Research Article

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Ambience Vibration Testing (Avt) Results to Estimate the Predominant Periods of Soil Motion (Ts) and the Shear Wave Velocity Profile (Vs) as a Function of Depth in an Anthropic Soil Zone (Infills), Associated with a Section of a New Tunnel Line of the Mexico City Metro

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Abstract
Results of Ambience Vibration Testing (AVT) measurements in free-field conditions are presented, estimating the predominant soil motion periods (Ts) as well as the shear wave velocity profiles (Vs) as a function of depth, to help address the detected issues in an anthropic soil zone (infills, with a length of 80 meters), over the tunnel layout (approximately 35 meters deep) of the METRO construction project, westward of Mexico City, where differential settlements on the ground surface and potential damage to local residential structures have been observed. A total of 23 triaxial accelerometers were used, strategically located along two walkways (streets) within the area of influence of the interest zone. AVT results show that the estimated Ts periods within the anthropic soil zone do not exhibit significant changes, for practical purposes, with variations between 0.330 and 0.417 seconds, consistent with the expected values for a stiff Lomas-type soil, according to the Earthquake Standards of the RCCM-2023, currently in force in Mexico City. In relation to the estimation of the shear wave velocity (Vs) model as a function of depth, using 60-minute recordings synchronized in time with a GPS, it was corroborated that the soil characteristics are of a stiff type, consistent with the previously shown results of the dominant periods of soil motion (Ts); initially, there is an average thickness of 6 to 9 meters of loosely compacted material (poorly consolidated sediments) with velocities less than 200 m/s, and the shear wave velocity gradually increases as a function of depth, with velocities of 500 and 600 m/s at depths of approximately 40 and 45 meters, respectively.

Keywords
Ambience Vibration Testing (AVT), Shear Wave Velocity (Vs), Predominant Periods of Soil Motion (Ts), Anthropic Soil / Infills, Mexico City Metro, Earthquake Design, Soil Dynamics, Seismic Design

Introduction

This study investigates the dynamic properties of an anthropically altered soil zone (infills) in Mexico City, a critical area for a new Metro tunnel line, where observed differential settlements and potential damage to residential structures necessitate a thorough geotechnical analysis. Utilizing Ambience Vibration Testing (AVT) in free-field conditions, this research precisely quantifies the predominant periods of soil motion (Ts) and the shear wave velocity (Vs) profiles as a function of depth. The findings aim to inform ongoing construction and mitigation efforts by providing essential data on the seismic behavior of this challenging soil, comparing it against the current Earthquake Standards of the Mexico City Building Regulations (RCCM-2023).

Background and Objectives

According to the physical progress achieved in the excavation works during the construction of the tunnel trace along the new Metro line comprised between an existing access port and a station (approximately 35 meters deep), infill materials were found in a sub-track of 80 m length in the area of interest with a soil defined as anthropic, a situation that has compromised the continuity of field works. As a result of the observed problem, several possible solutions have been proposed, such as concrete injection works on the excavation front, to improve the behavior of the properties of the anthropic soil type. Along with the above anomalous situation, it became necessary to follow up the review of the behavior of the housing structures that are located on the surface, located over the project trace, in the same area of the anthropic soil [1].

In order to review the corresponding dynamic properties of the aforementioned anthropic soil zone (infills), and thus ensure the structural safety of the tunnel itself and of the housing on the surface, a campaign of Ambience Vibration Testing (AVT, hereinafter) measurements was conducted in the open field, using 23 triaxial accelerometers strategically located along two small streets (Sebastián de Aparicio and Francisco Arrillaga), almost parallel to each other, in order to estimate the predominant periods of soil movement (Ts), as well as the corresponding profiles of the shear wave velocity (Vs) in accordance to the depth; the photographic report shown at the end of this work describes some details of the types of sensors placed along the two smaller streets of interest. Figure 1 shows a floor view of the area under study, as well as the location of the instruments placed in the open field, including the six houses that were studied for this report, for which the fundamental periods of vibration measured in the field were compared with the analytical results determined with three-dimensional finite element models, using a special computer program.

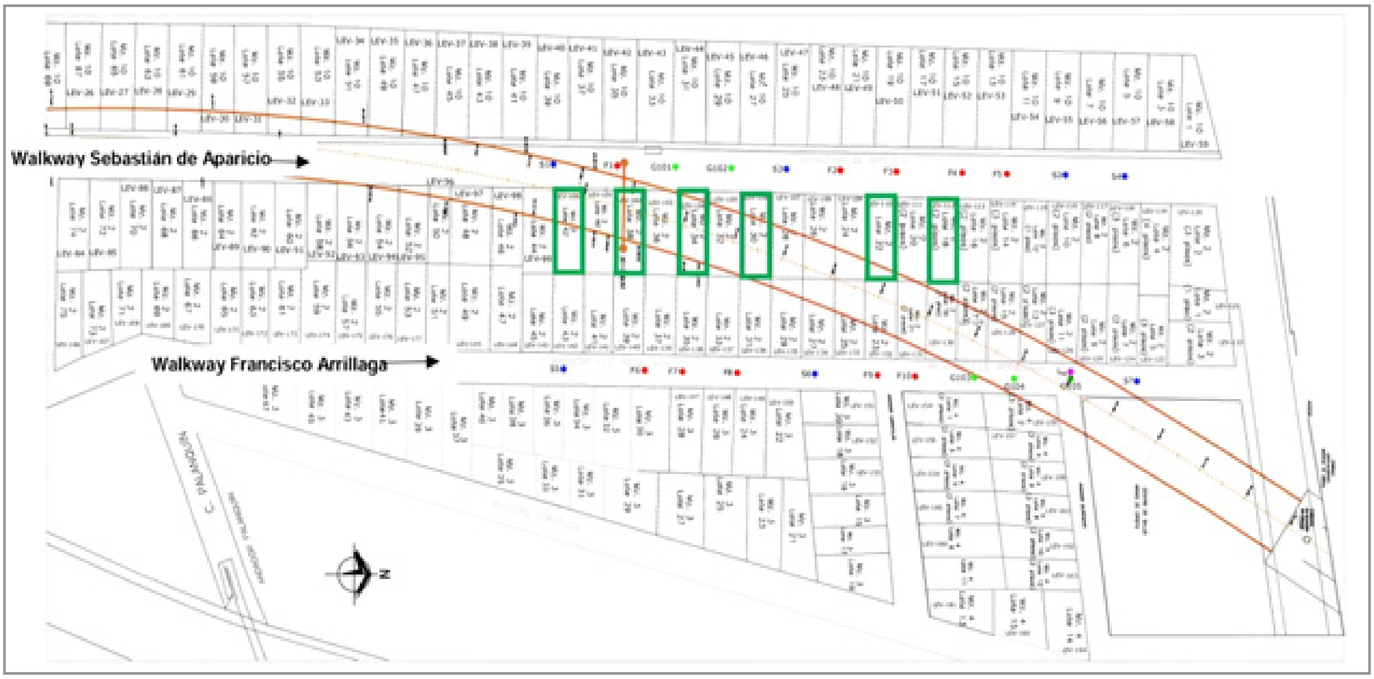


Figure 1: Floor view of the tunnel trace of the new Metro line, where the area of anthropic soil (fillings) is shown in magenta color, as well as the location of the triaxial accelerometers on the walkways (streets) Sebastián de Aparicio and Francisco Arrillaga, used during the measurements of the Ambience Vibration Tests (AVT) to estimate the corresponding predominant periods of soil movement (Ts); as a reference, the location of the six selected houses on the walkway Sebastián de Aparicio are marked in green, for which the fundamental periods for environmental vibration were determined and whose results are described in another work [2].

In summary, the predominant periods of soil movement (Ts) were estimated, with the support of AVT measurements carried out in open field, using triaxial accelerometers strategically placed along the two walkways (streets) of interest, on the surface of the tunnel trace in the anthropic soil zone, between a access port and a station of the new Metro line. Furthermore, in order to corroborate the above results, the corresponding profiles of the shear wave velocity (Vs) which are dependent of the depth were determined. The analysis considered 60 minutes of ambient vibration records, synchronizing all devices at the same time.

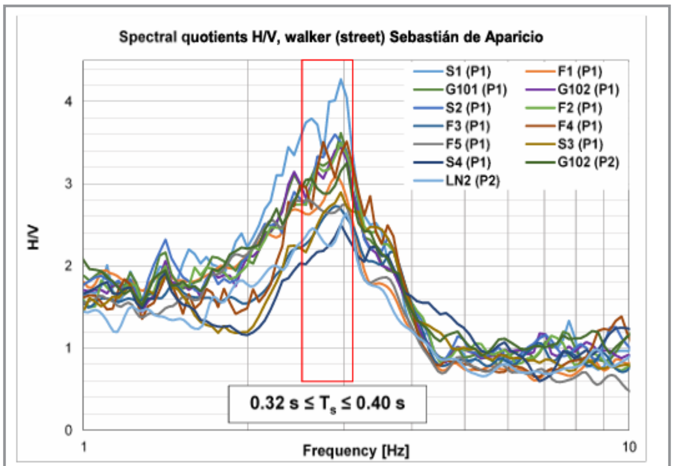
Results for the T_s

After reviewing and analysing all the records of the different sensors used in the AVT, placed along the two small streets (walkways) described above, the respective spectral H/V coefficients against the frequencies (Hz) were obtained, in order to understand the dynamic behavior of the site in the area of interest of the anthropic soil (infills), where the period is the reciprocal frequency. Figure 2 presents the comparison of these results, describing the main ranges of the dominant periods of movement (Ts), corresponding to the location of each of the sensors used in both walkways (streets), namely: $0.32 \text{ s} \leq Ts \leq 0.40 \text{ s}$ (walkway Sebastián de Aparicio) and $0.31 \text{ s} \geq Ts \geq 0.37 \text{ s}$ (walkway Francisco Arrillaga), with almost zero differences between the two streets, for practical purposes, and with small values, characteristic of a firm type soil. As a reference, and in order to understand the variation of the dynamic properties of the predominant period of soil movement (Ts), according to the three soil types identified in Mexico City, it is appropriate to consider the following intervals, namely: soil type 1 (Lomas) Ts < 0.5 s; soil Type 2 (Transition) 0.5 s < Ts < 1.0 s; Soil type 3 (Compressible) Ts > 1.0 s. For the purpose of seismic design of structures and according to the NTC-Seismic of the current Construction Regulations in Mexico City, a Ts= 0.5 s corresponds to this particular type of soil. Table 1 shows a summary of the predominant periods of soil movement (Ts), based on measurements of the AVT on site, performed with the different triaxial accelerometers placed on the surface of the anthropic soil zone (infills) detected on the new Metro line [3].

Table 1: Summary of Results of Estimates of the Predominant Periods of Soil Movement (TS), Based on Measurements of AVT on Site, Performed on the Surface of Walkways Sebastián de Aparicio and Francisco Arrillaga

Location	Device		Ts (s)
Walkway Sebastián de Aparicio	1	SARA 1	0.337
	2	FORTIS 1	0.341
	3	GÜRALP 101**	0.337
	4	GÜRALP 102**	0.337
	5	SARA 2**	0.346
	6	FORTIS 2**	0.337
	7	FORTIS 3**	0.341
	8	FORTIS 4**	0.329
	9	FORTIS 5**	0.410
	10	SARA 3	0.337
	11	SARA 4	0.337
	12	GURALP 102***	0.329
	13	LENNARTZ 2***	0.330
Walkway Francisco Arrillaga	1	SARA 5	0.411
	2	FORTIS 6	Sin registro
	3	FORTIS 7	0.417
	4	FORTIS 8	0.417
	5	SARA 6	0.337
	6	FORTIS 9	0.335
	7	FORTIS 10*	0.335
	8	GÜRALP 103*	0.346
	9	GÜRALP 104*	0.346
	10	GÜRALP 105*	0.337
	11	LENNARTZ 1*	0.330
	12	SARA 7*	0.337

• Located, practically on the vertical projection of the tunnel in the area of anthropic soil, walkway Francisco Arrillaga.
• Located, practically in front of the vertical projection of the tunnel in the area of anthropic soil, walkway Sebastián de Aparicio.
• Additional test performed as a reference during the measurement of the T1 of the six houses of interest.



a) Walkway (street) Sebastián de Aparicio

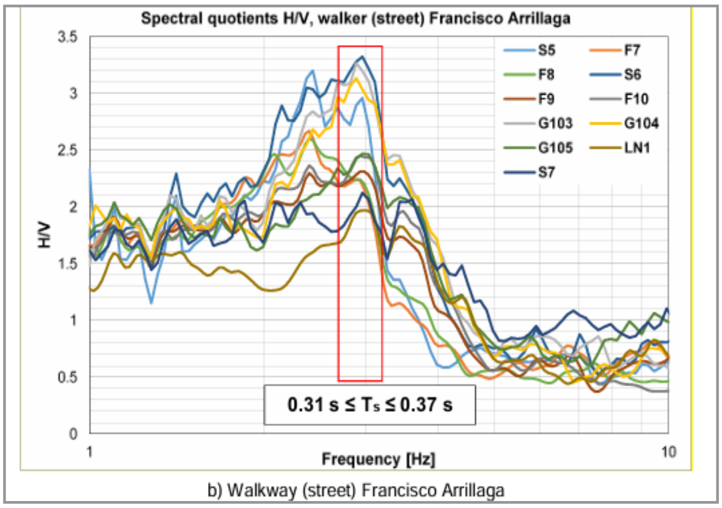


Figure 2: Comparison of Spectral quotients H/V against natural frequencies (Hz), according to the measurements of the AVT with the 23 triaxial accelerometers (type GÜRALP, FORTIS, SARA and LENNARTZ), placed along the walkways (streets) Sebastián de Aparicio and Francisco Arrillaga, in the area of influence of the anthropic soil (infills), detected in the construction of the tunnel trace of the new Metro Line.

Figure 3 compares the variation of the predominant periods of soil movement, Ts, estimated from the measurements of the AVT, performed at several points of the walkways (small streets) Sebastián de Aparicio and Francisco Arrillaga, area of the new Metro line, against the Ts= 0.5 s reported by the SASID application of the NTC-Seismic of the RCCM-2023. It is again corroborated that the results between the two small streets have a negligible variation, with small values applicable to a firm type of soil. Figure 4 shows the distribution of the Ts measured in the open field, according to the position of the accelerometers used, showing in magenta the area of interest of the tunnel trace, corresponding to the anthropic soil (infills).

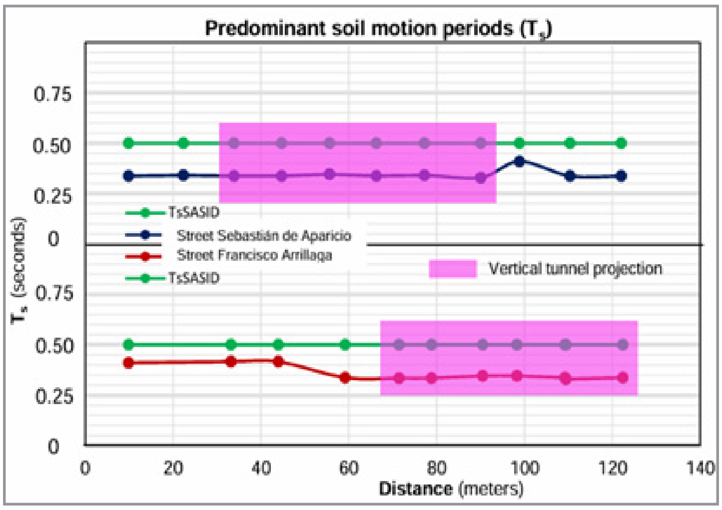


Figure 3: Comparison of the predominant periods of soil movement, Ts, estimated from the measurements of the AVT, carried out in the walkways (streets) Sebastián de Aparicio and Francisco Arrillaga, where the area of the anthropic soil, detected during the construction of the new line of the Metro, is shown in magenta color, against the Ts = 0.5 s for firm ground, according to the SASID design application of the NTC-Seismic of the RCCM-2023.

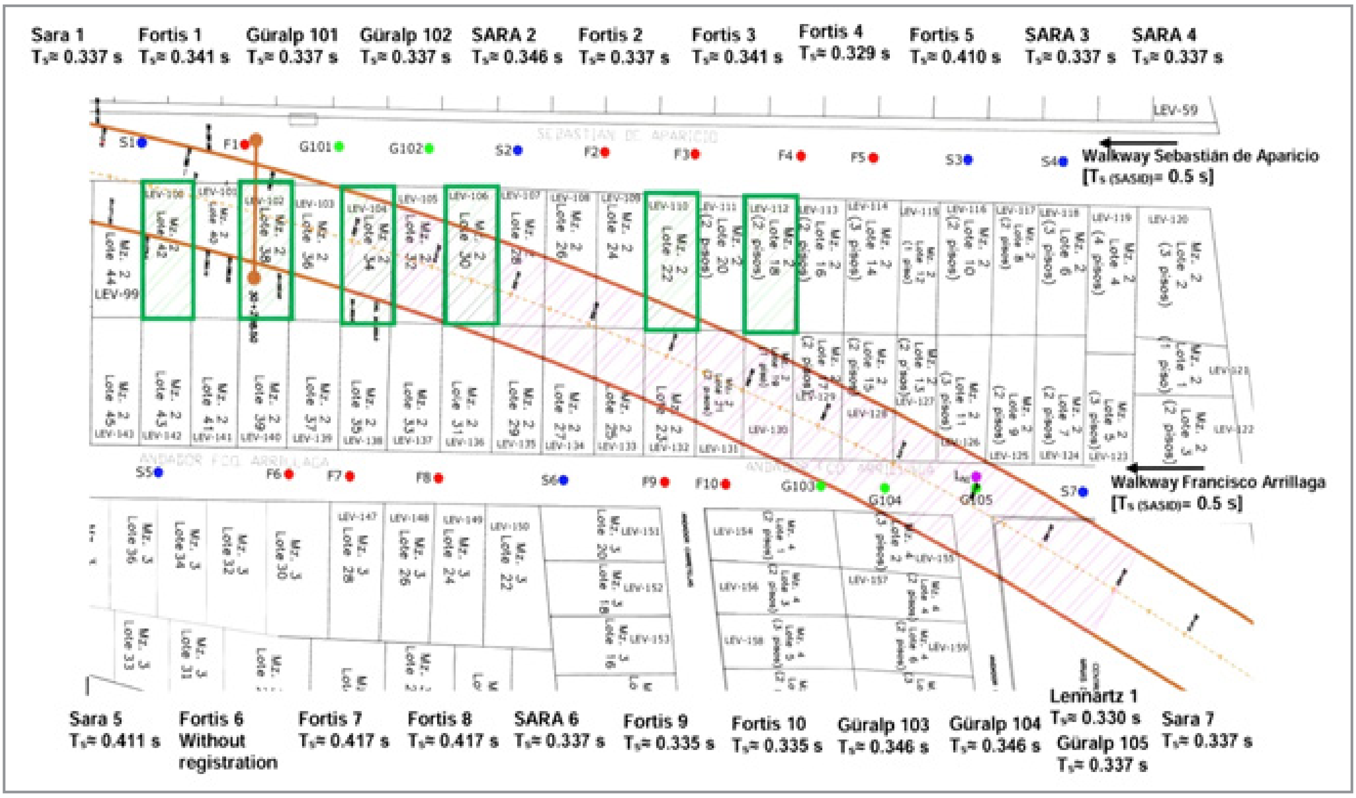


Figure 4: Floor view of the Ts measured in the open field over the walkways (streets) Sebastián de Aparicio and Francisco Arrillaga, including the position of the accelerometers used, where the area of the anthropic soil is shown in magenta, against the Ts= 0.5 s (constant along the two walkers) reported in the SASID of the NTC-Seismic.

For practical reasons, it should be reiterated that, according to the AVT executed, it is not perceived that the estimated Ts along the two walkers of interest, within the study area (anthropic soil), manifest changes in the dynamic properties of the soil. However, it is recommended to periodically monitor the period of the open-field soil, as well as to carry out a permanent topographic survey until the completion of the works, including the necessary tasks of the respective injections in the area of interest.

Results of Shear Wave Velocity (VS) as a Function of Depth

For the estimation of the structure of the shear wave velocity (Vs) depending on the depth, two linear arrangements of accelerometers (sensors) disposed along the walkways Sebastián de Aparicio and Francisco Arrillaga were used (see figure 5), according to the AVT discussed earlier. The sensors used are of intermediate period coupled to autonomous seismographs; the records of each station were synchronized in time with a GPS, based on intervals of 60 minutes.

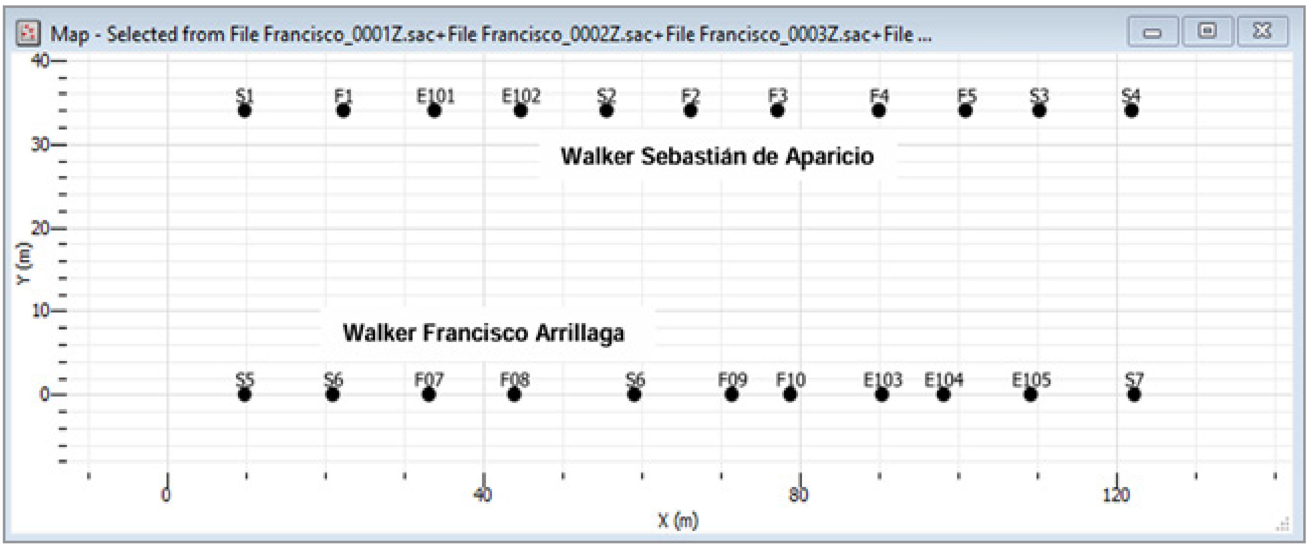


Figure 5: Linear arrangements of the sensors placed in the walkways (small streets) Sebastián de Aparicio and Francisco Arrillaga (Note: the nomenclature of the devices used is shown: S1= SARA 1, F1= FORTIS 1, E101= G101= Güralp 101, etc.)

In each of the linear arrangements, three models of shear wave velocity were estimated based on depth in order to know the variation of the Vs throughout the arrangement. The first model was assigned between the sensors S1, F1, G101 and G102 of the walkway Sebastián de Aparicio. The next model of shear wave velocities was obtained with the stations G102, S2, F2 and F3, and therefore model was assigned to the middle point of these sensors. Finally, to obtain the representative velocity model of the last part of the linear arrangement, the model was estimated with the stations F4, F5, S3 and S4. For the walkway Francisco Arrillaga the three corresponding linear arrangements were assigned between the stations: S5, F7, F8 and S6; S6, F9, F10 and G103; G103, G104, G105 and S7.

Thus, based on the available information, following the open-field measurements made on both walkways (anthropic soil area), figures 6 and 7 present the comparisons of the results of shear wave velocity (Vs) models based on the estimated depth of the linear arrangements, between the different measuring stations placed on the two walkways. Figure 8 compares the results of Vs models based on the estimated depth of the linear arrangements, according to the stations located in the walkways Sebastián de Aparicio (continuous line) and Francisco Arrillaga (dashed line).

The results obtained from the linear arrangement on the walkway Sebastián de Aparicio, according to the models of shear wave velocity (Vs) against depth, show that at the beginning there is a thickness of 9 m, approximately, of unconsolidated sediments with speeds less than 200 m/s, with respect to the end part of the arrangement; it is detected that the shear velocity is increasing gradually depending on the depth (see figure 9). On the other hand, for the arrangement of the walkway Francisco Arrillaga, there is a similar Vs distribution, with low compacted material in the first meters of depth, where the shear wave velocity does not exceed 200 m/s (see figure 10); the soil thickness with speeds less than 600 m/s tends to be smaller than in the walkway Sebastián de Aparicio.

For the purposes of having a reference, in relation to the previous results of the profiles of the shear wave velocity (Vs) depending on the depth, the chapter of Design by Earthquake and Wind of the Civil Works Design Manual of the Federal Electricity Commission (MDOC-CFE) proposes a classification of the soils according to their shear velocity (Vs), which can be estimated from Cone Standard Penetration Tests (CPT), and that are shown in table 2; this manual is used almost throughout the Mexican territory. It should be noted that, after comparing the values of Vs corresponding to the measurements of our AVT in both small streets, according to the results indicated in the figure 8, in the first 8-9 m of depth there is a medium density soil (ɣs ~ 1.5 t/m3), between 8-9 m and 19 m there is an intermediate soil between medium and firm density (ɣs ~ 1.8 t/m3), and below the 19 m, we can observe a firm and dense soil; the conditions of a rock-type soil are not achieved [4].

Table 2: Soil type classification, according to their shear wave velocity (Vs) and number of strokes, as stipulated in the MDOC-CFE

Soil type	Number of strokes	V_s (m/s)	Volumetric density, γ_s (t/m^3)
Rock	-	>720	2.0
Firm and dense soil	>50	360	1.8
Medium soil	15 - 50	180	1.5
Soft soil	<15	90	1.3

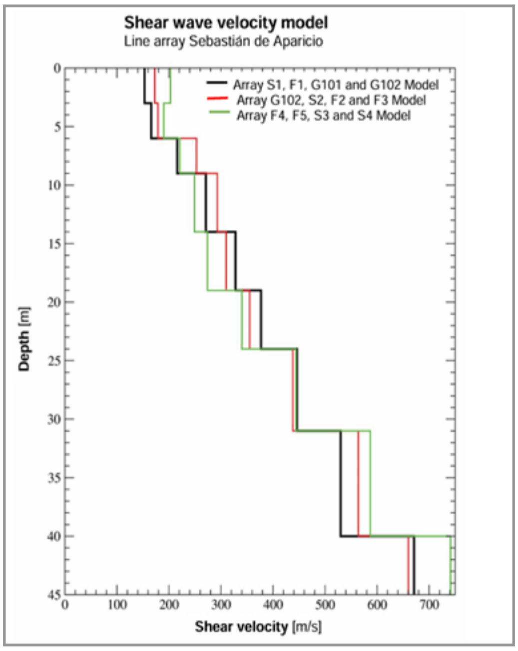


Figure 6: Comparison of the results of shear wave velocity (Vs) models based on estimated depth from linear arrays, among the different stations placed on the Sebastián de Aparicio walkway.

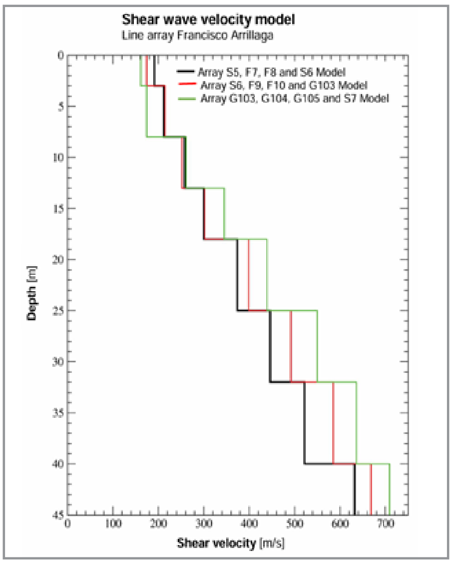


Figure 7: Comparison of the results of shear wave velocity (Vs) models based on estimated depth from linear arrays, according to the different stations placed on the Francisco Arrillaga walkway

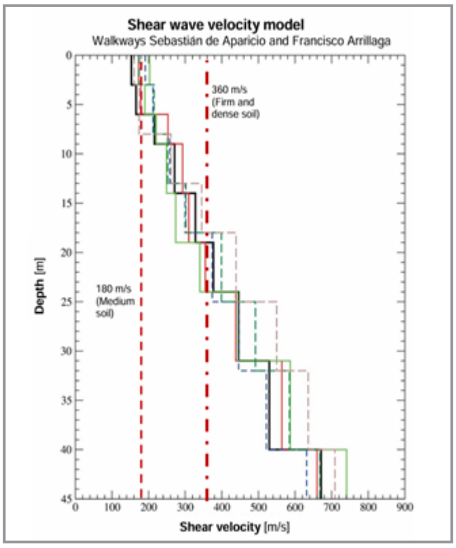


Figure 8: Comparison of the results of shear wave velocity (Vs) models as a function of estimated depth from linear arrays, according to the different stations placed on the Sebastián de Aparicio walkway (solid line) and Francisco Arrillaga walkway (dashed line).

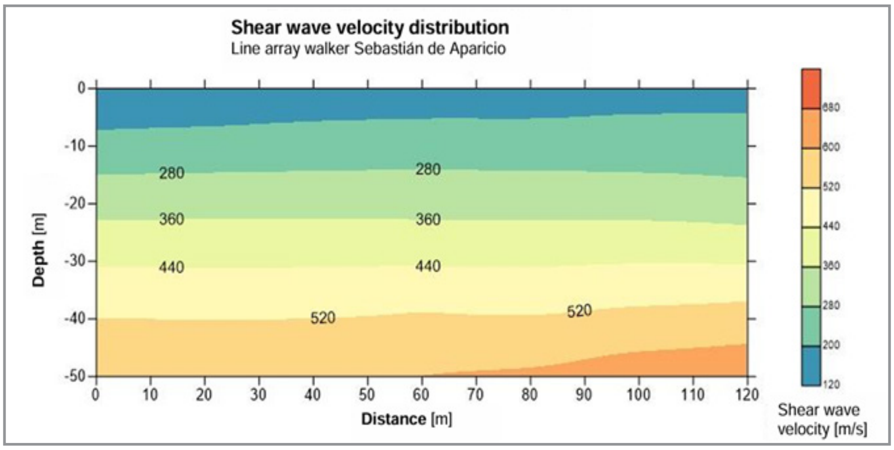


Figure 9: Interpolation of shear wave velocity (Vs) models based on estimated depths from linear arrays, among the different stations placed on the Sebastián de Aparicio walkway, showing that along that walkway there is the same variation in shear velocities with respect to depth.

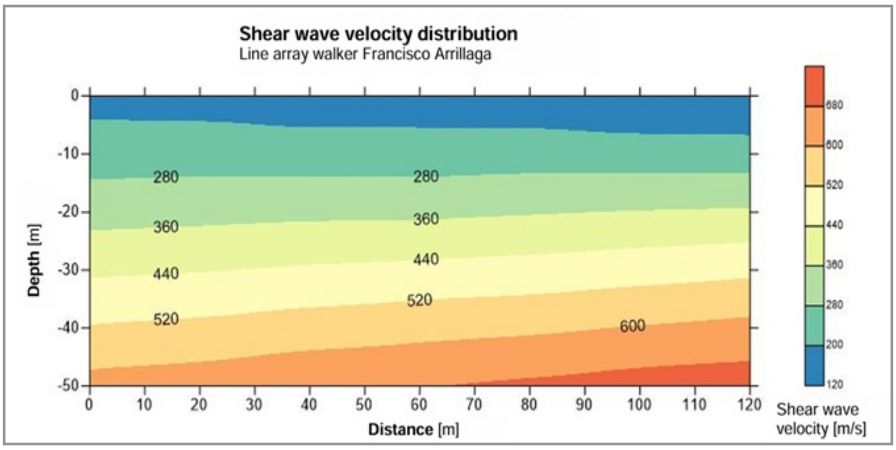


Figure 10: Interpolation of shear wave velocity (Vs) models based on estimated depths from linear arrays, among the different stations placed on the Francisco Arrillaga walkway, with a behavior similar to that detected on the Sebastián de Aparicio walkway, in relation to depth.

Photographic Report of the PVA Executed in Open Field

As a reference, the position of some of the 23 triaxial accelerometers used during the measurements of the PVA carried out on the walkways Sebastián de Aparicio and Francisco Arrillaga is shown below.

Subsequently, in order to know the distribution of the shear wave velocity depending on the depth along the linear arrangement of the seismic stations that were arranged on the two walkways of interest, an interpolation of the models obtained using a linear polynomial algorithm was performed, and the variation was charted in speed intervals of 80 m/s; figures 9 and 10 show the results with a similar variation of cutting velocities, relative to depth, received along the two walkways. It is noted that there is no abrupt change in the shear wave velocity laterally, which is congruent with estimates of the predominant period of vibration (Ts) estimated along the two arrangements of interest.

Conclusion

The results of the dynamic properties determined in the walkways Sebastián de Aparicio and Francisco Arrillaga, according to the performed AVT, present little differences. The dominant periods of soil movement (Ts), corresponding to the location of each of the sensors used in both corridors (streets) of interest, resulted between 0.32 s and 0.40 s, and 0.31 s and 0.37 s, respectively, with practically zero variation, and with small values, applicable to a firm type soil.

The pattern of behavior of the variation of shear velocities along and deep of both corridors tends to be very similar, which corroborates that it is a firm-to-medium characteristic soil, congruent with the results shown previously of the dominant periods of soil movement (Ts), according to the performed AVT.

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