconsolidated clays it was found that  $OCR^k$  (See equation 1) fitted the following formula (Rodríguez J., Escallón J. (2006)):

$$y = K * OCR^k \quad (4)$$

Where:

$$K = 324500$$

$$RSC = 3$$

$k$  = Function of the plasticity index given by the following formula

$$k = -0.00004 * IP^2 + 0.0145 * IP \quad (5)$$

For the case of the over consolidated clays the Standard deviation of  $K*OCR^k$  is  $\pm 71492$ .

Formula (5) is consistent with the tendency observed by Hardin and Drnevich (1972) for the values of  $k$  as function of the plasticity index, even though higher values are found for the over consolidated clays in Bogotá (see table 3).

Additionally it is observed the  $K$  values for peat are adjusted to an exponential relationship as function of the plasticity index, given by the following formula (Rodríguez J., Escallón J. (2006)):

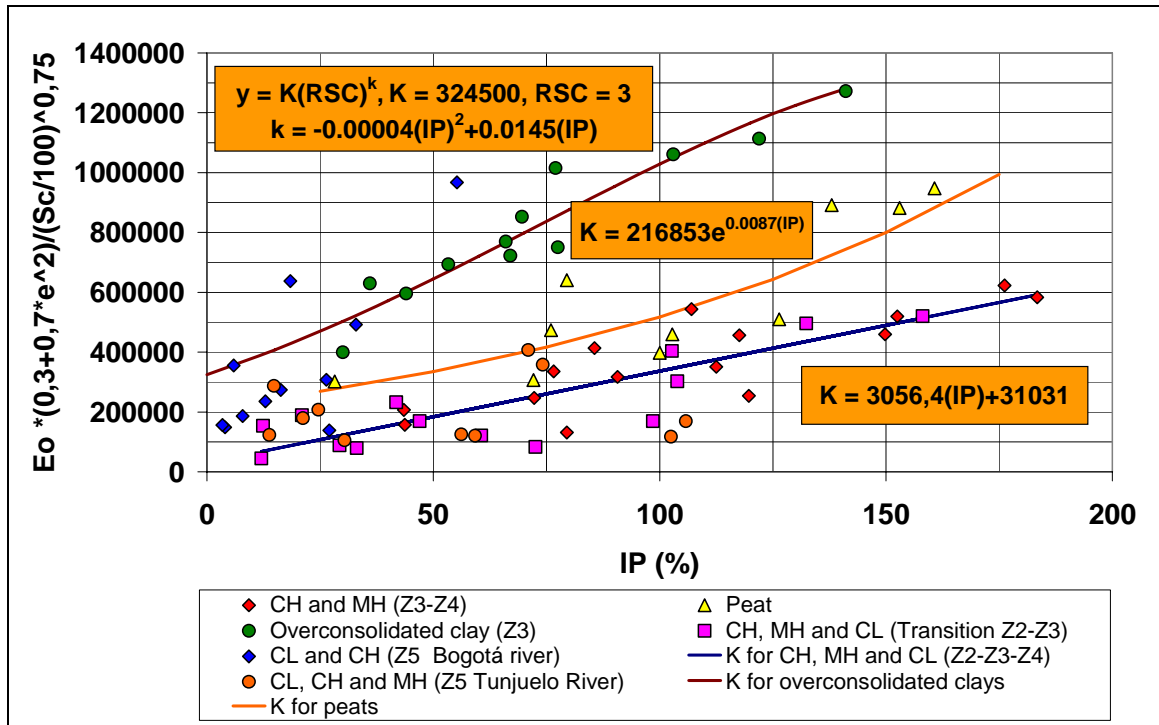
$$K = 216853e^{0.0087*IP} \quad (6)$$

**Table 3. Variation of k with IP**

Plasticity index (IP)	k*	Plasticity index (IP)	k**
0	0	0	0
20	0.18	20	0.27
40	0.3	40	0.52
60	0.41	60	0.73
80	0.48	80	0.9
≥100	0.5	100	1.05
		120	1.16
		≥140	1.25

\*Computed from Hardin and Drnevich (1972)

\*\*Values obtained from equation 4 (Rodríguez J., Escallón J. (2006 a)).



**Figure 2. Correlation between K and the plasticity index (from Rodríguez and Escallón, 2006)**

A sensibility analysis of the parameters in equation (1) was carried out to properly normalize the data in order to obtain the best data fit. It was found that expression (2) is valid and that the power  $m$  (power of stress ratio) that better fits the data is 0.75 (Rodríguez J., Escallón J. (2006)). This value is typical of clayey soils. This analysis was based on nearly 30 local site response analysis using down hole tests for shear wave profiling each meter and also dynamic laboratory tests using mostly dynamical triaxial tests.

In order to compare the K values found for the nearly normally consolidated lacustrine clays of Bogotá with other values found, the K values used to obtain the E modulus were divided by  $2(1+\nu)$  because the K values reported in the literature are referred to the G modulus, in addition the K values were also divided by  $\sigma_{ref}^n$  since the K values used for comparison fit the following formula:

$$Go = KF(e)(\sigma'_c)^m \quad (7)$$

Which varies from the formula (1) used in this research by the term  $1/\sigma_{ref}^n$ . Table 4 shows K values reported in the literature and also the equivalent K values found by Rodríguez and Escallón (2006) to compute the G modulus if equation (7) would have been used. It can be seen on table 4 that the data from Rodríguez and Escallón (2006) considered for the first time such a wide range of clayey soils. In addition, the equivalent K values are similar to those found in the literature but with a wider range than any of the other authors considered

had reported. It is also important to point out that among the data considered, K values have been obtained using Vs field information from down hole tests along with determination of geotechnical properties from samples obtained using Shelby samplers.

**Table 4. Constants in proposed empirical equations on small strain modulus**

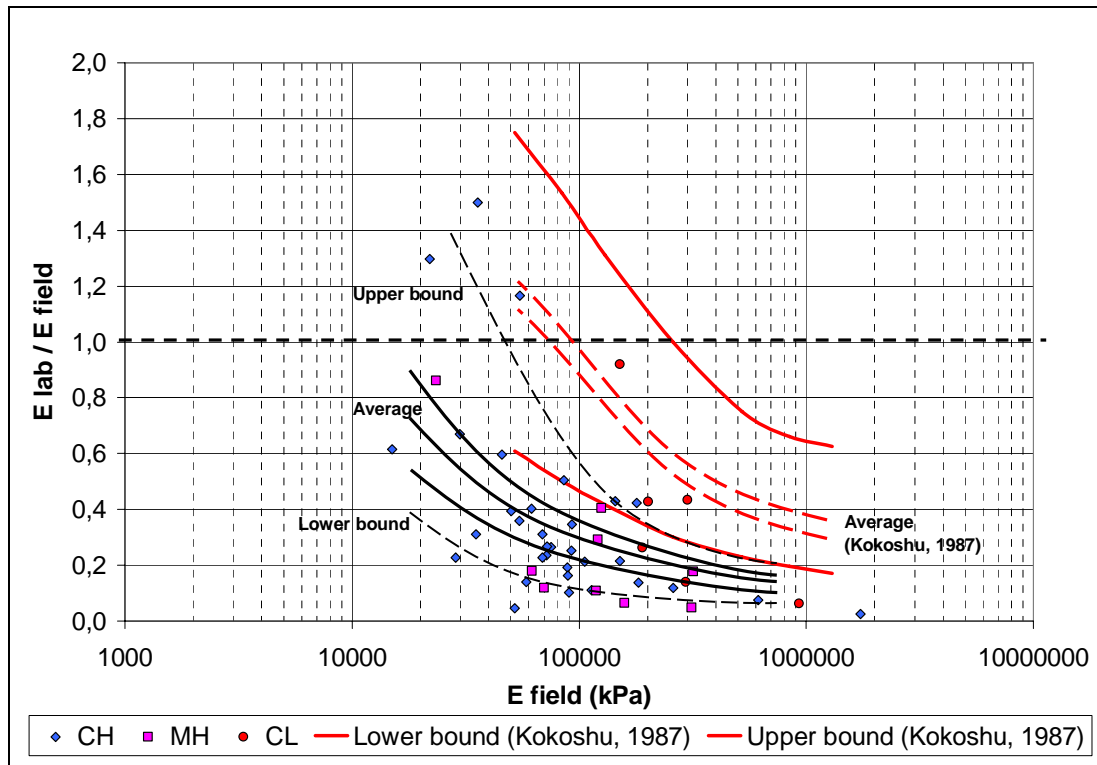
References	K	F(e)	n	Soil material	Test method
Hardin - Black (1968)	3300	$(2.97-e)^2/(1+e)$	.5	Kaolinite, etc.	Resonant column
Marcuson - Wahls (1972)	4500	$(2.97-e)^2/(1+e)$	.5	Kaolinite, IP=35	Resonant column
	450	$(4.4-e)^2/(1+e)$	.5	Bentonite, IP=60	Resonant column
Zen-Umehara (1978)	2000 - 4000	$(2.97-e)^2/(1+e)$	.5	Remolded clay, IP=0-50	Resonant column
Kokoshu et al, (1982)	141	$(7.32-e)^2/(1+e)$	.6	Undisturbed clays, IP=40-85	Cyclic triaxial
Rodríguez - Escallón (2006)	1075 - 6664	$1/(0.3+0.7e^2)$	.75	Lacustrine clays, IP=12-183	Down hole

Down hole tests were performed in most of type B and C sites, and the correlation was used to complete the Vs database where enough geotechnical information was available in order to produce longitudinal profiles of the S-wave velocity.

It should be noticed (Rodríguez, 2005), that the lake soils in Bogotá have Vs values in the field in the range 100 to 150 m/s, with void ratios in the order of 3 or higher and plasticity indices over 100 and up to 300 in some cases. These soils show a relatively high intact strength, with mobilized friction angles in the order of 28 degrees in triaxial tests that decrease to some 15 degrees after straining to critical state and even lower values at residual state. Therefore these soils are highly structured, sensitive, and compressible and with low shear stiffness. These conditions make these soils quite particular compared to other soils commonly reported in the literature, and very sensitive to effects in sampling and handling of samples.

Undisturbed samples of clayey soils have been taken from more than 50 sites in order to evaluate the dynamic response of soil deposits. Most of these samples have been tested in cyclic triaxial apparatus, some by deformation and some by stress control in combination with bender element measurements. The bender elements measurement have been valuable in the determination of Young's modulus at low strain in the laboratory and in addition is useful for determining the low strain damping ratio based on the logarithmic decay exhibited by the signal, the bender elements device have been also useful for monitoring the response of the sample since in the case of the Javeriana University laboratory the GDS system available has them installed inside the triaxial chamber. A few resonant column tests results were also available. Experience in testing these soft soils has shown (Rodríguez, J. A. (2005)) that stress controlled tests are more reliable than strain controlled. Also, it has been identified that the soil samples are very susceptible to sampling and handling, and that the test procedure can adversely affect the results. This has been identified by the range of variation of the dynamic modulus obtained in many cases and the lack of consistency of some test results with the expected behavior as a function of soil type and state. This is in sharp contrast with the excellent correlation obtained between soil type and state and the measured Vs values in the field

Since bender elements tests have been performed for samples obtained from nearly ten sites, it was seek to establish correlations between Young's modulus at low strain in the laboratory with the Young's modulus obtained from the field in order to properly normalize the data at higher strains. The tests data for clays and clayey slits in figure 3 show a general tendency of the Young's modulus obtained in the laboratory to decrease as the stiffness of the clayey materials is higher, figure 3 also shows the upper and lower bounds as long as the tendencies limiting the average. The tendencies showed of the laboratory Young's modulus to decrease with increasing field Young's modulus was used to estimate the maximum laboratory Young's modulus to normalize the Young's modulus at different strains in order to fit dynamical curves for seismic analysis. For comparison purposes it is shown the tendencies found by Kokoshu (1987) in figure 3, showing that for a range of E modulus obtained in the field between 140 Mpa and 1000 Mpa the lower bound found by Kokoshu (1987) is the same as the upper bound found in this research.



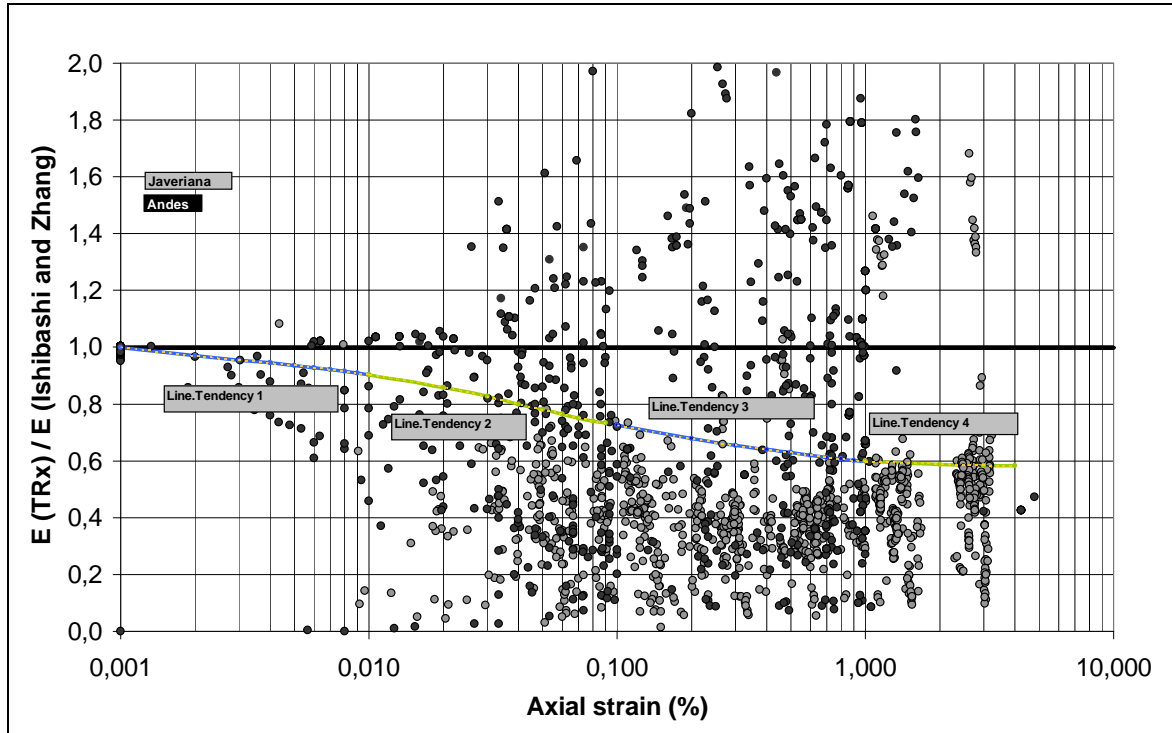
**Figure 3.  $E_{lab} / E_{field}$  versus  $E_{lab}$ , distinguishing type of materials and indicating the tendencies found**

The reduction of the ratio  $E_{lab}/E_{field}$  as  $E_{field}$  increases, the scatter of the data and the low values are caused by problems possibly related to aspects such as: poor sample quality and the effect of sampling and testing which produce important stress changes causing mainly volumetric deformation of the samples. These deformations in turn decrease the stiffness and depend on the time between sampling and testing as well as the confining conditions during this time. Another important aspect to take into account is the effect of the confining pressure on the stiffness of soils. If the sample is confined to a lower pressure than in the field, this would cause a decrease in stiffness in proportion to the ratio of field to lab confining pressures. Since the value of  $K_0$  is somewhat uncertain, it is possible that this effect may be important in causing the scatter showed in Figure 3. Due to the fact that the aspects responsible for the decrease of the ratio  $E_{lab}/E_{field}$  as  $E_{field}$  increases have a larger effect on soft clayey soils such as the lacustrine soils of Bogotá than for the types of soils analyzed by Kokoshu (1980), the tendencies obtained in this research are lower than the ones obtained by Kokoshu (1980).

In order to validate the data and obtain reliable relationships for the variations of dynamic properties with the strain level, the Young's modulus at different strains obtained from all the dynamic tests performed were normalized by the values of Young's modulus obtained by multiplying the values of  $E/E_{max}$  computed using the Ishibashi and Zhang formulas (Ishibashi and Zhang, 1993) by the Young's modulus at low strain obtained from the bender elements test. The data normalized is shown in Figure 4 as a function of strain. This figure distinguishes from dynamical tests performed in the two labs that do these tests in the city.

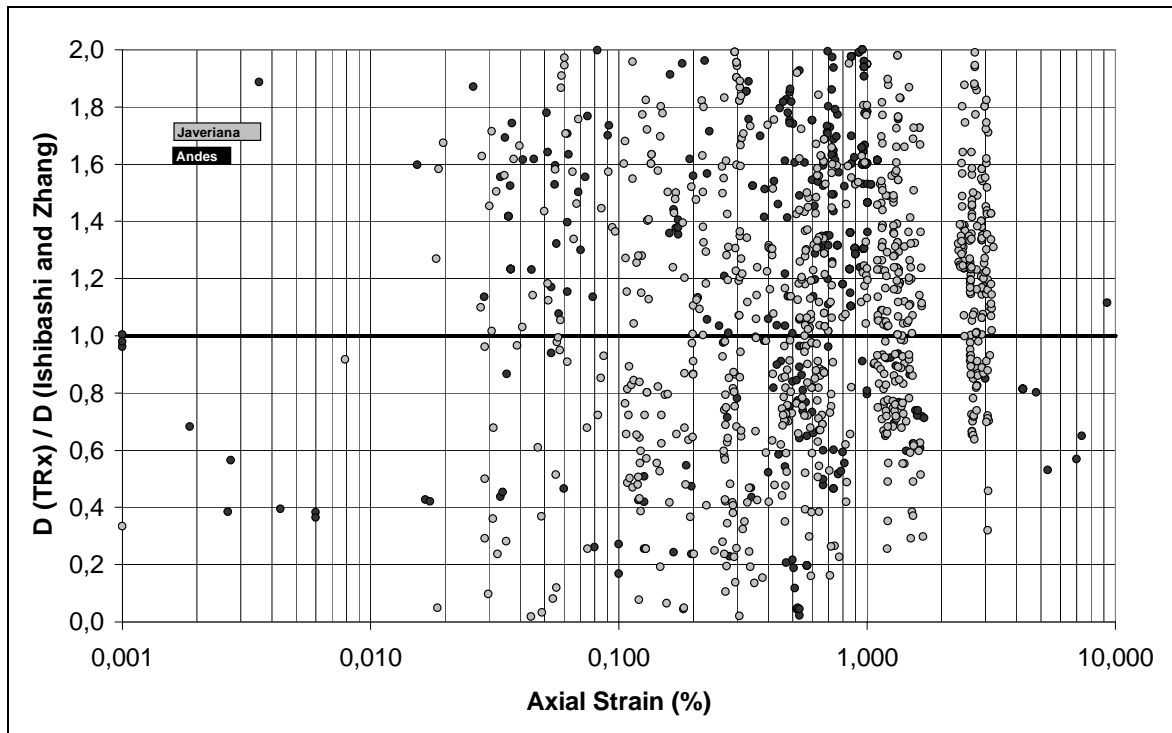
Based on the results a correction curve which multiplies the curve of reference (Ishibashi and Zhang, 1993) was traced in order to obtain dynamical curves for using in dynamical response analysis for Microzonation purposes. It can be seen from the figure that the scatter is less for larger strains as the effect of sampling is less relevant for larger strains. Taking the range of interest for earthquake response analysis, the stiffness of the soft soil of Bogotá, seems to be lower than the values reported by Ishibashi and Zhang by a factor of about 0,80. There is no evidence that the Bogotá soils may have a very stiff structure that holds with little degradation to relatively high strain levels as is the case of other structured soils such as the Mexico City soils. This situation has proven to be very dangerous as the soil responds almost elastically to the earthquake shaking therefore producing very high amplification.

With the aim of evaluating the tendency of the damping ratio increase with the strain a similar procedure was followed. The reference values computed using the Ishibashi and Zhang formulas were used to normalize the data obtained by laboratory testing. The results show a great scatter with no specific trend; in addition it is observed that most of the data ranges between 0.7 and 1.5 times the values of reference.



**Figure 4. Ratio of E lab modulus – E modulus computed using the Ishibashi and Zhang for tests that used the Bender Elements device**

It is important to point out that the differences between the low strain damping ratios between the data obtained from bender element tests based on the logarithmic decrement of the signal and the damping ratios computed using the Ishibashi and Zhang formulas are large. Laboratory damping ratios are between 3 to 10 times those computed using the Ishibashi and Zhang formulas. This is important because the seismic response then is lower if the damping ratio curves start in values larger than those computed by Ishibashi and Zhang's formulations.



**Figure 5. Ratio of lab damping ratio to the damping ratio computed using the Ishibashi and Zhang formulations**



### 3 – VARIATION OF VS ALONG THE VALLEY

Based on the shear wave velocity database, longitudinal and transversal profiles were selected for displaying the Vs variation among the zones and with depth. Table 5 shows the points contained in the section 1, which crosses zones 2, 3 and 4, column 1 of table 5 shows the zone where the point is located, in case the point is located in a transitional area between two zones, it goes with double symbol such as: Z3\_Z2. In addition since every point has been geo-referenced using the Arcview software every point has also a number after the zone. Column 2 of table 5 shows the distance between points along the profile, column 3 shows the height above the sea level, and finally column 4 shows the total distance, which is more than 10 Km for the whole profile.

**Table 5. Points of Analysis of the #1 longitudinal profile**

PROFILE 1			
Point of Analysis	Distance Between Points (m)	Height above sea level (m)	Total Distance (m)
Z4.21	0	2600	0
Z3_Z4.01	593	2600	593
Z3.30	1899	2600	2492
Z3.56	2818	2600	4717
Z3.53	2818	2600	5636
Z2_Z3.18	3149	2670	5967
Z2_Z3.14	5785	2600	8934
Z4.19	7413	2600	13198

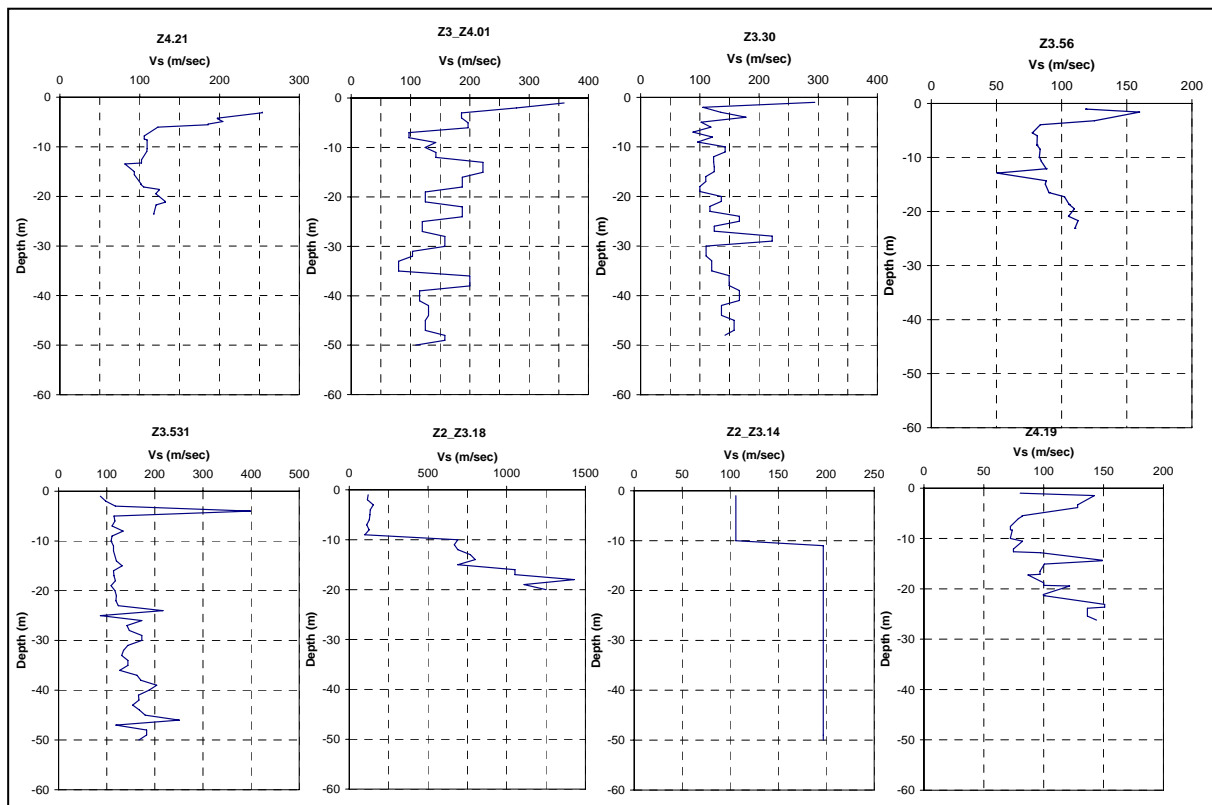
Figure 6 shows the transitional behavior of the Vs from east to west, along section #1 shown on figure 1. It is observed that the Vs values range between 100 and 200 m/sec for most sites up to 50 m below the ground surface which is generally part of the Sabana formation. It also shows an increase of stiffness with depth as predicted from equation (1) due to the increase of confining pressure and with the decrease of void ratio. It is also important to note that point Z2\_Z3.18 shows much greater values of Vs under 10 m from the ground surface, which is due to the fact that below the Sabana formation constituted mainly by clayey deposits of lacustrine origin, the Subachoque formation it is found which is much stiffer and from alluvial origin. This formation is generally found 50 m below the ground surface, but close to the hills it can be found closer to the ground surface, which is this case. In addition the Vs profile shows a transition in the weathered rocks of the Bogotá formation which is constituted mainly by claystones having Vs values ranging from 1000 to 1200 m/sec. The information available in general is limited to depths from 50 to 100 m, while the soil profiles usually reach deeper depths, up to a maximum of 450 m in the city. This implies a need to extrapolate the dynamical parameters from the borings to the bottom of the profile.

### 4 – DEPOSIT THICKNESS

In order to define the models of seismic response it is necessary to define the variation of the dynamical properties with depth from the ground surface to the bedrock level. This implies that the information available must be extrapolated since there are just few down holes tests performed below 50 m of depth and even less below 100 m of depth.

The geological information indicates that there are two formations in the Sabana deposit. The Sabana formation, formed by lacustrine clayey soils, which is shallow but reaching depths up to 250 m, and the Subachoque formation of alluvial origin characterized by sequences of sands, silts and clays in the bottom part of the deposit that can reach down to 450 m depth. The dynamical behavior of the two formations is relatively uniform, but different between them. As shown before, the increase of stiffness with depth is mainly a consequence of the increase in confining pressure; this fact allows estimating the stiffness parameters with depth.

In order to define the profiles is necessary to define the contact depth between the Sabana and Subachoque formations. There are some borings, mainly water wells that have allowed knowing this contact depth. Also the processes of formations are determining factors accounting for the geometry of the deposit. Therefore a correlation between the slope of the bottom of the valley and the slope of contact of the two formations is expected, as well as proportionality between the total thicknesses and the thicknesses of the two formations.



**Figure 6. Longitudinal profile # 1**

## 5 - CONCLUSIONS

A detailed evaluation of the available information from local seismic site response analysis carried out in the city has been accomplished with the aim of assessing the dynamical behavior of the Bogotá soils. This evaluation has covered the low strain as well as the range of strains needed to take into account for local site response analysis. Based on this evaluation a geo-referenced database which the sites having geotechnical information has been completed and recommendations for selecting the dynamical properties of the soil profiles for seismic analysis have been provided.

Classification and state parameters of the soils were analyzed and related to the Vs values measured in the field as well to the low strain stiffness of the soils obtained in the laboratory. The results have been normalized with data reported in the technical literature in order to identified tendencies and similitude.

Based on the information analyzed it has been possible to establish a correlation between the low strain dynamical stiffness with material type parameters such as the plasticity index and the material state (void ratio, overconsolidation ratio and confining pressure), as it has been reported in the literature. The parameters obtained are also consistent with the data reported in the literature. The linear correlation found between the low strain dynamical stiffness as a function of the parameter of normalization K defined by Rodriguez and Escallon (2006) and the plasticity index of the clayey soils ranging from 30 to 190 % was used with the aim of estimating the values of Vs based on basic geotechnical parameters.

A large scatter of the data obtained from laboratory tests has been found. Samples quality and tests procedure problems have been identified as possible causes of such scatter. This scatter produces uncertainty not allowing seeing the tendencies of behavior and comparing with tendencies published in the literature. A large amount of lab tests data show very low stiffness values, which would have an important effect on the seismic response computed, making this too low. In case these low values are due to sampling and testing problems, the results obtained based on theses low values would imply a risky condition since the seismic response would be higher.

Taking into account these considerations, the analysis of the data allowed defining certain recommendations for characterizing the dynamical properties of the soils found in the city with conservative criteria based on an envelope of the general trend found and the data published in the international technical literature.

Based on the analysis of the information available of the Sabana and Subachoque thicknesses, and taking into account geomorphologic considerations, tendencies of these two formations depth's variations were established allowing the extrapolation of the thicknesses in the whole area of the city.

To sum up, the results of this study have allowed defining tendencies of variation of the shear wave velocity and defining criteria for obtaining the dynamical curves of soil response as a function of basic geotechnical parameters for the soils of the city. By doing so it is possible to fully obtain the dynamical properties of every site of the city where geotechnical information is available.

## REFERENCES

- Hardin, B.O., and Black, W. L. "Vibration Modulus of normally Consolidated Clay," Journal of the Soil Mechanics and Foundations Division, ASCE, 94 SM2, 1968.
- Hardin, B. O., and Black, W. L. "Closure to vibration modulus of normally consolidated clay," Journal of Soil Mechanics and Foundations, ASCE, 95, SM6, 1531-7, 1969.
- Hardin. B. O., and Drnevich, V. P. "Shear modulus and damping in soils: design equations and curves," Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 98, No. SM7, pp. 667-692, 1972.
- Ingeominas, Los Andes University. "Seismic Microzonation of Santafé de Bogotá," Ingeominas Publishing, 1997. (In Spanish)
- Ishibashi I. and Zhang X. "Unified dynamic shear moduli and damping ratios of sand and clay," Soils and Foundations, Vol 33, No. 1, pp. 182-191, 1993.
- Kokoshu T. "Cyclic triaxial test of dynamic soil properties for wide strain range," Soils and Foundations, Vol 22, No 2, pp 45-60, 1980.
- Kokoshu T., Yoshida Y., and Esashi Y. "Dynamic soil properties of soft clay for wide strain range," Soils and Foundations, Vol 22, No 2, pp 1-18, 1982.
- Marcuson W.F. and Wahls H.E. "Time effects on dynamics shear modulus of clays," Journal of Soil Mechanics and Foundations, ASCE, 98, SM12, pp 1359-73, 1972.
- Rodríguez J. A. and Escallón J. P. "Evaluation of the low strain dynamical properties of the Bogotá soils," Journal of the Colombian School of Engineering, 2006. (In Spanish)
- Rodríguez J. Yielding and stress strain relationships for Bogotá clays. 16th Intl. Conf. On Soil Mech. And Found. Eng. Osaka. 2005.
- Torres, V. Vandenberghe, J., Hooghiemstra, H. "An environmental reconstruction of the sediment infill of the Bogotá basin (Colombia) during the last 3 million years from abiotic and biotic proxies," Palaeogeography, Palaeoclimatology, Palaeoecology 226, pp 127– 148, 2005.
- Zen K., Umehara Y., and Hamada K. "Laboratory tests and in situ seismic survey on vibratory shear modulus of clayey soils with various plasticities," Proceedings of the 5<sup>th</sup> Japanese Earthquake Engineering Symposium, pp 721-8, 1978.