SUBSURFACE SHEAR WAVE VELOCITY ESTIMATION BY COMBINATION OF HVSR AND MASW METHODS

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ABSTRACT

Shear Wave Velocity (Vs) down to seismic bedrock provides information about subsurface geological structures and is an essential parameter for evaluating seismic hazard evaluation and reducing of earthquakes consequences. Shear Wave Velocity can conventionally be evaluated applying several seismic methods, but non – invasive shallow seismic methods like S – wave refraction and Multichannel Analysis of Surface Waves (MASW) appear to be the most appropriate in terms of time and cost efficiency, and urban area complications if using invasive methods for Vs evaluation. When surveyed in urban areas, other difficulties might be present. S-wave refraction method has a restricted depth penetration because of weak source while MASW method is restricted in penetration depth because of high frequency waves. Horizontal to Vertical Spectral Ratio (HVSR) is based on ambient noise measurements and is effective when surveying in urban areas to determine the predominant frequency of the soil. The Shear – Wave velocity could be obtained by inversion modeling of HVSR. The application of Vs model obtained from MASW to HVSR curves is a means to address the generation of a Vs soil model for higher depth level. Combining MASW results with Horizontal to Vertical Spectral Ratios (HVSR) method might be a reliable solution to soil characterization and S – wave velocity estimation. In the present paper, the data obtained from a test point in Tirana city for the Vs estimation by the combination of MASW and HVSR methods are reported.

***Keywords*:** Shear Wave Velocity, HVSR, MASW, soil model, ambient noise

1. INTRODUCTION

The behavior of seismic waves during an earthquake is very important for the specialists involved in the area and site amplification is a determinant factor in understanding that behavior. Shallow, soft surface layers may modify seismic signal characteristics by ground motion amplification. This phenomenon is called site effect and produces earthquake damages at a larger scale than expected. Several earthquakes in the past (Mexico 1989, Kobe 1995, Izmir 1999 etc.) showed the effect of seismic waves amplification. Albania is a seismically very active country. Duni *et al.*, (2010) said that the strongest earthquake hitting Tirana had these characteristics: Ms=5.4 and intensity Io=7-8 degree (MSK-64). The induced surficial effects showed the effect of ground conditions to the intensity of the earthquakes. Tirana is characterized by several earthquake events with Io=8 degree (MSK-64). Several earthquakes of magnitude M=5.3-5.6 hit Tirana in the last century (Duni *et al.*, 2010).

The buildings with natural period of vibration equal or close to ground natural period has been damaged seriously compare with other buildings vibrating in different period because of resonance phenomena that can increase vibration amplitude (Keçeli and Cevher 2015) of the buildings.

The Shear – Wave Velocity (Vs) is a key parameter for buildings construction because of dependence of elastic stiffness on the near surface material with response of the buildings. Vs estimation is valuable for the soil response to earthquakes and seismic susceptibility analysis in urban areas (Stephenson *et al.*, 2015). Several seismic methods can be used to evaluate shear – wave velocity. Some invasive seismic methods like cross – hole, down – hole, up – hole or PS logging tests have an accurate evaluation of Vs but using these methods is very difficult in urban areas in terms of cost, time and infrastructure. Other non-invasive methods like S wave Seismic Refraction, Multichannel Analysis of Surface Waves (MASW), Spectral Analysis of Surface Waves (SASW) Spatial Autocorrelation (SPAC) or Refraction Microtremor (ReMi) are more appropriate to be used in evaluating shear – wave velocity in urban areas. Conventionally, the problem of Vs estimation in greater depth is resolved by combination of Horizontal-to-Vertical Spectral Ratios (HVSR or Nakamura's) technique, which is based on ambient noise measurements and seismic methods such as Multichannel Analysis of Surface Waves (MASW) method.

Horizontal to Vertical Spectral Ratio (HVSR) method

The HVSR method was presented from Nakamura (2000) who used Vertical to Horizontal Spectral Ratio to estimate fundamental frequency (f_0) in presence of artificial tremors. This technique has been used successfully in site characterization (Gosar and Lenart 2010; Manne *et al*., 2012; Tun *et al*., 2016) and is well – accepted as very effective in urban areas. The H/V method has been widely used in microzonation studies to predict site response to earthquake seismicity, to estimate unconsolidated sediment thickness and to map the bedrock surface and fault locations.

HVSR method is considered as "passive" seismic method because it does not require an artificial seismic source, such as an explosive charge or hammer blow (https://water.usgs.gov/ogw/bgas/hvseismic/). Microtremors induced by wind, ocean waves, human activity etc. are the main natural sources that are measured in three components to determine and evaluate the fundamental seismic resonance frequency of a site through spectral ratio analysis of horizontal and vertical ambient seismic noise.

Ibs-von Seht and Wohlenberg (1999) said that for a two-layer model relation of the seismic resonance frequency and sediment thickness is given by:

$$h = a \cdot f_0^b$$

For sites that can be approximated as a two-layer model (Figure 1), the seismic resonance frequency, f_{rn}, of the n^{th} mode is related to sediment thickness, *Z*:

$$f_{rn} = (2n+1)\,(V_s / 4Z) \text{ where:}$$

V_s - average shear-wave velocity of the sediment layer overlying bedrock (in m/s),

If n= 0, fundamental resonance frequency, f_{r0} is obtained. Delgado *et al*., (2000) computed the H/V spectral ratio as:

$$H/V_{(\omega)} = \sqrt{\frac{S^2(\omega)_{NS} + S^2(\omega)_{EW}}{2S^2(\omega)_V}}$$

where:

[$S(\omega)_{NS}$ and $S(\omega)_{EW}$] term is the horizontal spectra of the ambient seismic noise

[$S(\omega)_V$] is the vertical spectra of the ambient seismic noise

ω- the angular frequency.

Sediment thickness, *Z,* and resonance frequency can be given by relation:

$$Z = af_{r0}^{\,b}$$

Where *a* and *b* are determined empirically from non-linear regression of f_{r0} data acquired at sites where *Z* is known.

Multichannel Analysis of Surface Waves (MASW) technique

The MASW technique was introduced by the Kansas Geological Survey (Park *et al.*, 1999). The MASW method involved multichannel recording and processing techniques that are similar to those used in conventional seismic reflection surveys (Olafsdottir *et al.,* 2018). The MASW method has improved the characterization of dispersion relationship by sampling spatial wave-field with multiple receivers. It makes identification and isolation of the noise possible and only one-shot gather is needed. Vertically polarized Rayleigh wave is used for the geotechnical surface wave surveys. The propagation velocity of a Rayleigh wave in heterogeneous medium is dependent upon the wavelength (or frequency) of that wave. Short wavelength will be influenced by material closer to the surface, while longer wavelength Rayleigh waves are reflecting the properties of deeper material. Dispersion of Rayleigh waves (dependence of phase velocity on frequency) is used in sampling shallow and deeper materials. Dispersion is used to produce dispersion curves or correlations between velocity and frequency (or wavelength). By inverting this curve shear wave velocity can be obtained, considering that S – wave velocities are the main influence on dispersion curve. This inversion is updated until the synthetic dispersion curve closely matches the field curve.

Geology and geomorphology of Tirana

Tirana city is part of the PreAdriatic depression, in southern part of Molasses synclinal of Tirana which gradually deeps northwest, towards the Adriatic Sea. Tirana syncline is around 80 km long and 10 – 12 km wide and is considered an asymmetric syncline. Aliaj *et al.,* (2003) said that it consist of Miocene molasses (overlaying transgressively the carbonate – flysch structures of Ionian and Kruja zones) and partly by Pliocene molasses in the north. Miocene molasses is represented by Serravallian, Tortonian and Messinian deposits.

Serravallian deposits are 600 m thick and are represented by lithotamnic and organogenic limestones in the lower part and clays and sandstones in the upper part. Tortonian sediments are represented by clays and in upper part by clay – sandstone combination, 100 -200 m thick. Messinian sediments are represented by massif sandstones with clay and alevrolites interlayers. They are approximately 1500 m thick. Pliocene deposits are represented by a 500 m thick and stone – alevrolites – clays combination. From Tirana city towards northwest, the syncline is covered by alluvial Quaternary sediments overlaying molasses Miocene – Pliocene deposits (Figure 1).

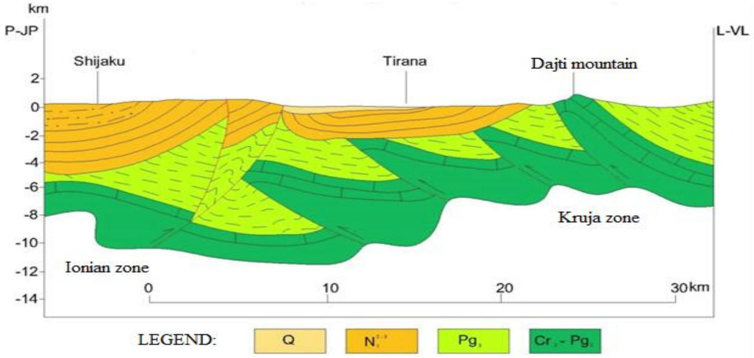

Fig. 1: Geological section of Shijak – Dajti Mountain line (Aliaj, 2000) *Q- Quaternary sediments mostly represented by coarse gravels combined with clay – sand layers,* N_1^{2-3}*– Neogene deposits (Pliocene – Miocene deposits) mostly lithotamnic and organogenic limestones, sandstone- alevrolite clays combination.* Pg_3*– mostly Flysch of Kruja zone,* Cr_2 *–* Pg_2*– Limestones, limestones flysch.*

The Quaternary sediments are represented by the coarse gravels combined with clay – sand layers. These deposits are around 15 – 20 m thick in Tirana city and gradually thicker towards north (up to 200 m, near Mati River).

Tirana city is located at the most southeastern part of lowland area, around 100 – 140m above the sea level. The depression is surrounded in the East, South and West by hills of low altitude, mainly consisting of molasses deposits dating since the Miocene. The structure is graben like, bounded in the west from Preza backthrust and in the east from Dajti thrust (Aliaj et *al*., 2001). Compressional faults are currently active and generate earthquakes. Aliaj *et al*., (2010) said that earthquakes of magnitude 5.7 Richter and epicentral intensity VIII MSK-64 are generated and registered in this fault area.

Estimation of V_S by HVSR and MASW methods combination

Active source MASW methods and HVSR method have been applied to estimate the VS and the predominant frequency f_0 estimation, respectively, at the test points in Tirana (Karriqi 2016). A 24 channels Geode seismograph was used for the MASW surveys. Tromino was used for the microtremors surveys. Also, historical geotechnical data (Koçiaj *et al*., 1988; Konomi *et al*., 1988) were considered and used to generate the H/V curves of geotechnical models involving the Grilla software (Moho srl). It employs codes that generate synthetic H/V curves based on the simulation of the surface-waves field in plane-parallel multi-layered systems. Synthetic generated curves are compared with factual H/V curves from micro-tremor surveys. An equal procedure was used for the Vs generated from MASW surveys. In the present paper, data obtained from the Test Point 1, in Tirana, Albania, to illustrate Vs estimation by the combination of MASW and HVSR methods are reported.

Figure 2 depicts the Test Point 1 located in an old football field, near "Qemal Stafa" stadium and surrounded by a construction site (new stadium, different buildings etc.).

Fig.2: Location of Test Point 1 (from Google Earth).

Historical data from "Seismic Microzonation of Tirana" project (Koçiaj *et al.,* 1988; Konomi *et al.,* 1988) categorized this site as part of geotechnical zone IV_3^b which parameters are in the Table 1 reported. These parameters were used to generate synthetic H/V curve for this site (Figure 3) and to compare it with the factual curve from micro-tremors survey. Results reported that the geotechnical model does not generate the same curve in terms of frequency picks as the factual one. The factual H/V curve shows three frequency picks: 45 Hz, 2.8 Hz and 1.53 Hz. Synthetic H/V curve generates two picks: 26.5 Hz and about 7 Hz.

Table 1. Geotechnical model of zone IV_3^b (Koçiaj *et al.*, 1988; Konomi *et al.*, 1988)

Thickness (m)	Vs (km/s)	Volumetric weight (T/m^3)
1.0	150	1.45
1.5	250	1.6
1.5	350	1.74
3.5	350	1.74
5.0	450	2.0
	700	2.1

This geotechnical model does not represent this specific site but rather a broader area. This might be the reason that synthetic H/V curve generated from this model does not fit with factual curve generated from micro-tremors surveys at Point Test 1.

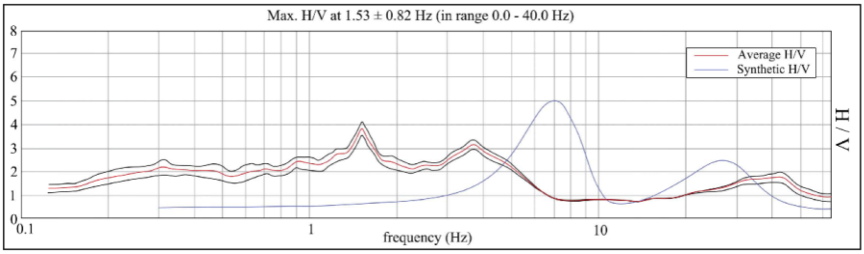

Fig. 3: Comparison of factual and synthetic curve generated from geotechnical model IV_3^bat Test Point 1

A Vs profile model was generated from MASW data processing and interpretation for the Test Point 1. This Vs profile model can be used to generate a synthetic H/V curve. Figure 4 depicts the Vs profile model generated from MASW data processing. MASW data processing generates a Vs profile model represented by two layers. Layer 1 has these characteristics: Vs = 270 m/s and a thickness of 21 m. Layer 2 has these characteristics: Vs = 500 m/s and undefined thickness. The mean volumetric weights of layers material for this Vs interpretation are 1.6 (T/m^3) and 1.8 (T/m^3), respectively. Data reported that Vs30 = 310.7 m/s. The depth interval where MASW data are confident is from 2m to 38 m deep (Duni 2011).

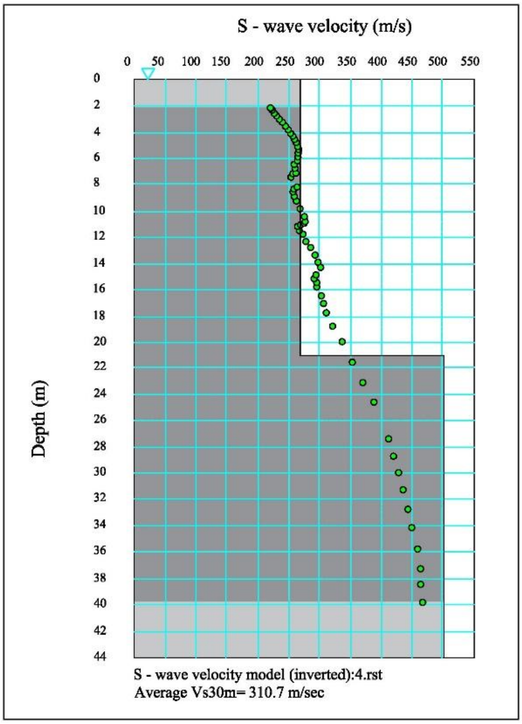

Fig. 4: Vs profile model generated from MASW data processing at Test Point 1.

The Vs and volumetric weights of layers interpreted from MASW surveys are used for the synthetic H/V curve generation (Figure 5).

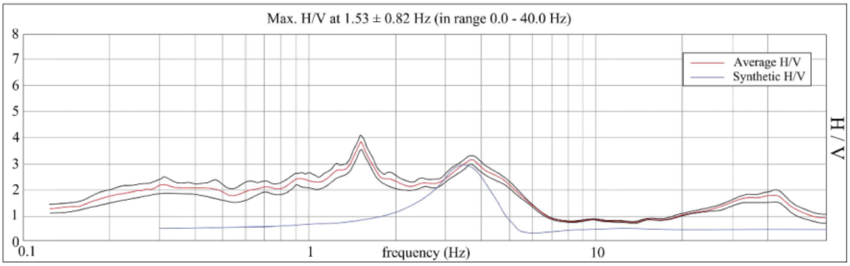

Fig. 5: Comparison of actual curve and synthetic curve generated from MASW in the Test Point 1.

As can be denoted by the comparison of synthetic and factual H/V curves, all the curves match at 3.8 Hz pick. Picks at frequencies 45 Hz and 1.53 Hz are not represented in the synthetic curve due to the 45 Hz pick caused by the near surface layer (from the surface to around 1m thick) consisting of grated coal and fine coarse gravel mixture used for better drainage of surface waters. At this depth MASW has a lack of data. Also, the 1. 53 Hz pick is caused by a layer located deeper than MASW maximal depth of study.

To determine the layer that causes predominant frequency pick at 1.53 Hz, a model is generated with the same parameters of MASW interpretation from the surface to the 38 m of depth (which parameters proved to generate a synthetic H/V curve fitting factual H/V curve) and, using different parameters, try to model a layer at depth which will generate a pick at 1.53 Hz, fitting with factual H/V curve (Figure 6).

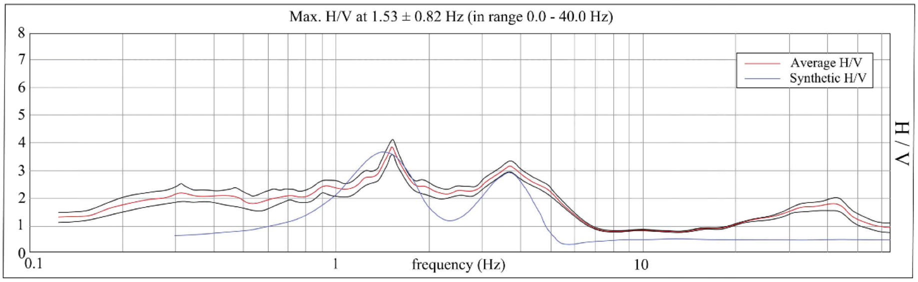

Fig.6: Modeling a layer at depth which will generate a pick at 1.53 Hz at Test Point 1.

The pick at frequency 3.8 Hz is related to Vs model obtained from MASW data interpretation and is caused by a layer boundary located at 21 m of depth. The upper layer (or the first Layer) has a Vs = 270 m/s while the lower layer (Layer 2) has a Vs= 500 m/s. The 1.53 Hz pick is caused by a layer boundary located at 100 m of depth. According to HVSR interpretation the third Layer has a Vs= 900 m/s. The Vs model obtained from the H/V synthetic curve in the Test Point 1 for a three-layer model is in Figure 7 depicted.

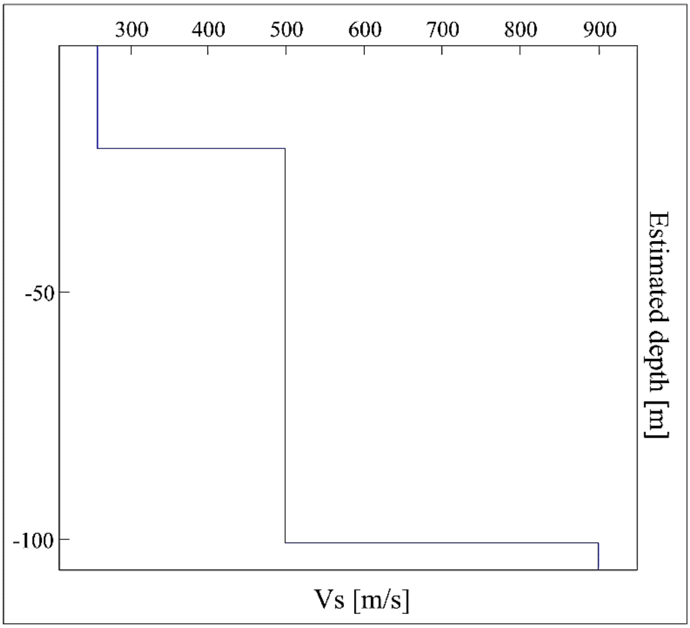

Fig. 7: Vs model by synthetic H/V curve for a three-layer model at Test Point 1.

2. CONCLUSIONS

The Horizontal to Vertical Spectral Ratio (HVSR) method reveals valuable information about the characteristics of the subsurface and helps us to construct the subsurface model. Combining and integrating information obtained from HVSR and MASW methods results in a more reliable subsurface model. Such combination provide the Vs model for the uppermost tens of meters (MASW results) while, HVSR method provides additional information and constraints for the subsurface model for significantly greater depths.

Generating and comparing synthetic H/V curves obtained from geotechnical model with factual H/V curve generated from micro-tremors surveys of the site where Test Point 1 is located does not show any match to the actual specific site.

Synthetic H/V curves generated from MASW data interpretation matches with factual H/V curve at 3.8 Hz pick. Picks at frequencies 45 Hz and 1.53 Hz caused by a near surface layer and from a deep layer respectively are not represented at synthetic H/V curve. MASW method suffers a lack of data in near surface (first two meters) and at greater depths.

This lack of study at greater depth may be compensated by HVSR method. To determine the layer that causes predominant frequency pick at 1.53 Hz, a model is generated which maintain the same parameters of MASW interpretation and, try to model a layer at depth using different parameters, which will generate a pick at 1.53 Hz, fitting with factual H/V curve. If the best fit is obtained, a Vs profile from the near surface to the greater depths could be generated. In our case at Test Point 1, a boundary at 100 m of depth is determined. MASW and HVSR methods combination results very effective, practical and easy to use (comparing with other methods) in urban areas, helping to determine Vs profiles of underground layers.

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