Tests with the MASW method (Multichannel Analysis of Surface Waves) in the urban area of São Paulo, Brazil.

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Abstract

The use of underground space in big cities has become the alternative to large projects, particularly in the expansion of road systems. The geological and geotechnical characterization in these locations is often difficult by the absence of outcrops and space for research excavations. The MASW method (Multichannel Analysis of Surface Waves) has been pointed as a great alternative due both its practicality and well as its low cost. This study compares the results obtained using the MASW and the crosshole test. The MASW data acquisition in the field is very similar to that used in studies by seismic refraction, however, we tested different minimum offsets and different seismic sources. Data processing was performed by using the free software Geopsy, yet little spread in the Brazilian geoscience community. The results showed that the adopted minimum offset significantly influences the quality of the image obtained while the variation of the seismic source showed little influence on the final result. Considering the uncertainties involved, the results obtained with the MASW method were generally close to those of the crosshole test. The comparison with the SPT test data also showed convergence of the results.

Introduction

The dynamic shear modulus (G_{din}) is an important parameter for many geotechnical engineering projects, such as in calculations of foundations under dynamic loads. G_{din} is obtained from material densities and S-wave propagation velocities (V_S). Seismic test between boreholes (crosshole) is considered the most accurate from all in-situ seismic methods to determine V_S. However, it has disadvantages, because it is necessary the execution and casing of at least two boreholes, making it time-consuming and costly.

These constraints have made the Multichannel Analysis of Surface Waves (MASW) method (Xia et al., 1999; Park et al., 1999) an interesting option for mapping of S-wave velocity field especially in terrain recognition phases in engineering designs. V_S 1D-profiles of shallow subsurface and even 2D-sections from multiple-profile interpolation can be obtained with the use of MASW method. Specific characteristics of surface waves, such as their generation easiness and large amplitude, enable the application of MASW method in areas where other geophysical methods proved to be inadequate, for instance, in urban or high-noise areas.

Since it is a relatively new method, its application is not widespread in Brazil yet (Lima Júnior et al., 2012), becoming important the comparative studies of its application in different geological and geotechnical situations.

This paper presents the accomplished testing results in a densely built area, and with high levels of traffic noise in São Paulo city, in SP. Data obtained from MASW method presented herein were compared to those ones obtained from crosshole seismic testing (V_S profile) acquired years earlier to support a project related to São Paulo metro (subway) line. The comparison between MASW and crosshole data aimed at evaluating MASW potentialities and limitations as an auxiliary method in geotechnical investigations for urban areas. All data processing and inversion were performed by using free Geopsy and Dinver (Geopsy Project) software's.

Study Area

The study area is located in São Paulo city / SP, along Roberto Lorenz Street and next to Francisco Morato Avenue (Figure 1).

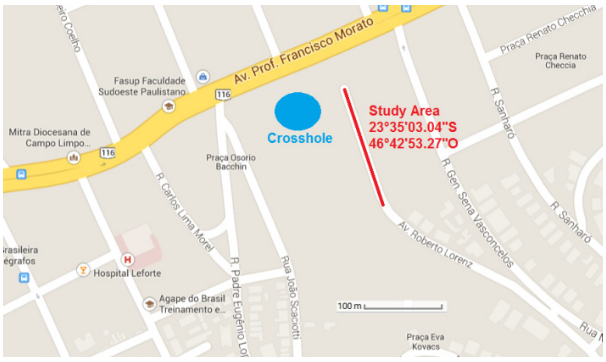

Figure 1. Map showing the studied area with location of the MASW test (redline) and the crosshole test (blue oval-shaped area). Google Maps, 03/11/2015.

Method

MASW method is based on Rayleigh wave dispersive behavior when propagates in a vertically heterogeneous medium, in which different wavelengths travel through different layer thicknesses in subsurface. Each wavelength is submitted to different elastic properties that define its propagation velocity.

The method's objective is to obtain a shear-wave velocity profile versus depth. It can be described in three distinct steps: acquisition, processing, and inversion.

The acquisition step is similar to that one employed for refraction or reflection tests ones where a source generates seismic waves that are received by a linear array of geophones, generating a seismogram. In the processing step, it is extracted the dispersion curve showing the phase velocity versus frequency wave. Dispersion curve is used in the third step, the inversion one, where S wave velocity profile versus depth is finally obtained. For recording Rayleigh waves are used vertical-component geophones, whose natural frequency depends on the desired scale of investigation, are used to record Rayleigh waves, though natural low frequency (<10 Hz) geophones are usually employed.

In this study it was used a 48-channel data acquisition system (Geode model by Geometrics Inc.), seismic sources of vertical impact of drop weight types (≈30kg) and sledgehammer (≈6kg), and geophones of 4.5Hz. Different field arrays were tested, varying offsets and spacing between geophones to avoid spurious near field and far field effects (Park et al., 1999). Table 1 shows the adopted acquisition geometries.

Source	*Offset* min. (m)	*Offset* max. (m)	Δg (m)	T (s)
Sledgehammer	5, 10	52- 57	1	2
Weight drop	5, 10, 20, 30	52-124	1, 2	2

Table 1. Acquisition Parameters tested where Δg is the spacing between the geophones and T the time of the acquisition window.

In the processing step, all data were initially submitted to fk and band-pass filtering to attenuate the loud traffic noise of Francisco Morato Avenue, perpendicularly located to field arrays and opposite to the positioning of active seismic sources. Then, dispersion images were generated and dispersion curves were extracted and interpreted. In this process the intensities of near and far field effects as well as the signal-to-noise ratio of all seismograms were evaluated. This paper presents two records: one obtained with the use of a sledgehammer, and another with the use of weight drop source. The extraction of dispersion curve from the dispersion image is essentially based on the observation of the energy maximums. However, not all maximums are necessarily associated with surface wave energy. Thus, it is considered in the interpretation the expected curve behavior similar to the exponential function graph corresponding to a stratified model, and with velocities increased with depth. Dispersion images obtained from the two records considered herein and their respective dispersion curves (in black) are shown in Figures 2 and 3.

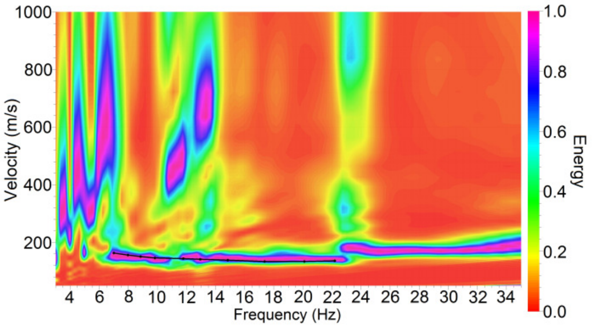

Figure 2. Dispersion frequency - phase velocity image and the extracted fundamental mode curve (black line). Obtained from 15m minimum offset seismogram, acquired using weight drop source.

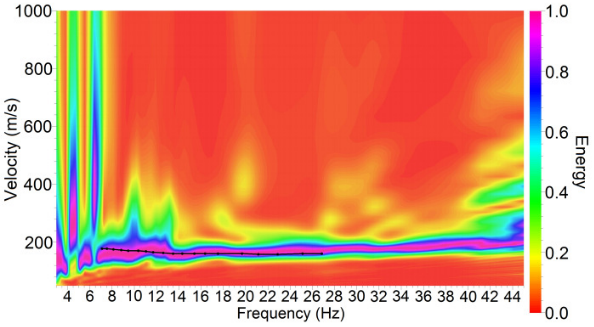

Figure 3. Dispersion frequency – phase velocity image and the extracted fundamental mode curve (black line). Obtained from 20m minimum offset seismogram, acquired using sledgehammer.

In the inversion step, the profile of S wave velocity versus depth from extracted dispersion curve is obtained. Dinver, Geopsy package routine, which performs the inversion, uses Neighborhood algorithm (Sambridge, 1999), modified by M. Wathelet (2008). The algorithm is based on a stochastic direct search method to find models with acceptable adjustments within a multidimensional parameter space. Comparison of dispersion curve generated by inversion with the experimental dispersion curve provides a misfit value, indicating how close the generated model is of a "real" solution. The algorithm uses previous samples to guide the search for improved models by using Voronoi diagram concept to finding and investigating the most promising elements in a parameter space.

Crosshole Seismic Test Data

When performing a crosshole test, two orthogonal arrays (one approximately perpendicular and another longitudinal to Francisco Morato Avenue) were adopted with a hole, common to the both arrays, where the generating S-waves source was positioned. Obtained crosshole seismic test data is shown in Figure 4. In comparing the two results the divergences between velocity values for equivalent depths are noted. In general there are differences reaching 25%, with higher values related to longitudinal arrangement. Such velocity anisotropy may be associated with an inherited rock structure and still present in residual soil. However, this result analysis is beyond this work scope.

Notwithstanding, the differences in values between them, there is in both a velocity increment in the approximate depths reaching 15 and 20 meters, suggesting the existence of interfaces between distinct geological materials in such depths.

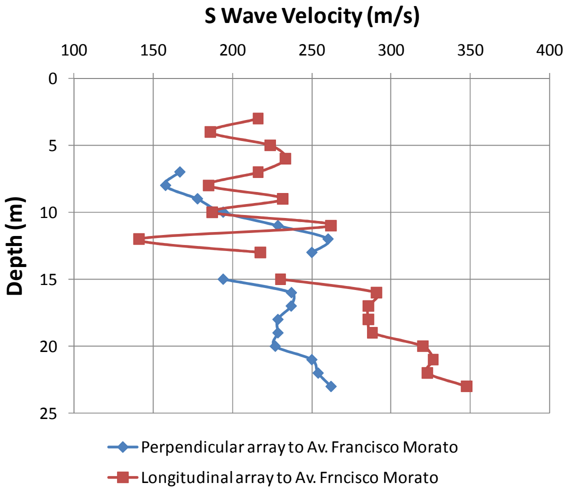

Figure 4. Crosshole seismic test results of the study area.

Figure 5 provides a descriptive profile of one of the boreholes conducted for crosshole testing execution. Residual soils are described up to 20 m depth. Figure 5 also shows SPT (Standard Penetration Test) results, indicating interfaces at 15 m and 20 m in depth, approximately.

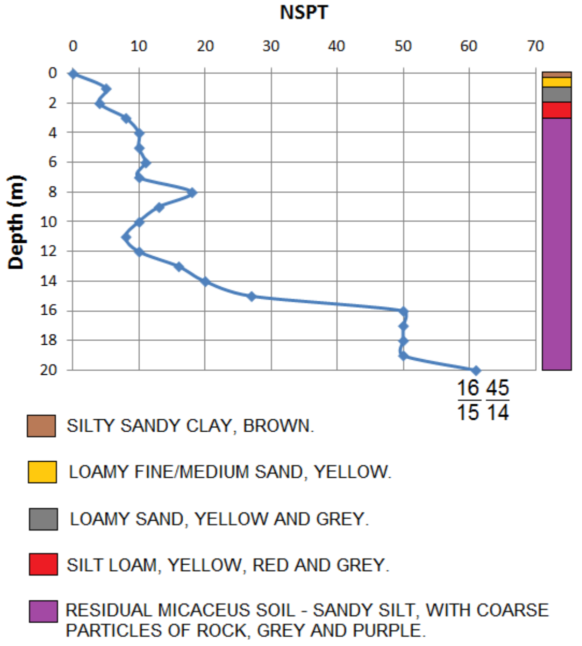

Figure 5. Geological material and NSPT profiles, from one of the boreholes used for the crosshole test.

Results

Results of acquired data with the use of different geophone spacing (1 m and 2 m) did not reveal differences in the signal-to-noise ratio that reflected in dispersion images with very distinct qualities. However, the minimum offset parameter resulted in images of different qualities due to the near and far field effect. Despite generating higher energy, the drop weight source did not result in better images than those ones obtained from data generated with the sledgehammer with respect to sampling lower frequencies for the the dispersion curve, as it could be a priori expected. Whereas, the use of sledgehammer source allowed at obtaining dispersion curves that reached higher frequencies.

The initial model employed in the inversion step (Table 2) was defined based on crosshole testing (Figure 4), geological and NSPT profiles (Figure 5), and data dispersion curve (Figures 3 and 4) information, the latter case, to inferring the minimum and maximum thicknesses taking into consideration the sampled wavelength (from values of phase velocity and frequency).

Initial geological model for inversion (model with 7 uniform layers + half-space)
0m to 30m divided into thickness layers of 4,29m
V_p: 500m/s to 2000m/s
V_s: 100m/s to 500m/s
Density: 1200kg/m^3 to 2000kg/m^3
Poisson ratio: 0,3 to 0,5
Half-space (30m forward)
V_p: 500m/s to 4000m/s
V_s: 150m/s to 2000m/s
Density: 1500kg/m^3 to 2800kg/m^3
Poisson ratio: 0,2 to 0,3

Table 2. Initial geological model used for inversion of the data.

Figures 6 and 8 show inversion results, and Figures 7 and 9 show the respective experimental and numerical dispersion curves from modeling, respectively. Data were inverted several times with the same initial model, resulting in converging inversions indicative of the robustness of the final inversion result.

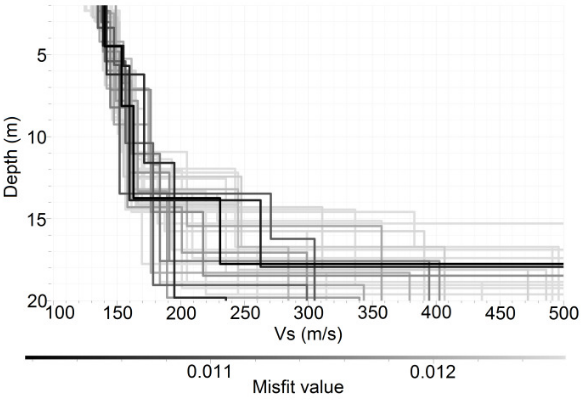

Figure 6. Shear wave velocity profiles obtained from the inversion of surface waves data acquired using weight drop source. The darker lines indicate the lowest misfit results.

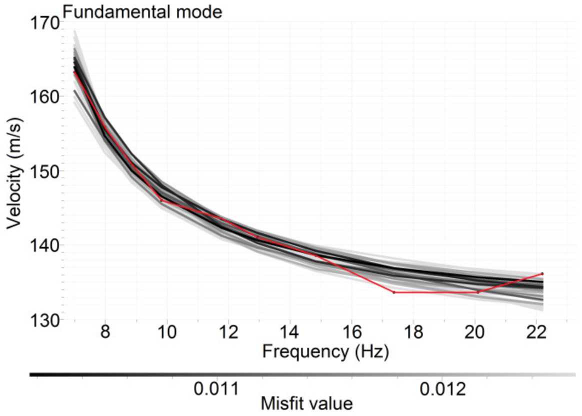

Figure 7. Comparison among the experimental (from the seismograms acquired using weight drop source) and numerical dispersion curves obtained from the models. The darker lines indicate the lowest misfits.

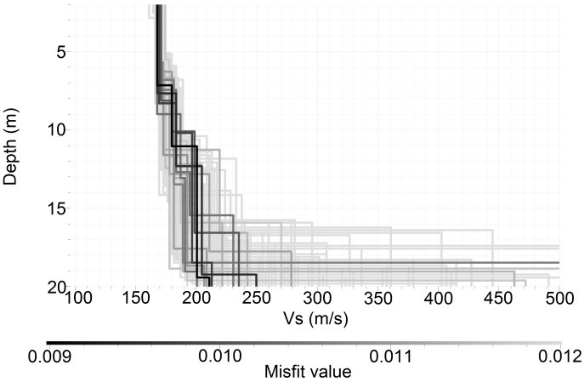

Figure 8. Shear wave velocity profiles obtained from the inversion of surface waves data acquired using sledgehammer source. The darker lines indicate the lowest misfit results.

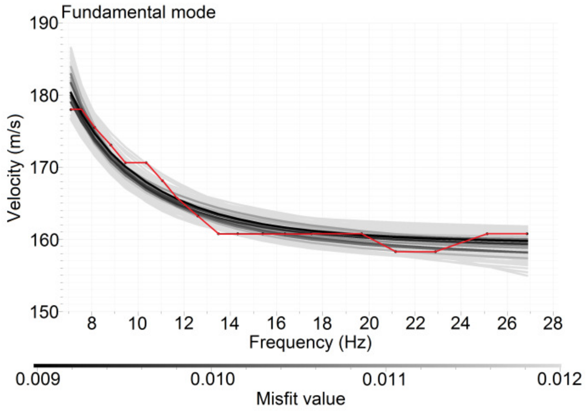

Figure 9. Comparison among the experimental (from the seismograms acquired using sledgehammer) and numerical dispersion curves obtained from the models. The darker lines indicate the lowest misfits.

1-D velocity models obtained from inversions (Figures 6 and 8) show approximate maximum depth of 18 m, and resolution over 4 m for layer thicknesses. This is also the minimum depth of investigation. Obtained average V_S velocities vary between 160m/s and 180m/s up to 10 m depth, increasing for the band between 170m/s and 200m/s up to 15 m. Results suggest significant interfaces in the approximate depths at 7 m, 11 m, 15 m and 18 m, where larger velocity variations are perceptible.

In the comparison between data obtained with the two methods, it was observed MASW test and crosshole average velocities do not present differences higher than 25% up to 10 m depth. However, differences on the order of 60% are noted between the 10 m to 15 m interval.

The most significant differences observed, when results obtained with MASW test with those ones obtained with crosshole testing are compared, can be attributed to different factors: the own uncertainties inherent in the methods, and in conditions of the accomplished experiments. In the latter case, there is (I) the no coincidence between sites where the two tests (crosshole and MASW) were carried out, which led to the assumption that geology should not significantly vary between the two points (Figure 1), and finally (II) those one related to differences observed between velocities obtained with perpendicular and longitudinal arrangement of crosshole testing (Figure 4), in the order of 25%, suggesting an important anisotropy of the geological material.

When comparing the depth values of the most significant interfaces in MASW and crosshole profiles, it is verified convergence of results. The 7 m depth interface noticed through MASW does not have correlation on crosshole data. This interface can be observed in SPT test result (Figure 3), which also allows identify interfaces at 8 m, 14 m and 20 m depth. However, SPT interface at 8 m should be examined with reservations, since representing a single value within the trend observed for the profile, and it could represent, for instance, the presence of a single remaining block of the rock.

Comments and conclusions

The use of different space geophones did not result in dispersion images with very distinct qualities. Nevertheless, the variation of the minimum offset parameter interferes in the image quality. The use of drop-weight source, despite generating more energy, did not result in superior images than those ones obtained with data generated with sledgehammer. The latter also propitiate the obtaining of dispersion curves reaching higher frequencies.

Considering the involved uncertainties, results obtained with MASW were generally close to those ones obtained with crosshole method. The comparison with SPT data also showed convergence between results.

It is believed the increased depth of investigation in the study area may be reached with the analysis of MASW data generated by passive source, such as the noise generated by vehicle traffic that is pretty intense on site. Analyzes in this direction are being made and preliminary results were being promising.

Acknowledgments

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