Thickness and shear wave velocity measurement of sediment package at meteorite impact crater site of Colonia , Sao Paulo City , Brazil.

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Abstract

To obtain shear wave velocity profile for near-surface application many geophysical technique are used. The most recently used approach is the joint inversion of H/V spectral ratio curve and dispersion curve extracted from multi channel analysis of surface waves (MASW) survey. However in some cases its difficult to acquired dispersion curve in engineering application frequency range 1-30 Hz. In those situation dispersion curve can be indirectly inverted from all the available points of frequency-VRayleigh curve to shear wave velocity and depth. This result a series of (s-wave velocity and depth) values through which a best fit trend can be passed. The best fit give us an idea of rate of shear wave velocity increase with depth and shear wave velocity at one meter depth. This information can later be utilized in inversion of Rayleigh wave ellipticity curve.

1. Introduction of H/V technique and geological setting of the study area.

The H/V spectral ratio method is usually applied as a tool for the seismic hazard analysis, i.e. microzonation. It is simply the ratio of two component of seismic noise wave field i.e. ratio of horizontal and vertical Fourier amplitudes of noise spectra's (Bonnefoy-Claudet et al., 2006a). Nogoshi and Igrashi (1971) were the first researchers to offer a method which is based on microtremor recordings. It became known as horizontal - to - vertical spectral ratios (referred as H / V, HVSR) method.The works of many researcher points out that information provided by this simple, low-expense method of spectral ratio of ambient seismic noise recording shows very good result in agreement with strong motion analysis. In fact, since the beginning of this method,as it was used in areas where soft sedimentary cover overlays stiff bedrock. Many authors have shown that it has been very encouraging in indication of the fundamental resonance frequency of the site. In recent years this method has been widely used in the impedance contrasts recognition between unconsolidated sediment and bedrock, and in the identification of the site based effect. The objective of this study is to utilized this method in a nearly swampy location of Colonia, Sao Paulo city, Brazil, for the thickness estimation of soft sediment package over the bedrock (basement in this case). The H/V technique is employed at Colonia site because of its geologic setting , A thick package of soft sediment overlying on hard basement rock, this unconsolidated soil rock interface give rise to very high velocity and density contrast which is very favorable for horizontal-over-vertical (H/V) application.

The Colônia structure is located in the southern suburbs of the Sao Paulo city, Brazil (fig.1). It has a circular geometry (diameter of 3,6 km) comprising an annular ring of hills surrounding a depression. The structure is mostly a swamp. Its origin is attributed to an impact of meteorite (Riccomini et al., 1989). The structure is formed in crystalline basement rocks of Neoproterozoic age and the depression is mainly filled with organic-rich sediments of Quaternary age. The main rock types of the basement comprise schist, quartzite, gneiss, migmatite, diorite, quartz-diorite (Sadowski et al., 1974).

The total depth, estimated by seismic reflection investigation (fig .1), which not reached the central part of the structure (Riccomini et al., 2011) is around 340 m (sedimentary infill plus breccia). The stacking velocity function in this investigation (fig.2) showed a continuous increment of P-wave velocity with depth, starting from approximately 1500 m/s to 2150 m/s, which is consistent with the expected increasing compaction of the sediments.

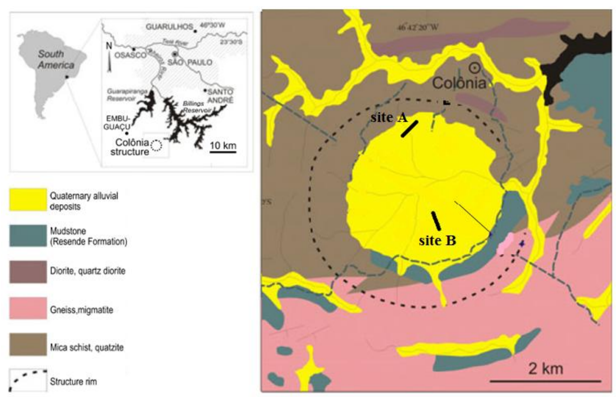

fig. 1. Location (left) and geological map of the Colonia structure. The black thick lines indicates the locations of MASW tests while thin line indicate reflection line.(modified from Riccomini et al., 2011).

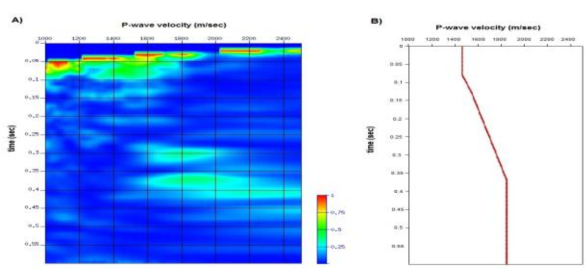

fig.2 - Semblance plot with panel at middle (A) and (B) stacking velocity function of cdp gather 750 from Colonia seismic reflection investigation (P-wave) (modified from Riccomini et al., 2011).

2. Methodlogy and Objectve of the studty

H/V curve techniques are strongly conditioned by the properties (depth and impedance contrast) of the interface between the soft sediment and the bedrock (Parolai et al., 2005) while it is poorly informative about the s-wave velocity of the sedimentary layers. On the other hand the dispersion curves of array technique (i.e. MASW , multi channel anaylisis of surface waves park et, al .1999)) constraints mainly the s-wave velocity structure of the subsurface soil. However, dispersion curve provides very uncertain information about the deep subsurface specially below the fundamental frequency of site due to filtering effect of media, Therefore, when either H/V or dispersion curves are used singularly for the subsurface structure retrieval, there is a un-resolvable trade-off between the model parameters (velocity and thickness of the soil layers) that hampers the inversion analysis results. To overcome this trade-off between the model parameters, can be achieved by joint inversion of H/V and dispersion curve.However to acquire MASW and ambient noise recording at same site might not be possible due to some local problem in field seting like accessibilty such as in the Clonia sturcure, where most of the strucure is coverd by heavy vegitation and water , it is diffcult to acquire MASW and ambient noise recording at same sites, to map the sediment package thickness estimation. we suggest here an aproach in which the average shear wave velocity increase trend with depth can be obtianed from direct inversion of dispersion curve. Which is assumed to be the representative for the whole area (i.e the Colonia sturcture, the geology of crater is not changing to much with the Colonia crater strucure vicintiy). The aproach was that at any accessible location of the structure an experimental dispersion curve can be obtained through MASW (fig.1). the MASW survey perofrmed at two diffrent (fig.1) location with in the Colonia crater structure . For the estimation of H/V curve, we need ambient noise recording on three components (two horizontal and one vertical) which were obtained by 7 ambient noise measurement at 6 different locations shown in (fig. 3) with a broadband 3 component seismometer Nanometrics Trillium compact 120-s. The ambient noise wave field measurements were made for 5 hours at five locations while 24 hours at CLN4 and CLN5 stations(fig .3), the recording was increased because of the nearby agricultural activity so to avoid cultural noise.The ambient noise roecording has been made following the guidelines developed under the SESAME (2004) recommendations. To obtain the fundamental frequency of the site a window of one hour recording were processed and the reliability condition proposed by SESAME (2004) for the H/V curve and peak were followed, fig.5 indicates the H/V curves of all stations.

Table 1. MASW acquisition parameters for active and passive source

Type of MASW	Active	Passive
Source	Sledgehammer 10 kg	Cultural noise
Minimum offset (m)	1, 5, 6	_____
Geophone interval (m)	1	1
Number of Geophones	96	96
Length of the array (m)	95	95
Sampling interval (ms)	0.5	--------
Record length (s)	1	15, 20, 30

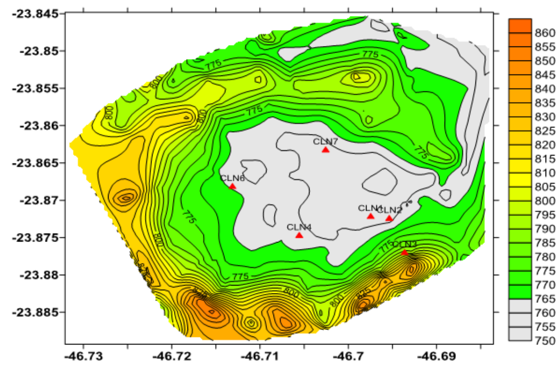

fig. 3.Topographic contour map (contour interval 5m) of Colonia structure. Triangles indicate the location of stations used for ambient noise recording. CLN4 and CLN5 are at same location that's why we showed here only CLN4. (Legend bar on the right shows the scale of contours in m).

The dispersion curve retrieved from MASW by analyzing all data (fig.4) are obtained only in a narrow frequency band (1.1-3.8 Hz) fig.4d. MASW survey of these two different sites A and B (fig. 1) are analyzed, the dispersion image of MASW arrays are given in fig. 4a, b, c. At site A the active source data does not give a clear dispersion image that's why it is omitted from the analysis. The experiential dispersion curve obtained from the data are zoomed in (for clear visibility in vertical scale) (fig. 4d)

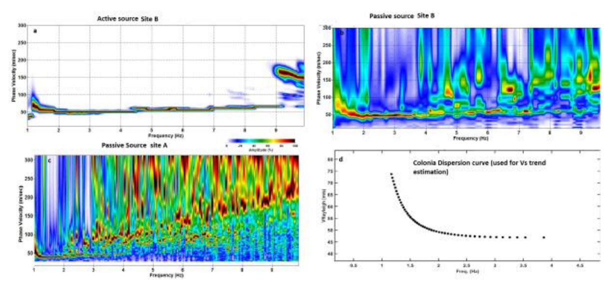

fig.4 shows dispersion curve images of experimental records of site B (velocity in dispersion curve images is in m/sec). (b) Dispersion curve images passive source at site B (c). Dispersion curve images of passive source of site (d). Experimental dispersion curve obtained from data at Colonia is shown in the bottom (used for vs-velocity trend estimation).

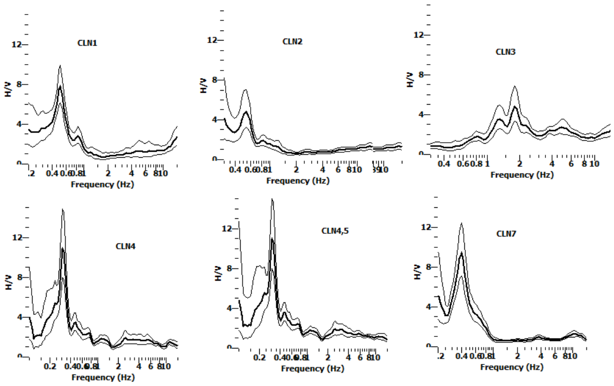

fig. 5. H/V curves of all stations. All the curves are obtained by fulfilling the criteria for clear curve and peak, bold-line is the H/V curve, lower and upper narrow lines indicate upper and lower bound of standard deviation.

3. **Average shear wave velocity increase trend and composite sediment thickness (h)**

The rate of increase of average shear wave velocity for engineering application up to the bedrock is thoroughly investigated by Parolai (et al., 2002) and D'Amico et al., (2008). The average shear wave velocity increase trend up to bedrock can be written in general form as follows

$$\mathbf{VS(z)}= \beta_0(1+z)^b \text{ equation 1}$$

where Vs(z) is the average shear wave veloctiy upto bedrock β_0 is velocity at one meter depth, b is the rate of increase of shear wave velocity with depth up to bedrock. T.T Tuan et al., (2015) derived an excellent mathematical procedure to calculate an approximate formula for composite thickness (h) of n arbitrary layers over the bedrock. The derivation of the formula is beyond the scope of this study that's why we limit ourselves only to the final result which is given as

$$\mathbf{h} = \left(\frac{\beta_0^2(1-b)}{2\pi^2}\right)^{\frac{1}{2(1-b)}} f_0^{\frac{-1}{1-b}} \text{ equation 2}$$

where **h** is composite thickness of sedimentpackage upto bedrock , f_0 is fundamental peak frequency of H/V curve The procedure we are using here required an approximate idea of two parameters β_0, b for eq.2 (as fundamental frequency is easily obtained from H/V curve peak). The probable values of these two parameters can be obtained from the suggested relationship found in literature for different geologic materials (i.e., for compact soil β_0=210 m/s and **b**=0.20, for sandy soil β_0=170 m/s and **b**=0.25, for very recent soil β_0=110 m/s and **b**=0.40) The most reliable values of β_0 ,**b** can be obtained from the borehole data or by some other preliminary geophysical survey (D'Amico et al.,2008), however borehole are rarely available at each site. To overcome this problem we are suggesting these values can be obtained indirectly by the interpretation of effective Rayleigh dispersion curve. The fundamental mode of the Rayleigh wave dispersion curve coincides with the above framework of rough idea of parameter β_0, b.to obatined these values of β_0, b , a direct inversion of dispersion curve is made, for each point of dispersion curve coressponding shear wave velocity and depth are estimated by using a rough approximation by

$$VS_h = 1.1VR(f) \quad \text{Depth } h = \frac{VR(f)}{2f} \quad \text{equation 3}$$

where VSh , h , is shear wave velocity and depth at given point , the direct inversion of dispersion curve are achived by using the eq.3 for all points of dispersion curve,the VSh and h values obtained from ecah point of dispersion curve are obtained and ploted, a best fit line are pass through these VSh and h values to obtained the near surface s-velocity inrease trend with depth fig.6 . The best fit gives the value of b and $\beta_0$value , the value of β_0 is taken directly from dispersion curve at higher frequency (50 m/s in this case) β_0, b values along with peak frequency of each site (table.2) are input to eq. 2 , and thickness of corresponding H/V roecorded sites (fig.6) are obtained.

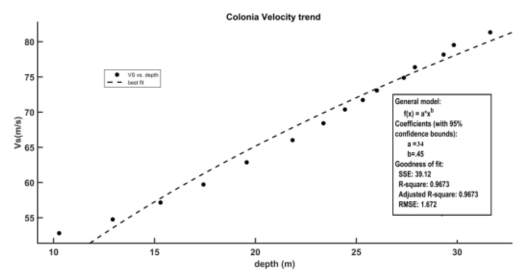

Figure 6. Best-fit through shear wave velocity and depth which give value of b=0.45.

Table 2. Shows the fundamental frequency of each station and their corresponding thickness estimated from equation (2).

Stat. name	f_0	$f_0^{\frac{-1}{1-b}}$	$\left(\frac{\beta_0^2(1-b)}{2\pi^2}\right)^{\frac{1}{2(}}$	h
CLN1	0.50	3.52	47.3	166
CLN2	0.52	3.28	47.3	155
CLN3	1.9	0.31	47.3	15
CLN4, 5	0.31	8.40	47.3	397
CLN6	0.31	8.40	47.3	397
CLN7	0.38	5.8	47.3	274

4.Inversion for the shear wave velocity retriravial;

For the inversion of ellipticity and to sample the parameter space we have employed neighborhood algorithm (NA) (Wathelet , 2008) which is a derivative-free method as compared to the linearized method (Meneke 1989). NA belong to family of global optimization inversion strategies like genetic algorithm and the simulated annealing. Sambridge (et al., 2002) have reviewed in detail the theoretical aspect and application of this inversion approach. NA is considered very good inversion strategy because it has the advantage over the other approaches as it utilizes all previous model information to sample the new model (Sambridge 1999). The misfit is estimated using eq.(4)

$$\mathbf{misfit}_{\mathbf{Ellipticity}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\log(\mathrm{Emod}) - \log(\mathrm{Eexp})}{\sigma i^2}\right)^2} \quad \text{equation 4}$$

where Eexp is an experimental ellipticity curve at frequency f, Emod is modeled ellipticty curve at frequency f, σ_i is the associated measuring errors and N is the frequency sample number.

The H/V curve are considered as Rayleigh elliptic curve ,which is employed in almost all H/V curve inversion alogorithm , however the H/V curve is not the true represntative of Rayleigh wave ellipticity , as both Rayleigh and Love waves contribute to the H/V spectrum (Bonnefoy-Claudet et al., 2008) and the presence of both surface wave types has to be considered for inversion algorithms. Therefore, the proportion between Rayleigh and Love waves in the noise wave field has to be inferred or assumed prior to the inversion. to over comethis problem and minimize the contribution of Love wave to the horizontal component of H/V curve Hobiger (et .al, 2009) proposed a technique - known RayDec for the estimation of Rayleigh wave ellipticity from a single three component sensor by utilizing the vertical component as a master trigger and stacking a large number of horizontal components. (see for detail Hobiger et al., 2009).We have employed RayDec to obatined ellipticity curve for each ambient noise recording site. The right flank of the ellipticity is used for inversion analysis (Hobiger et al., 2013). However left flank is considered here to put constraints on the peak frequency of ellipticity curve(H/V) .We used the 30% of the peak frequency length on the left flank and double the peak frequency on the right flank. The rest part of ellipticity curve is not considered for inversions.The shear wave velocity increase trend and sediment package thickness (h) are input to the inversion of ellipticity curve and inversion profiles are obtianed. (fig.7).

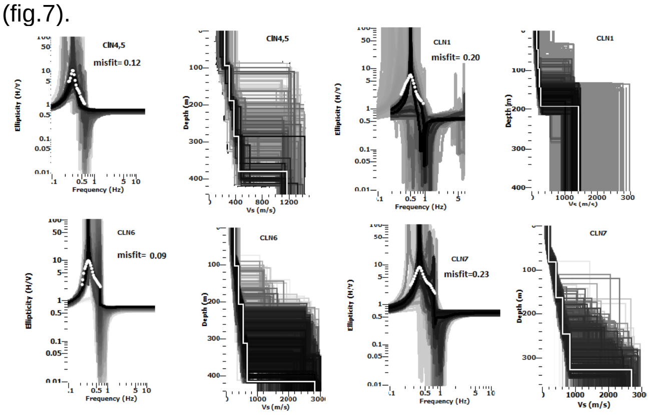

Figure 9. Inversion profiles and misfit values for CLN4,5 , CLN1 ,CLN6 and CLN7. Lowest misfit model profile of VS is shown in white for all the stations.

4. Discussion and Conclusion

The result of the H/V curves here follows the trend of local geological setting (Colonia). The CLN4,5 and CLN6 shows the same fundamental resonance frequency which based on this type of interpretation approach give the thickness of soft soil to be around 400 m. Riccomini (2011) shows the thickness of soft sediment around 340 m by using reflection seismic at different but almost same peripheral position of the Colonia circular structure. The thickness of sediment toward the edge of the bowl shape structure decrease which is identifiable from the station CLN3 which shows a thickness of 15 meter. As we know from previous discussion that an ellipticity inversion alone would yield ambiguous results. If information constraining the superficial shear wave structure is added, the ellipticity inversion can then be used to constrain the deeper part of the structure. However, in case of very deep bedrock and when the obtained experimental dispersion curve are showing only a part of the whole dispersion curve and not the complete curve because of the local geological setting. So how to use this experimental curve information for the joint inversion is trying to address in this paper. To constraint the superficial shear wave velocity in those situations can be added to the inversion by finding out the trend of shear wave velocity increase with depth from the utilization of that narrow frequency band experimental dispersion curve by best fitting of VS-depth values. Which gives information about the s-velocity increase trend with velocity at one meter depth in addition. The fundamental frequency $(\mathbf{f_0})$ along with s-wave increase trend (**b**) and s-wave velocity at one meter depth $(\boldsymbol{\beta_0})$ are used to find composite thickness (**h**) of sediment package. All these information can be provided to the ellipticity curve inversion at the end to get shear wave velocity 1D profile.

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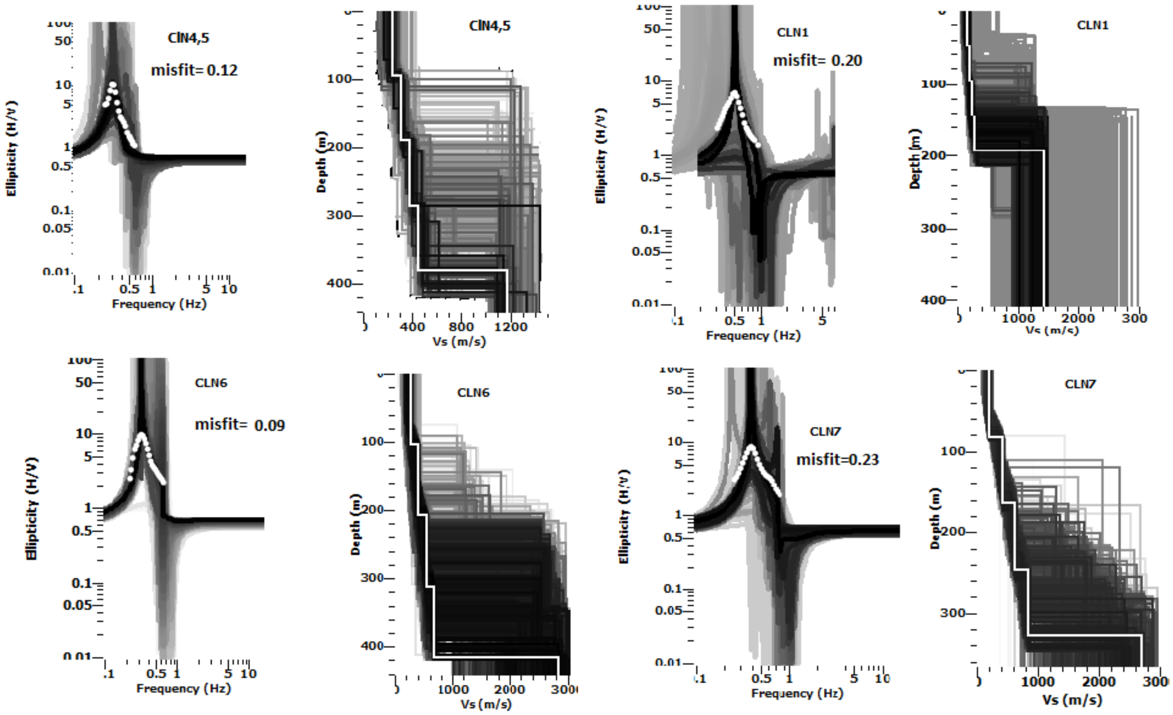

figure7

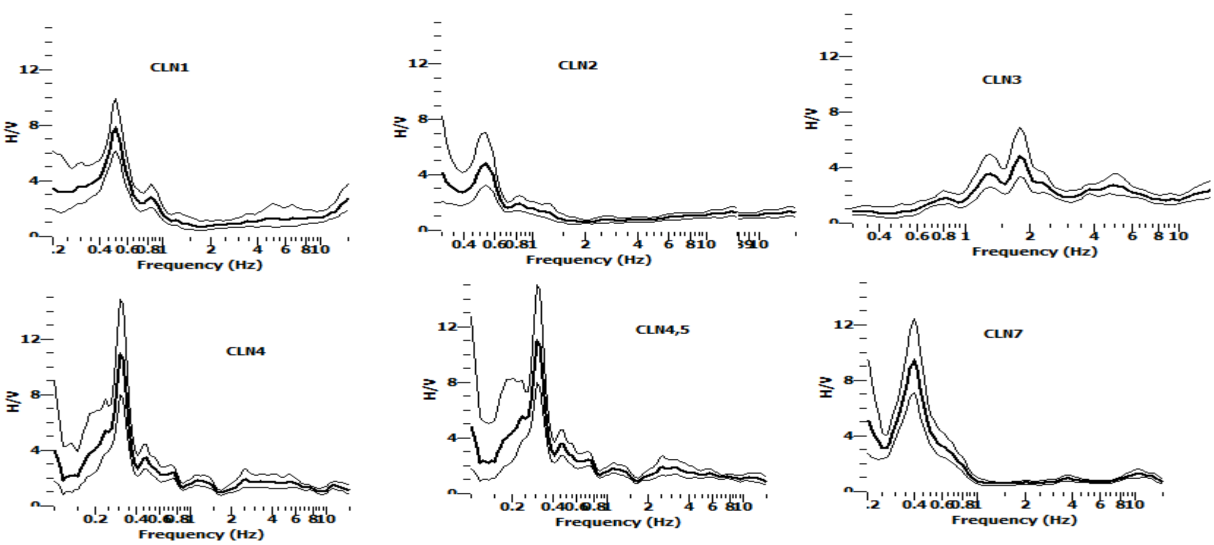

figure 5