# Joint inversion of multimode Rayleigh waves for geotechnical characterization of soils at a test site in Ubatuba/SP using the MASW method.

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## Abstract

This paper discusses the use of MASW method (multichannel analysis of surface waves) using the join inversion of fundamental mode with the first mode of dispersion data of surface waves, based on results from a survey in area of erosion and landslide in Ubatuba city, state of São Paulo. Here we also discuss aspects related to the acquisition, processing and data inversion. The approach of using fundamental and first mode brought greater stability in the inversion process, compared with the results using only the fundamental mode. Moreover, the method was less sensitive to the superficial layers (up to 10 meters) compared to GPR and refraction methods. The multimode inversion of Rayleigh waves was able to map deeper interfaces where the layers have distinct elastic properties (i.e. different shear waves velocities).

## Introduction

This paper presents results of MASW tests - Multichannel analysis of surface waves (Park et al., 1999, Xia et al., 1999) conducted in the region of Ubatuba, place of occurrence of many mass movements in the State of São Paulo.

The MASW method is based on the dispersive character of Rayleigh waves in stratified sites. From the seismogram is obtained the dispersion curve, which presents the functional relationship between the phase velocity and frequency of Rayleigh wave and whose behavior, ultimately depend on the characteristics of geological half-space. From the inversion of the dispersion curve can infer the vertical distribution of S-waves velocities. Empirically it has been shown that the energy of higher modes tends to become more dominant with increasing source-receiver distance. In some cases, the components of shorter wavelength of the fundamental mode are masked by higher modes of Rayleigh waves at a higher frequency range, thus hindering the data analysis. This work proposes to perform the inversion that takes into account the dispersion curves of higher modes. Where a comparison is made between the two results (only the fundamental mode and fundamental mode with higher mode) compared to geological information available in the area. We also discuss some aspects of the acquisition of data and obtain the dispersion curves and inversion.

## Method

We consider the method as a process with three phases: acquisition, processing and inversion. The acquisition involves procedures that favor the generation and recording of Rayleigh waves in a wide band of frequencies. Data were acquired with 24 geophones of 4.5 Hz in a linear array with spacing between the geophones of one meter, with hammer source of eight kilograms with a minimum offset of one, four, nine and fifteen meters.

In the process for obtaining the dispersion curves were followed the steps proposed by Lima Junior (2007) with the aim of choosing the better data and that his signal had not contaminated with these unwanted effects of near-offset and far-offset. Analyzing the maximum energy in the phase velocity-frequency dominium of the data sets acquired with the different minimum offsets employed, showed better signal-noise ratio for lower offsets as shown in Figure 1.

As it is observed that with increasing of minimum offset, the higher modes in the dispersion curves for the data acquired are evident and the main objective of this research was to study the inversion of Rayleigh waves with the use of higher modes for the treatment of dispersion curves.

In the case of the inversion process, the Surfseis software (Park et al., 1999; Xia et al., 1999) performs several iterations until obtaining the final inversion. The iterations finish after reaching the criterion of number of times (maximum 30) or the root mean squared error (RMS). The verification is performed according to the difference between the theoretical dispersion curve (generated by the initial model) and observed (generated by the raw data), making changes in the initial velocity model to adjust the curve until the real model.

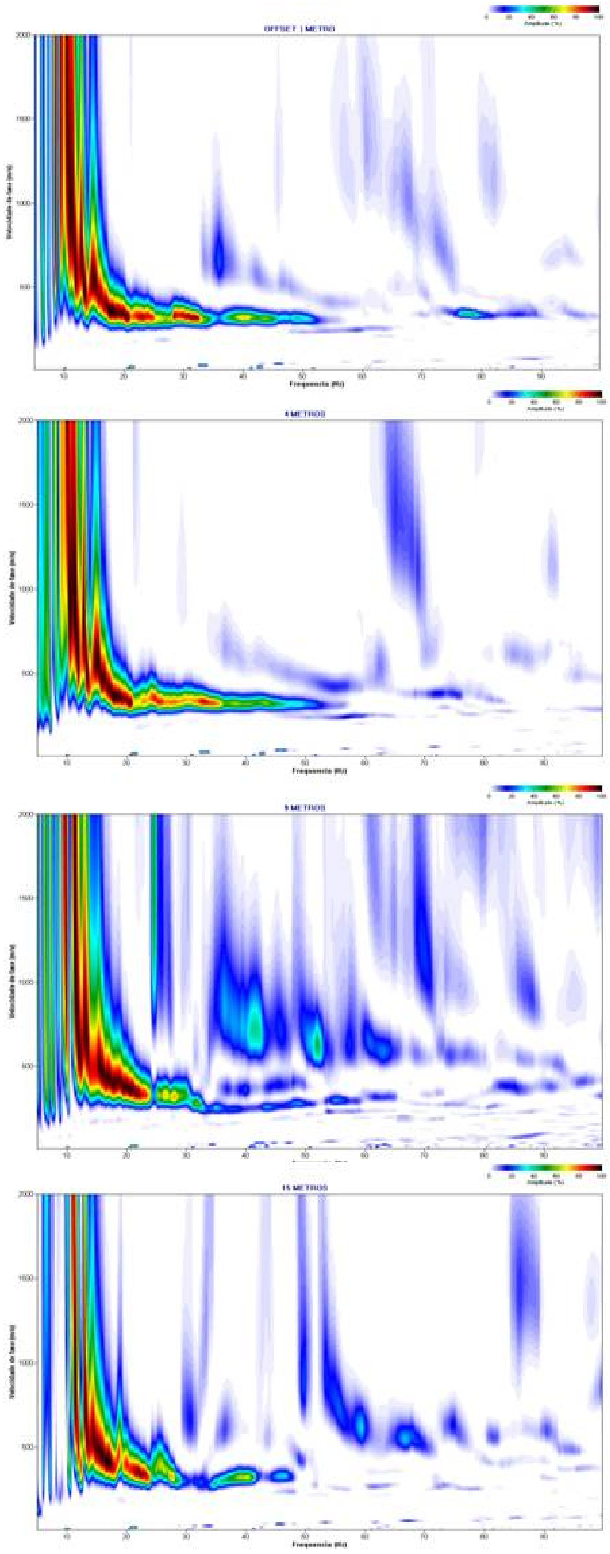

**Figure 1 –** Images of the dispersion trends from the data sets acquired with minimum offset of one, four, nine and fifteen meters.

## Results

Theoretical fundamental and first mode curves were calculated by using a forward modeling scheme and the results were compared against the real curve (picked from the dispersion trends). For the first approach we considered in the inversion process only the fundamental mode and for the other one we used both, fundamental and first modes. For the initial model we consider the following properties for the different layers: S-wave velocity, P-wave velocity, density and thickness.

Because the effects of near-offset (source very close to the first receiver) and far-offset (distant source causing large attenuation and low signal-noise ratio), we chose the data of four and nine meters to the inversion process.

The forward model for the initial inversion process for both the four and for the nine meters was the same in order that the position of the receivers was in the same area, changing only the position of the source. The final inversion for data obtained with minimum offset of four meters, resulted in distinct profiles of Vs when considering only the fundamental mode as compared with the analysis of the fundamental mode in conjunction with the first mode of Rayleigh waves (Figure 2a). The same was true for data obtained with an offset of 9 meters (Figure 2b).

In analyzing the data acquired with an minimum offset of four meters (fundamental and fundamental + first mode), there is a good correlation of Vs profile for the shallowest horizons, finding that the fundamental mode is well defined and that the final model obtained is consistent for both approaches. In the case of data obtained with the minimum offset of nine meters, the inversion process resulted in an unstable velocity profile for the shallow horizons. This may be because the data have a signal-noise ratio lower than that given to four meters and is “contaminated” by higher modes in the lower frequencies. But for deeper horizons (~ 8 m) the inversion shows similar results for both approaches.

As the focus of this paper is to examine the contribution of higher modes in the inversion in order to achieve more uniqueness for the final model, we can see a good similarity between the Vs profiles for the shallow horizons (~ 10 m), with discordance for greater depths (Figure 3). Note that the join inversion data show ever deeper profile by the fact that the same frequencies in the dispersion curves of higher modes have higher phase velocity (Luo et al., 2007).

GPR-CMP test (Ground Penetrating Radar-Common Mid Point) were conducted at the same site as well as collected soil samples, which characterized by their granulometric composition (Figure 4a). The GPR data were collected with 200 MHz antennas. The 1D profile in terms of dielectric constant versus depth are shown in Figure 4 (b).We also conducted refraction tests using the same equipment (Geode/Geometrics seismograph with vertical and horizontal geophones) in order to help the geological interpretation (Lima Junior, 2007). We analyzed the refractions data from P and S waves. The refraction data revealed a simple model of two layers with varying thicknesses along the survey. Table 1 shows the results.

Analyzing the results obtained with the MASW method, we observed the efficiency of the method in identifying the

interface located about eleven meters deep, which, correlated to the granulometric characterization data and field mapping, would be the altered bedrock composed of granite-gneiss.
Moreover, the method was less sensitive to the superficial layers (up to 10 meters) compared to GPR and refraction methods.
The multimode inversion of Rayleigh waves was able to map deeper interfaces where the layers have distinct elastic properties (i.e. different shear waves velocities). (Figure. 5).

**Table 1 -** Results of the interpretation of seismic refraction data.

| | **Thickness (m)** | **P Veloc. (m/s)** | **S Veloc. (m/s)** | **Poisson ratio** |
|---|---|---|---|---|
| **Layer 1** | 2,27 a 4,8 | 370 - 390 | 186 - 220 | 0,26 - 0,33 |
| **Layer 2** | X | 1000 - 1200 | 500 - 650 | 0,29 - 0,34 |

## Conclusions

The conclusions or important considerations that come with the development of this research can be classified under the advantages and disadvantages of the multimode inversion of Rayleigh wave data. Analyzing the maximum energy in the phase velocity-frequency plot we observed a better signal- noise ratio when employed smaller minimum offset, but it is also observed that with increasing offset, the higher modes are more distinguished. The approach of using fundamental and first mode brought greater stability in the inversion process, compared with the results using only the fundamental mode. Moreover, the method was less sensitive to the superficial layers (up to 10 meters) compared to GPR and refraction methods. The multimode inversion of Rayleigh waves was able to map deeper interfaces where the layers have distinct elastic properties.

## References

Lima Júnior, S.B., 2007. Employment of the Rayleigh waves for the purpose of geotechnical characterization of soils in a test area in Ubatuba / SP. Master's Thesis, University of São Paulo, 81p.

Luo, Y., Xia, J., Liu, J., Liu, Q., Xu, S., 2007. Joint inversion of high-frequency surface waves with fundamental and higher modes. Journal of Applied Geophysics 62, 375-384.

Park, C.B.; Miller, R.D.; Xia, J., 1999. Multichannel analysis of surface waves. Geophysics, v.64, n.3, p.800-808.

Xia, J.; Miller, R.D.; Park, C.B., 1999. Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves. Geophysics, v.64, n.3. p.691-700.

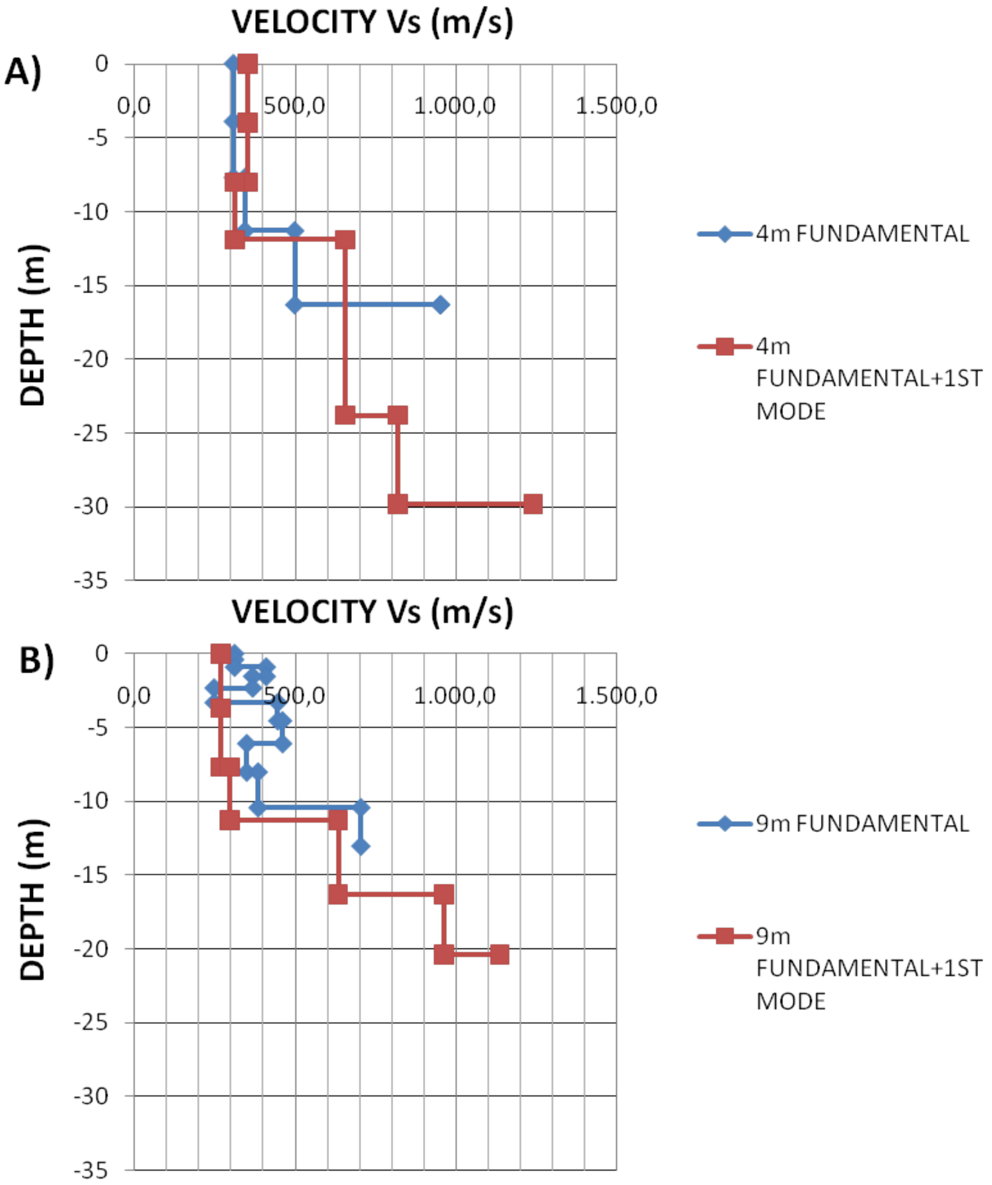

**Figure 2 -** Inversions data with offset of four (a) and nine meters (b) (with AGC gain) plotted the fundamental and higher modes and their (blue = fundamental mode, red = 1 th mode + fundamental mode).

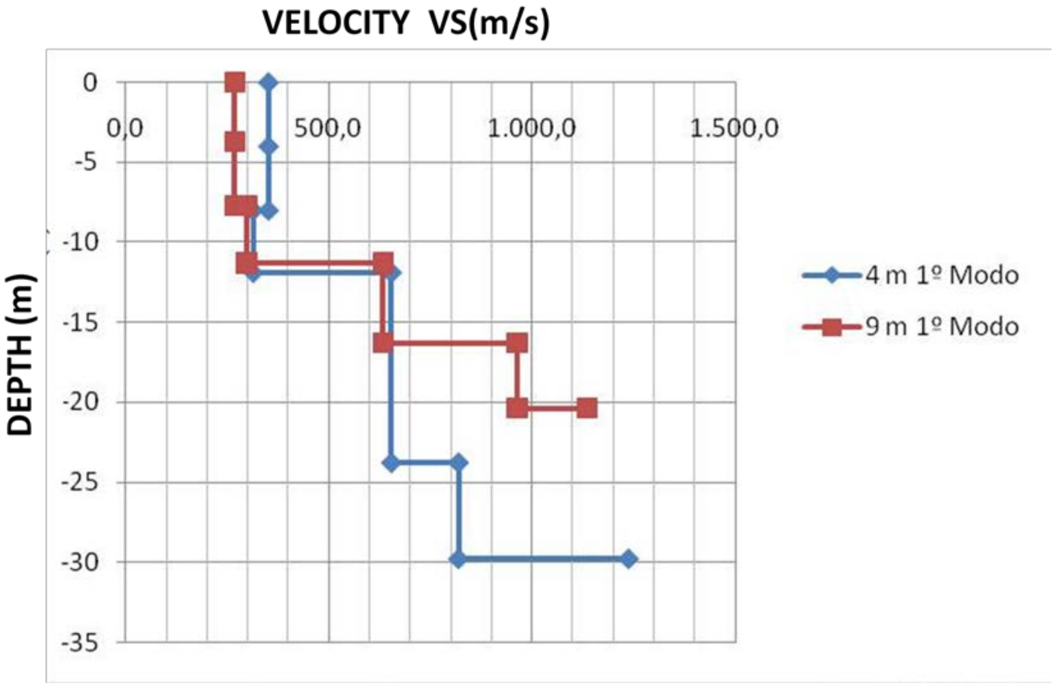

**Figure 3 -** Joint Inversion of the fundamental mode and first mode to the data of 4 and 9 meters.

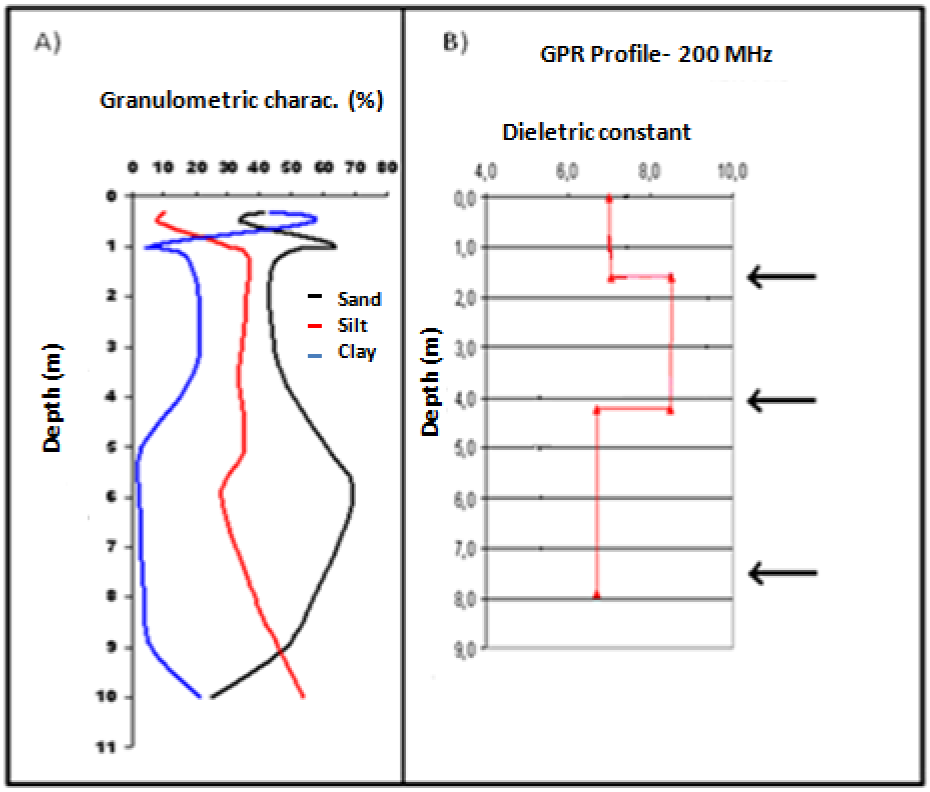

**Figure 4 -** Granulometric characterization curves (a) and GPR data with 200 MHz antenna (b) (Program for research in public policy-process FAPESP n 03/07182-5).

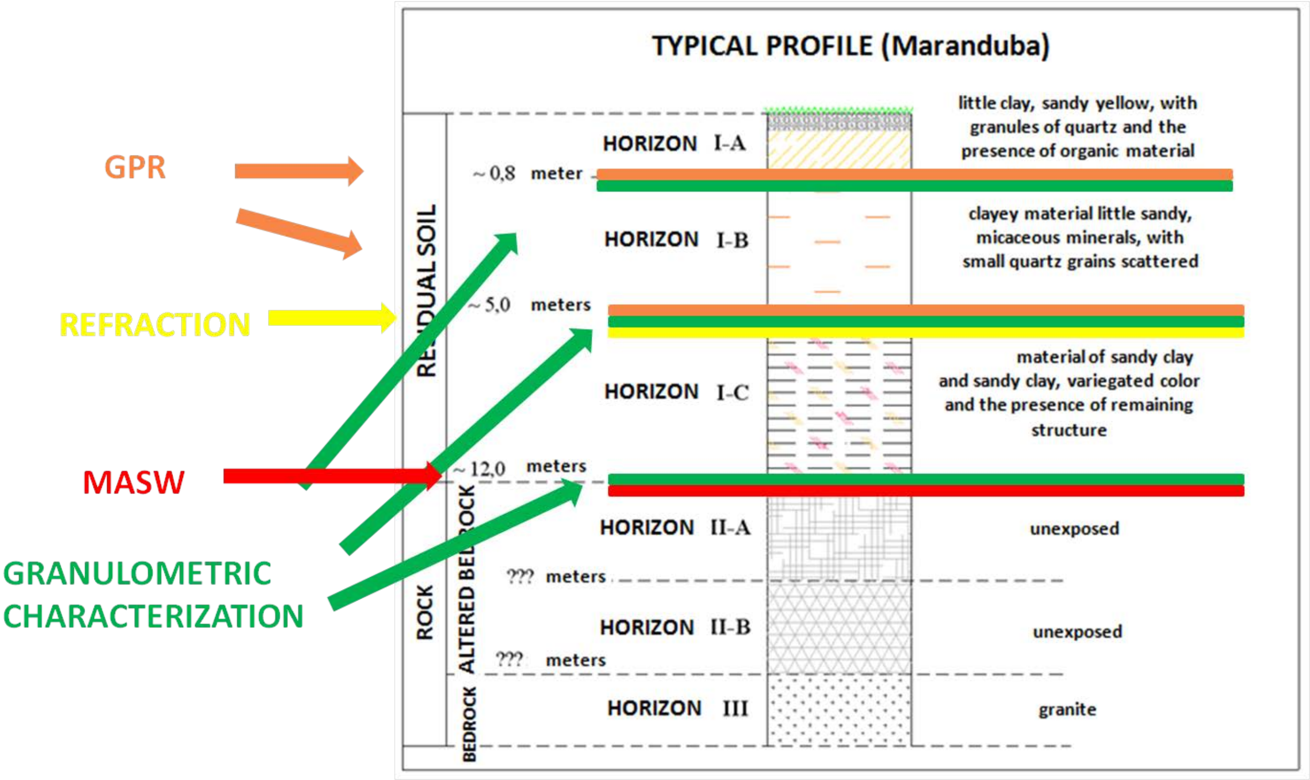

**Figure 5 -** Illustration showing the efficiency of MASW in identifying the interface in relation to other geophysical methods.