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Mapping the soil thickness in the Main Ethiopian Rift using passive seismic data and HVSR, case for Northern water divide between the Ziway-Shala lakes basin and the Awash basin

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ABSTRACT: A passive seismic survey was conducted in the northern water divide between the Ziway-Shala Lakes Basin, Central Main Ethiopian Rift (CMER), and Awash basin. Previous geophysical studies in the same area had mainly focused on mapping intermediate to deeper Earth geological structures, and little attention given to shallowest layer. In contrast, this study aimed to map these shallow geologic structures of soil layer undulations at this specific location of CMER. A rapid and non-invasive technique was employed, which involve recording three component measurements of ambient seismic noise data. The collected seismic noise data was processed and analyzed using the average of Horizontal to Vertical Spectral Ratio (HVSR) which helps to determine resonance frequencies of the survey stations. After frequency estimates were made for each station, corresponding depth estimates were obtained using the method of Nakamura. The point depth to the shallowest layer was determined for each site and these depth values were gridded and mapped to show subsurface topographic undulations or thickness of topsoil cover. The result showed that the shallowest bedrock layer was thickening northwards, toward the Awash basin.

Key words/Phrases: passive seismic, bedrock, spectral ratio, resonance frequency, undulation

INTRODUCTION

The Central Main Ethiopian rift (CMER) where the current study area is located is a tectonically and volcanically active region of the bigger Main Ethiopian Rift. Subsurface geologic structural study in the CMER for intermediate and deeper Earth have been studied by various researchers and for different purposes. Generally, several studies have focused on mapping intermediate and deeper geological structures (Korme et al. 2004; Maguire et al. 2006; Abebe et al. 2007). With respect to subsurface resources, the relationship of subsurface structures with groundwater dynamics (Kebede et al. 2021a), association of subsurface structures with geothermal resources (Kebede et al. 2022) and the connection of subsurface structures with respect to hydrocarbon (Kebede and Alemu 2022) were studied in the region. These studies showed that the topmost soil layer didn't get much emphasis because of the geophysical instrument resolution and interest of researchers in studying the shallowest soil cover.

To study the shallowest subsurface structures in this region, a passive seismic survey recording seismic noise (seismic tremor) was conducted to map the subsurface structures of the shallow layers of natural soils. The sources of noise include wind, ocean waves, and anthropogenic activities. These noise sources produce seismic energy that propagates in continuous excitation creating seismic resonance within nearby subsurface geological materials. Resonance is a function of the shear-wave velocity of the subsurface layers and their thickness, the amplitude either amplified or diminished depending on the acoustic impedance contrast. In recent years, the analysis of these data has become widely used for seismic site effects (Trupti et al. 2013), seismic micro-zonation(Roser and Gosar 2010; Gosar 2017), passive seismic stratigraphy(Chandler and Lively 2016; Torrese et al. 2020), Vs30 estimation from constrained Horizontal to Vertical (H/V) curve fitting studies(Roser and Gosar 2010), detection of buried hollows(Raines et al. 2016) and Archaeological Prospection (Zeid et al. 2017). The method is based on the spectral ratio of horizontal to vertical components (HVSR) of microtremors (Nakamura 2000) which help to extract the fundamental frequency of soft sediments overlying bedrock(Serge et al. 2015).

This study targeted to map the shallowest subsurface structures, and topmost impedance contrast layer, of the region between the water divide, the Ziway-Shala Lakes basin and the Awash basin (Figure 1). To accomplish this, passive seismic noise data, H//V spectral ratio and a depth determination method developed by Nakamura (Nakamura 2000) is used.

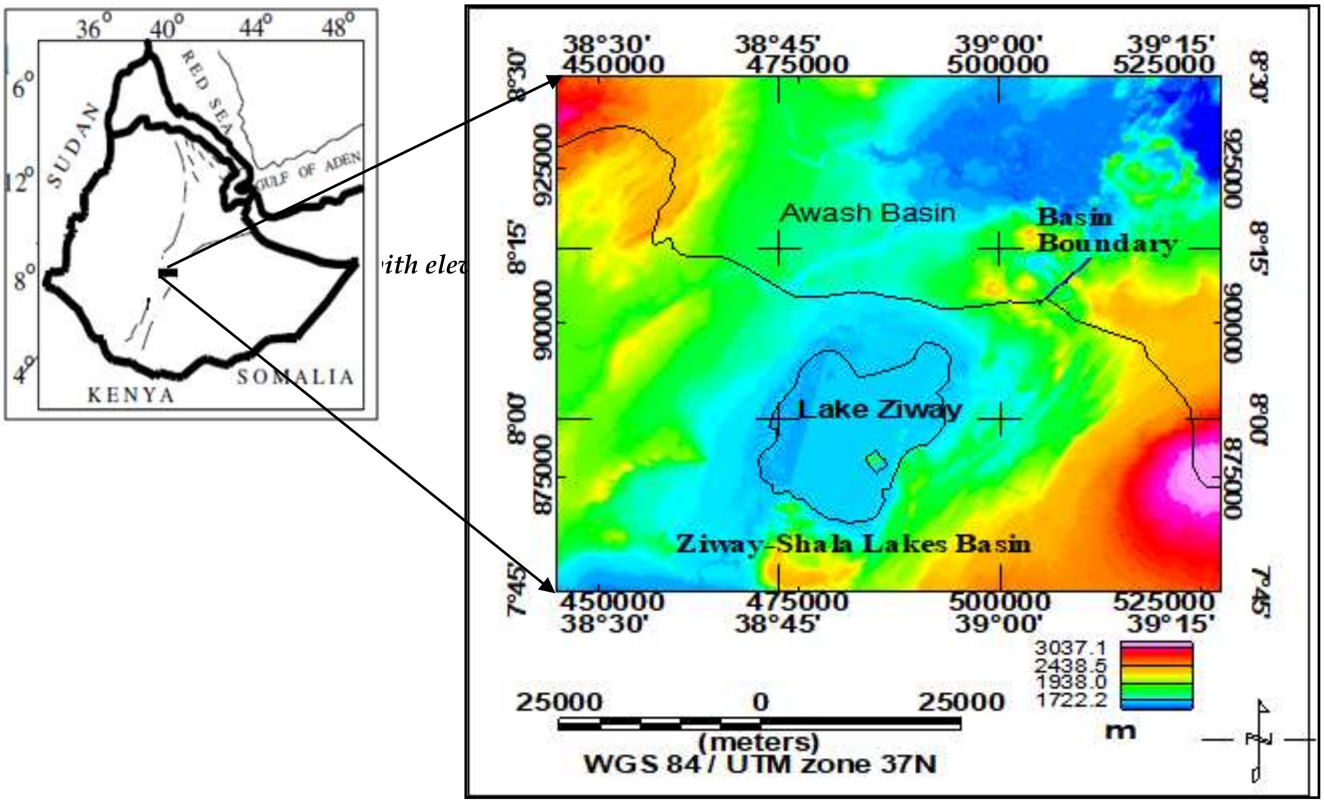


Figure 1 Study location showing the location of the water divide between Ziway-Shala lakes basin and Awash basin or between CMER and Northern Main Ethiopian Rift

DATA AND METHODOLOGY

Seismic Noise Data

The noise data utilized in this study consists of a set of time series recordings consisting of three-components, namely X, Y, and Z, as illustrated in Figure 2(b). These recordings were obtained using a highly sensitive TROMINO seismometer, designed to capture background seismic noise in a wide operating range of 0.1 Hz to 1,024 Hz. The TROMINO seismometer is an all-in-one instrument, comprising of ultra-lightweight and ultra-compact sensors and data acquisition system, which is capable of recording broad-band signals across all three components, i.e., North-South, East-West, and Up-Down, as shown in Figure 2(b). The ambient seismic noise data was saved in an internal partition of the TROMINO seismometer, following the guidelines outlined in the TROMINO User's Manual (2017). To extract meaningful insights from the data, proprietary software (Grilla) (Tromino®Grilla, 2009) was employed to facilitate the downloading, importing, viewing, and analysis of the recorded data. The survey was conducted to map the shallowest impedance contrast layer of the region that was not investigated by others geophysical investigations carried out in the area(Kebede 2020; Kebede et al. 2021b, a,; Kebede and Alemu 2022). The procedures for the measurements and data collection were comprehensively detailed to ensure that they are replicable and accurate. In order to collect seismic noise data, the first step was to select a suitable site in the study location. The site was chosen based on various factors, such as accessibility, proximity to potential sources of noise, and overall suitability for data collection. Once a site was selected, the seismometer was set up for data collection. To ensure accurate measurements, the seismometer was adjusted to magnetic north and the spikes (feet) were tightly coupled to the ground.

The seismometer was also leveled using the bubble-like leveling on the top of the unit to ensure that the recorded data was as precise as possible. Three perpendicular components of the seismic noise were recorded for approximately 10 minutes per site. The recording times of the survey were chosen to provide more spatial coverage in the area.

After the recordings were completed, the data was downloaded from the seismometer and processed using Grilla software. The software facilitated the downloading, importing, viewing, and analysis of the recorded data. This step was crucial to extract meaningful insights from the data and to ensure that the data was accurately analyzed. Overall, the data collection and processing methods employed in this study were meticulously designed to ensure the accuracy and reliability of the findings.

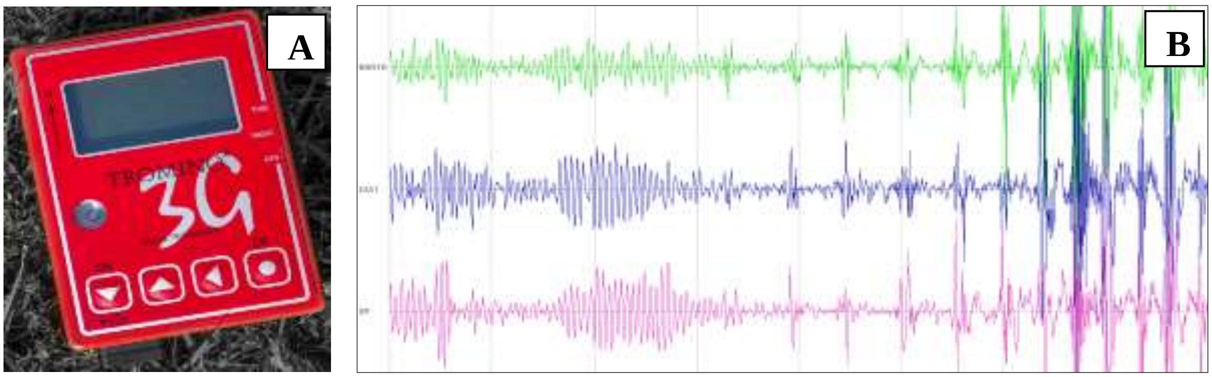


Figure 2TROMINO Seismometer (a) and the raw time series velocities data of three components that are recorded with TROMINO and viewed with Grilla software (b)

The two horizontal components (East-West and south-north) and the one vertical component (up-down) (Figure 2) are the main seismic data that were collected. About 62 single station measurements are collected at the boundaries between the Ziway-Shala Lakes basin and Awash basin near the water divide. All measurements (Fig. 3) were made for recording time of 10 minutes at 128 hz.

Figure 3. Single station measurement using TROMINO seismometer (TROMINO seismometer under the tan).

Methodology

The raw time series data (Figure.2(b)) were transformed to the frequency domain using Fast Fourier Transformation (FFT). The resulting two horizontal components and one vertical power spectrum were generated. This is followed by constructing Horizontal to vertical power spectral ratio (HVSR) graph. This HVSR ratio value (Eq. 1) at each frequency is defined in Roser & Gosar, (2010) as

$$HVSR(f) = \frac{\sqrt{H_{NS}(f).H_{EW}(f)}}{V(f)} \qquad (1)$$

Where,

$H_{NS}(f)$ is north-south, $H_{EW}(f)$ East-West horizontal spectra components and their resultants is simply called horizontal component (H)

$V(f)$ is the vertical spectra component

The shear wave resonance frequency manifests itself within this ratio value (Eq. 1). The peak frequency value was read from the graph resulting from equation 1 and using Grilla software.

The analysis of HVSR allows to estimate depth to impedance contrast of the layers. It is generally helpful to estimate the thickness of softer sediment cover laying over hard basement rocks ranging in depth from 0 to 500m. Generally, the following depth estimation approaches have been used by different researchers in different areas.

Unknown layer Thickness

The resonant frequency of the unconsolidated deposits was read from HVSR graph and the shear wave velocity is approximated either from 1D modeling or through characterization of soft layer geology of the area concerning shear velocity(Tromino®Grilla 2009). Having the resonant frequency and shear wave velocity, the depth to sediment- bedrock boundary can be determined using an equation (Eq. 2) derived by (Nakamura 2000)

$$Z = \frac{V_S}{4f_0} \qquad (2)$$

Where,

Z is the thickness of the unconsolidated sediments in m,

f_o is the resonance (peak)frequency (Hz) determined from HVSR and

V_S is the S-wave velocity of the location in m/s.

Equation 2 is used for the sites where sediment thickness is unknown with an approximation of the shear-wave velocity of the location under study. The shear wave velocities at shallow depth (high frequency) in the soft layer typically have 100 m/s for low-quality clays, turfs…, 200m/s for medium-good quality clays and sandy silts, 300m/s for typical of sand and gravel, 400m/s for typical gravel and altered/soft rocks and 500m/s typical of soft /layered sedimentary rocks (Tromino®Grilla 2009).

The three depth classes of the bedrock-like layer were estimated from depth frequency graphs (Figure. 4 (a, b and c))(Tromino®Grilla 2009) depending on frequencies range of (5-50 Hz, 1-10 Hz, 0.1-1 Hz). Depth estimates made based on equation 2 are used to cross-check depth estimates read from the standard graphs Figure. 4 (a, b and c) and frequency estimate based on H/V spectral curve and shear wave velocities given above.

The other method to estimate local sediment shear-wave velocity, is made based on equation 3. The depths (z_i)in the equation are obtained from collected nearby drilled wells. In the same way the resonance frequencies (f_{0i}) are determined from HVSR analysis of each respective survey stations.

$$V_s = \sum_{i=1}^{n} \frac{(4z_i f_{0i})}{n} \qquad (3)$$

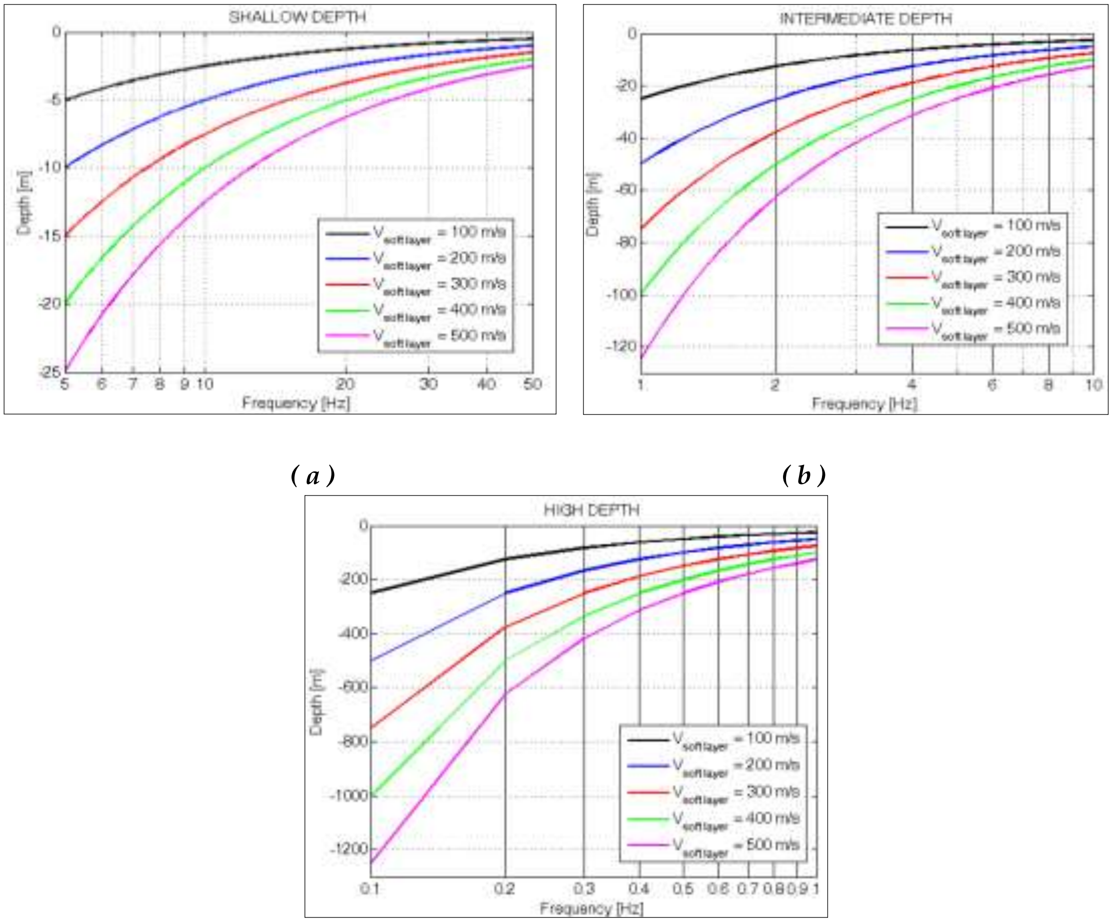
Where,

z_i is the thickness of the unconsolidated sediments (m) at location i,

f_{0i} is the resonance frequency (Hz) determined from HVSR and v_s is the shear-wave velocity of the location.

n is the number of locations where the depth to bedrock is known

Therefore, one can use the shear wave velocities estimated using equation 3 in equation 2 to estimate the depth of bedrock.



(a) *(b)*

(c)

Figure 4.Typical frequency - shear wave velocity - bedrock depth graphs for a 1-Dimensional, 2-layer Earth system, with high-frequency detail (a) mid-frequency detail (b) and low-frequency detail (c)adopted from Tromino manual (2009).

Known thickness and H/V peak frequencies

The sediment thickness can also be determined by the application of a power-law regression equation model given by(Ibs-von and Wohlenberg 1999).

$$z_i = c f_{0i}^{\;a} \tag{4}$$

Where,

f_{0i} are resonance frequency observed at each site

z_i are a range of known depths to bedrock that constrain the model

The constants c and a are to be determined from regression through linearization of equation 4. Thus, taking the logarithm of both sides of the gives

$$\ln z_i = \ln c + a \ln f_{0i} \tag{5}$$

This can be re-expressed as a linear function of the parameters as

$$z_i^* = c^* + a f_{0i}^* \tag{6}$$

Solving for the constants c^* and a using least square minimization we have a matrix solution of the form

$$\begin{bmatrix} c^* \\ a \end{bmatrix} = \begin{pmatrix} 2 & \sum f_{0i}^* \\ \sum f_{0i}^* & \sum f_{0i}^{*2} \end{pmatrix}^{-1} * \begin{pmatrix} \sum z_i^* \\ \sum z_i^* f_{0i} \end{pmatrix} \tag{7}$$

The constant parameters in equation 4 are determined by solving equation 7. These equations help to compute the thickness of the cover layer at any TROMINO readings away from drillholes based on the measured H/V peak frequency alone. However, the regression equation varies from one survey area to another survey area depending on the acoustic properties of the rocks. Therefore, the regression equation from one area cannot generally be used for other areas. This method is more reliable when there are sufficient drillholes available for such calibration.

Criteria for a reliable H/V curve and clear H/V peak

The automatically generated H/V curve should be checked for its reliability and clarity. Accordingly, The European project Site Effects Assessment using the Ambient Excitations criteria (SESAME guidelines) was used. The guidelines are in the form of a filled table and are generated automatically using Grilla software. These criteria were used to check the reliability and clarity of the H/V curve. According to SESAME 2005 guidelines, two criteria such as the standards for reliable H/V curve and six criteria for a clear H/V peak should be fulfilled for a single station analysis. The variables and parameters values for these guidelines are given in Table 1. The curves should pass this standard for acceptance or rejection.

Table 3. Criteria for a reliable H/V curve clear H/V peak (running Grilla software result in either "OK" or "No" in column shown in shade).

Max. H/V at 35.94 ± 0.58 Hz (in the range 0.0 - 64.0 Hz).		
Criteria for a reliable H/V curve *[All 3 should be fulfilled]*		
$f_0 > 10 / L_w$	*35.94 > 0.50*	
$n_c(f_0) > 200$	*21562.5 > 200*	
$□_A(f) < 2$ *for* $0.5f_0 < f < 2f_0$ *if* $f_0 > 0.5Hz$	*Exceeded 0 out of 1474 times*	
$□_A(f) < 3$ *for* $0.5f_0 < f < 2f_0$ *if* $f_0 < 0.5Hz$		
Criteria for a clear H/V peak *[At least 5 out of 6 should be fulfilled]*		
Exists f^- *in* $[f_0/4, f_0]$ | $A_{H/V}(f^-) < A_0/2$	*22.094 Hz*	
Exists f^+ *in* $[f_0, 4f_0]$ | $A_{H/V}(f^+) < A_0/2$	*56.469 Hz*	
$A_0 > 2$	*2.83 > 2*	
$f_{peak}[A_{H/V}(f) \pm □_A(f)] = f_0 \pm 5\%$	*|0.01617| < 0.05*	
$□_f < □(f_0)$	*0.58123 < 1.79688*	
$□_A(f_0) < □(f_0)$	*0.2144 < 1.58*	

Threshold values for $□_f$ ***and*** $□_A(f_0)$					
Freq. range [Hz]	*< 0.2*	*0.2 – 0.5*	*0.5 – 1.0*	*1.0 – 2.0*	*> 2.0*
$□(f_0)$ *[Hz]*	$0.25\,f_0$	$0.2\,f_0$	$0.15\,f_0$	$0.10\,f_0$	$0.05\,f_0$
$□(f_0)$ *for* $□_A(f_0)$	*3.0*	*2.5*	*2.0*	*1.78*	*1.58*
log $□(f_0)$ *for* $□_{logH/V}(f_0)$	*0.48*	*0.40*	*0.30*	*0.25*	*0.20*

Generally, the three depth estimation methods were stated in the methodology sections (2.2.1 to 2.2.3). The documentation was to show the state of the art in the usage of TROMINO seismometer. In our case, however, the estimate of depth to the bed-rock like layer (Figure 5) in the study region considered follows the procedures documented in section 2.2.1. Depth estimation was made following Eq. 2 and with peak resonant frequencies read from H/V spectral map. The shear wave velocity in the soft layer geology was obtained from information given in Figure 4 and the geology of borehole data near the study area. Overall, the depth we sought is shown in the form of a conceptual model (Figure 5). This figure shows stratified Earth having different impedance contrast layers, depth of overlying, shear velocities of overlying cover and resonant frequencies.

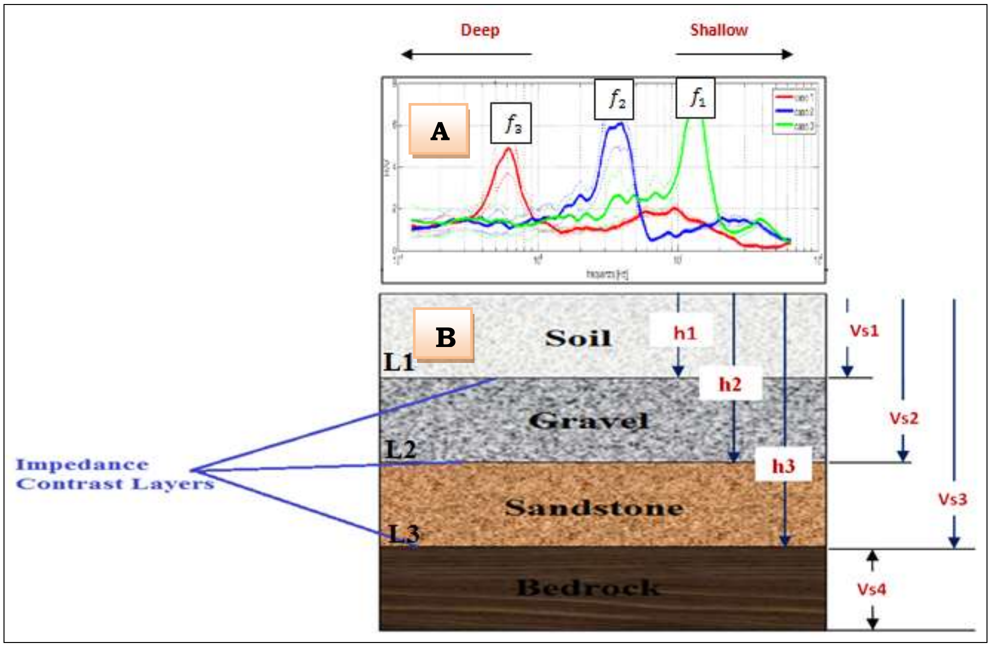


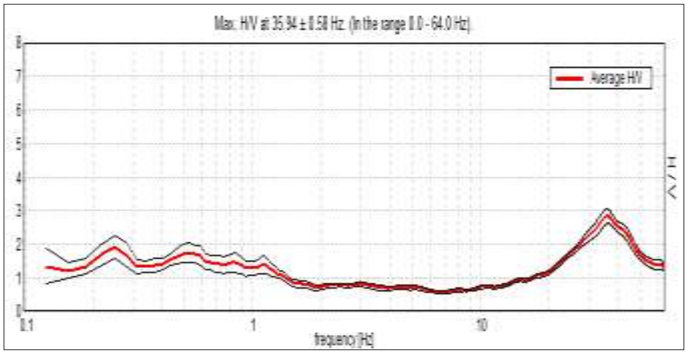
Figure 5. Multiple frequency peaks (f_1, f_2 and f_3) is read from the H/V spectral ratio curve and occurs at each respective impedance contrast layer (L1, L2 and L3). The h's are the thickness of the cover of each layer and Vs's are the shear velocities of the overlying formation

RESULTS

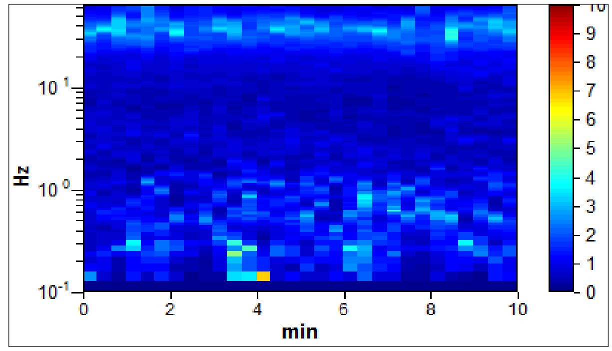
The horizontal to vertical spectral ratio (HVSR) is used to measure the thickness of unconsolidated deposits resting on bedrock and depth to bedrock. To achieve the objectives, three components time series data were collected and taken for the analysis. This data collection was followed by Horizontal to vertical spectral analysis. With inputs set to channel labels (north-south; east-west; up-down), GPS location: 038°47.2571 E, 08°12.7199 N (1696.9 m), Satellite no., 6, trace length of 10 minutes, sampling of 128 Hz, Window size of 20 s, smoothing type set to Triangular window and smoothing of 10%. Sample results were generated automatically using Grilla software for site name, Wokole (West of Meki Town). The graphs automatically generated for this site through these inputs were shown in Figure 6(a-d).

In addition to the four maps generated for each site (Figure 6 and Figure 7), filled word document (filled with "OK" or "NO") standards for reliable H/V curve and a clear H/V peak should be generated for a single station analysis. Accordingly, the Arbale site with UTM coordinate (512659, 889844) for example fulfilled the three basic criteria for reliability and the six-criterion mentioned for clear amplitude value (Appendix 1) (Figure 7a). However, the second site fulfilled the three basic criteria and did not fulfil two out of six (Appendix 2) (Figure 8a). This doesn't mean that the H/V curve is not working. In fact, a perfect recording on the rock would give NO to all these criteria.

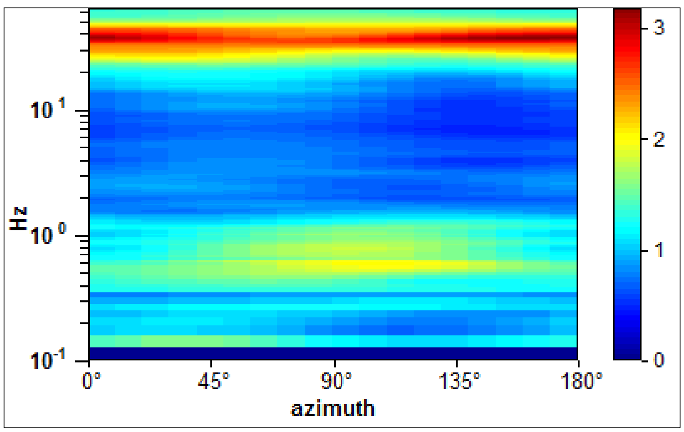
The fundamental frequency which can be used to estimate depth was read from Figure 7a and is 35.94 hz. The local geology of the area was taken as altered/ soft rocks. The value of shear wave velocity for such kinds of rocks is taken as Vs=400m/s. The depth estimate read from Figure 4 using this input was around 3.5 m. The depth was also estimated using equation (Eq. 2) and is equal to$3.478m$. In the second example (Figure 7), the depth value is calculated using equation 2 and is equal to $4.87m$. Similar procedures were followed to calculate the depth for all 52 sites that passes SESAME criteria.



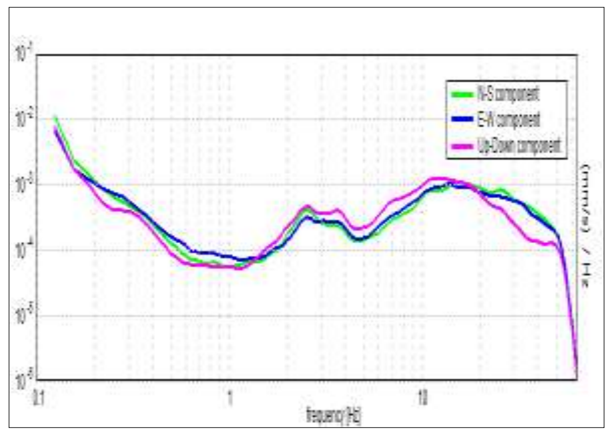
(a)



(b)



(c)



(d)

Figure 6. Grilla software output for Wokole site, West of Meki town. (a) Horizontal to Vertical Spectral Ratio map (b) H/V Time History map (c) Directional H/V (d) Single Component Spectra

Similarly, a single station results for the station name (AM7), GPS location 039°06.8890 E, 08°03.0067 N (east of Meki town) and similar inputs mentioned above were shown below in Figure 7 (a-d).

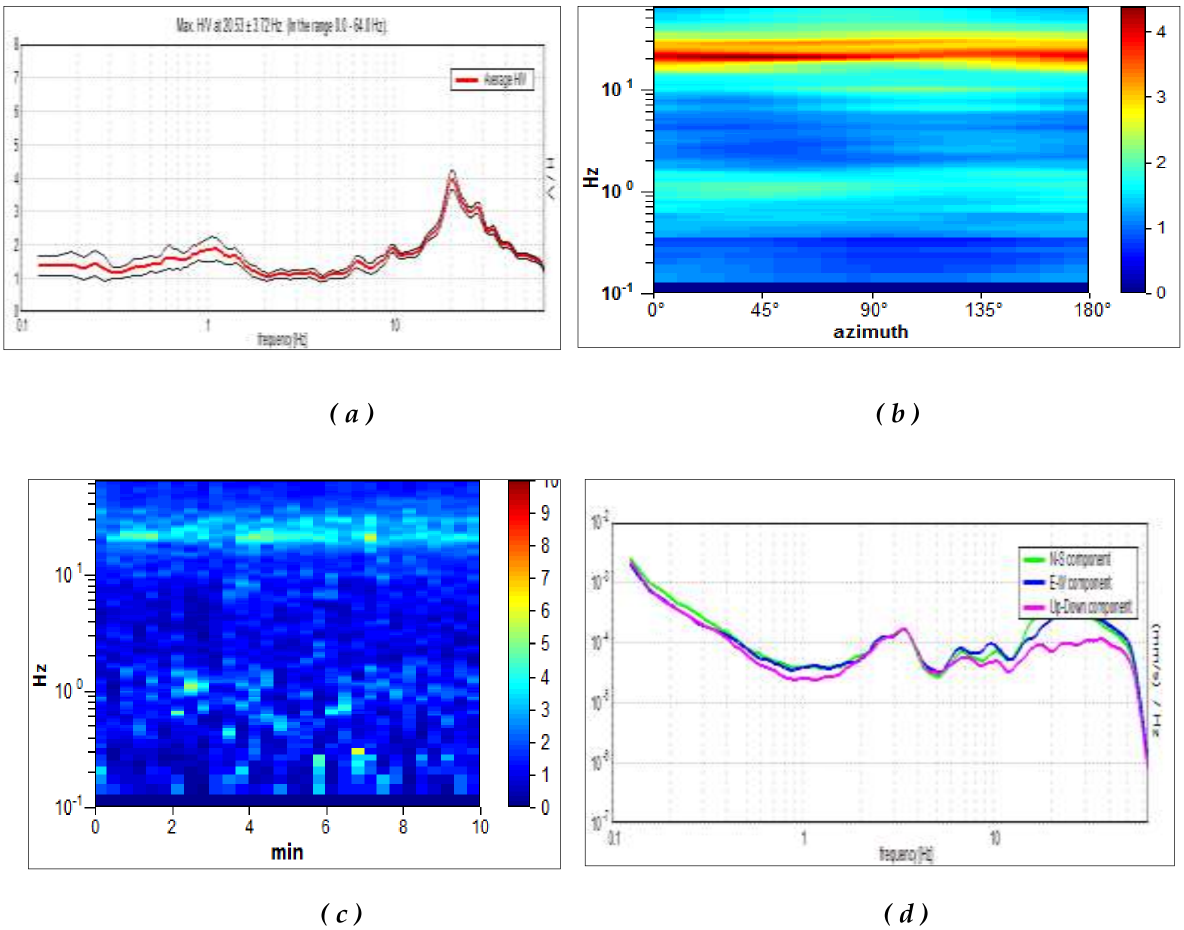


Figure 7 Horizontal to Vertical Spectral Ratio map (a) H/V Time History map (b) Directional H/V (c) and Single Component Spectra (d)

DISCUSSION

Out of 62 data collected only 52 data fulfilled SESAME criterion. Those data satisfying SESAME were subjected to single station analysis and help in mapping depth to a sediments-bed-rock like layer. Horizontal-to-Vertical spectral ratio (H/V) for each 52 sites was determined and fundamental frequencies were read. Depths for each site were determined similar to the results of a single station of the WOKOLE site (West of Meki Town) and AM7 (East of Meki Town) respectively. The processing generates H/V ratio maps from which resonant frequencies and subsequent depths were determined. The obtained depth values were gridded and are shown below in Figure 8.

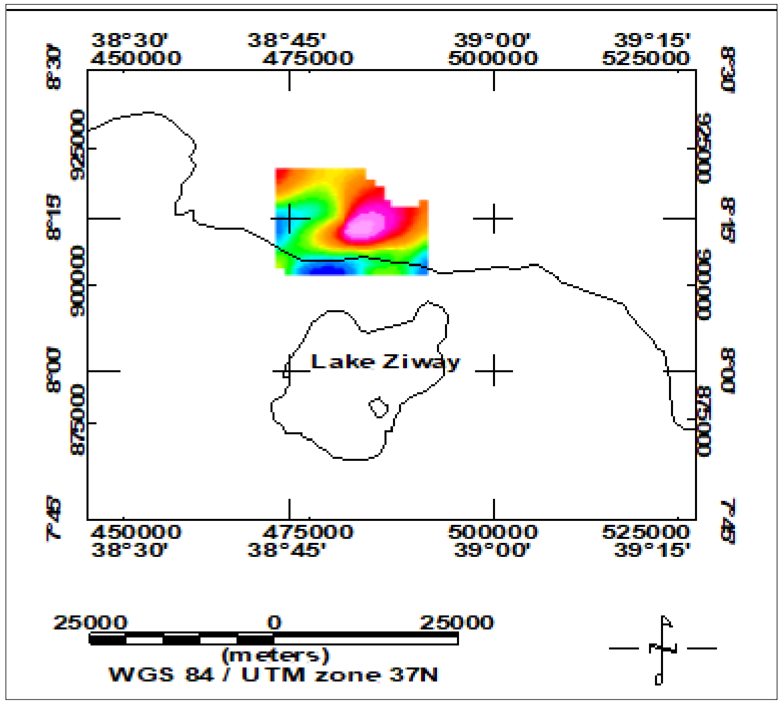
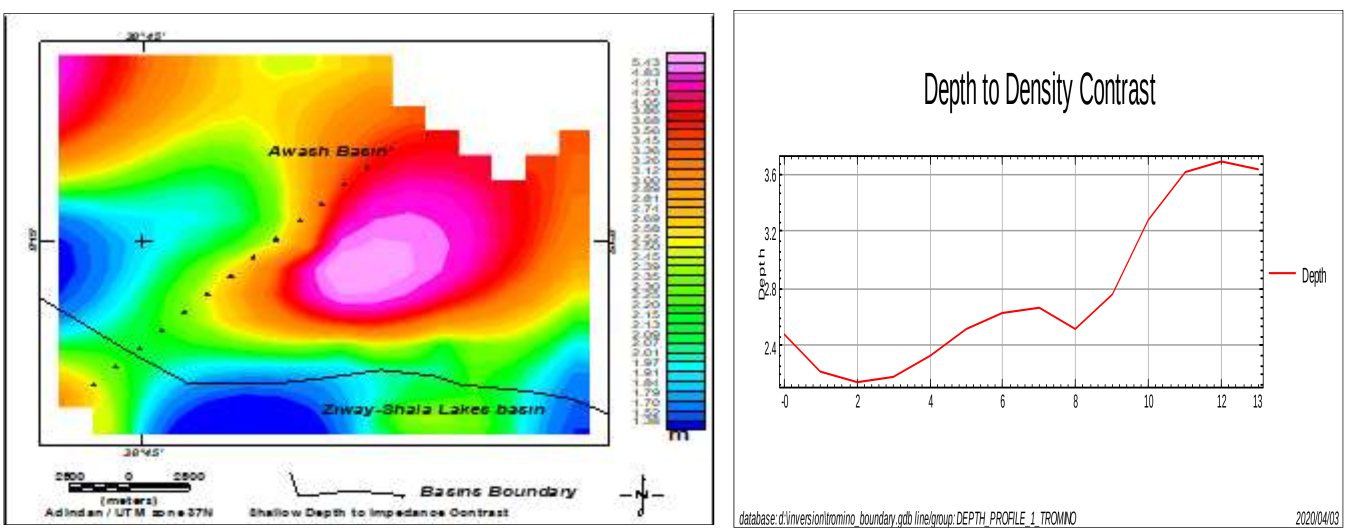


Figure 8. The Seismic noise data passing SESAME criterion are get gridded and mapped (near the water divide)

The overall depths estimate that passes SESAME criterion was gridded and scaled up and is shown in Figure 9a. This grid shows the shallowest density contrast depth and undulation of the topsoil layer in 2D. This topsoil cover in the study area is shown to deepen (thickened) northwards from Ziway Shala lakes basin to Awash basin (Figure 9(b).



(a) *(b)*

Figure 9. Depth estimates of the shallowest impedance contrast gridded and mapped to show the shallowest(topsoil) subsurface topography (a) and depth profile extracted from gridded bedrock topography map along the dotted line (b) (this is a bedrock undulating surface).

From gridded impedance contrast (Figure 9(a)), we observe that the thickness of overlying soils (bedrock topography) generally thickened northwards, towards the Awash basin as the line graph (Figure 9b) extracted from the grid (Figure 9a) shows. The bedrock in some regions is near the surface, exposed to air, in other places, it might be hundreds of meters deep, beneath loose sediments and broken rocks. The Earth's bedrock consists of many types of rock, such as sandstone, limestone, and granite. It has varying amounts of void spaces in them which groundwater accumulates and circulates. This topsoil cover could assist the shallow groundwater resource mapping and its dynamics.

The obtained depths do not agree with the shallow borehole depth of the sites. This might be the problem of the existence of strong acoustic impedance contrast within the sediments above the bedrock surface. These are observed not only in the two sites (East and West of Meki town) observed but also in almost all of the observation points. The other problem with using the HVSR method to map bedrock depth in the study area could be the lack of a strong acoustic impedance contrast at the sediment-bedrock interface. These might indicate that the bedrock is found at a depth beyond the depth of investigation using TROMINO seismometer at the surveyed time period of 10 minutes. Based on this one can propose a survey by increasing recording time from 10 minutes to 20 or 30 minutes.

CONCLUSIONAND RECOMMENDATION

Conclusion

Horizontal to Vertical spectral ratio (HVSR) was used to analyse the passive seismic data collected near the water divide of the Ziway-Shala lakes basin and Awash basin. The method was used to map the topsoil layer which is recognized by highest frequency signal in the region considered. The analysis involves first to generate the H/V spectral ratio curve automatically using Grilla software. Secondly, the results finds that the resonance or fundamental frequency (f_0) was read from this graph if and only if the maps pass SESAME 2005 criteria (reliability of H/V curve and clarity of H/V peak). Thirdly, approximation of shear-wave velocity of the location under study was made based on standards mentioned in section 2.2.1. Fourthly, the impedance contrast depth (depths at each station) was approximated based on method of the Nakamura. The depth estimates of each site were then gridded and mapped which could show undulation of the topsoil layer. This topsoil cover in the study area was shown to deepen (thickened) northwards from Ziway Shala lakes basin to Awash basin.

Recommendation

Passive seismic study measuring noise data and the single station analysis (HVSR) was used to estimate bedrock. This kind of study was not practiced well in Ethiopia in particular and worldwide in general. Based on the finding of the latest work the following recommendation are made:

✓The recording time of 10 minutes used in each station limits the method from mapping the lowest frequency (deeper) impedance contrast layer. It is therefore recommended to consider the use of increasing the recording time from 10 minutes to any time in the range 20-45 minutes for relatively deeper bedrock layer investigations.

✓Instead of taking shear wave velocity from standards (section 2.2.1) it would be better to approximate shear wave based on equation 2 (known depth to bedrock and frequencies).

✓It could be much use if this passive seismic method is used jointly with others geophysical methods (magnetic method, electrical method and active seismic method)

✓It is better to customize the method to study the whole CMER or any other sites in Ethiopia

✓It is also advisable to use the method in seismic site effects, seismic microzonation, passive seismic stratigraphy, **Vs30** estimation and archaeological prospection.

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REFERENCES

1. Abebe B, Acocella V, Korme T, Ayalew D (2007) Quaternary faulting and volcanism in the Main Ethiopian Rift. J African Earth Sci 48:115–124. https://doi.org/10.1016/j.jafrearsci.2006.10.005
2. Chandler VW, Lively RS (2016) Special section : Near-surface imaging and interpretation Utility of the horizontal-to-vertical spectral ratio passive seismic method for estimating thickness of Quaternary sediments in Minnesota and adjacent parts of Wisconsin. Near-surface imaging Interpret Util 4:. https://doi.org/10.1190/INT-2015-0212.1
3. Gosar A (2017) Study on the applicability of the microtremor HVSR method to support seismic microzonation in the town of Idrija (W Slovenia). Nat Hazards Earth Syst Sci 17:925–937. https://doi.org/10.5194/nhess-17-925-2017
4. Ibs-von S, Wohlenberg J (1999) Microtremor measurements used to map thickness of soft sediments. Bull Seismol Soc Am 89:250–259
5. Kebede H (2020) Mapping Geological Structures Using Integrated Geophysical Methods and Their Possible Implications, a Case Study of the Ziway-Shala Lakes Basin, Central Main Ethiopian Rift. Addis Ababa University
6. Kebede H, Alemu A (2022) Constrained 3D gravity interface inversion for layer structures: implications for assessment of hydrocarbon sources in the Ziway-Shala Lakes basin, Central Main Ethiopian rift. Heliyon 8:e09980. https://doi.org/10.1016/j.heliyon.2022.e09980
7. Kebede H, Alemu A, Kevin M (2022) Magnetic anomaly patterns and volcano-tectonic features associated with geothermal prospect areas in the Ziway-Shala Lakes Basin, Central Main Ethiopian Rift. Geothermics 105:102484. https://doi.org/10.1016/j.geothermics.2022.102484
8. Kebede H, Alemu A, Nedaw D (2021a) Mapping geologic structures from Gravity and Digital Elevation Models in the Ziway-Shala Lakes basin; central Main Ethiopian rift. Heliyon 7:e08604. https://doi.org/10.1016/j.heliyon.2021.e08604
9. Kebede H, Alemu A, Nedaw D, Fisseha S (2021b) Depth estimates of anomalous subsurface sources using 2D/3D modeling of potential field data: implications for groundwater dynamics in the Ziway-Shala Lakes Basin, Central Main Ethiopian Rift. Heliyon 7:. https://doi.org/10.1016/j.heliyon.2021.e06843
10. Korme T, Acocella V, Abebe B (2004) The Role of Pre-existing Structures in the Origin, Propagation and Architecture of Faults in the Main Ethiopian Rift. Gondwana Res 7:467–479
11. Maguire PKH, Keller GR, Klemperer SL, et al (2006) Crustal structure of the northern Main Ethiopian Rift from the EAGLE controlled-source survey ; a snapshot of incipient lithospheric break-up. Geol Soc London 269–291
12. Nakamura Y (2000) Clear identification of fundamental idea of Nakamura's technique and its applications. Proc 12WCEE, No 177–402
13. Raines M, Banks V, Chambers J, et al (2016) The Application of Passive Seismic Techniques to the Detection of Buried Hollows. In: 14TH SINKHOLE CONFERENCE. pp 423–430
14. Roser J, Gosar A (2010) Determination of Vs30 for seismic ground classification in the Ljubljana area, Slovenia. Acta Geotech Slov 1:
15. Serge E, Sauret G, Beaujean J, et al (2015) Characterization of super fi cial deposits using electrical resistivity tomography (ERT) and horizontal-to-vertical spectral ratio (HVSR) geophysical methods : A case study. J Appl Geophys 121:140–148. https://doi.org/10.1016/j.jappgeo.2015.07.012
16. Torrese P, Rossi AP, Unnithan V, et al (2020) HVSR passive seismic stratigraphy for the investigation of planetary volcanic analogues. Icarus 351:113970. https://doi.org/10.1016/j.icarus.2020.113970
17. Tromino®Grilla (2009) The short tromino ® how to. pp 1–26
18. Trupti S, Goverdhan K, Srinivas KNSSS, et al (2013) Site classification of Pondicherry using shear-wave velocity and horizontal-to-vertical spectral ratio. Nat Hazards. https://doi.org/10.1007/s11069-013-0746-3
19. Zeid NABU, Corradini E, Bignardi S, et al (2017) The Passive Seismic Technique ' HVSR ' as a Reconnaissance Tool for Mapping Paleo-soils : The Case of the Pilastri Archaeological Site , Northern Italy. Archaeol Prospect 24:245–258. https://doi.org/10.1002/arp.1568

Appendix 1: The SESAME, 2005 guidelines

Max. H/V at 35.94 ± 0.58 Hz (in the range 0.0 - 64.0 Hz).		
Criteria for a reliable H/V curve [All 3 should be fulfilled]		
$f_0 > 10 / L_w$	35.94 > 0.50	OK
$n_c(f_0) > 200$	21562.5 > 200	OK
□$_A$(f) < 2 for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5$Hz □$_A$(f) < 3 for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5$Hz	Exceeded 0 out of 1474 times	OK
Criteria for a clear H/V peak [At least 5 out of 6 should be fulfilled]		
Exists f^- in $[f_0/4, f_0]$ | $A_{H/V}(f^-) < A_0 / 2$	22.094 Hz	OK
Exists f^+ in $[f_0, 4f_0]$ | $A_{H/V}(f^+) < A_0 / 2$	56.469 Hz	OK
$A_0 > 2$	2.83 > 2	OK
$f_{peak}[A_{H/V}(f) \pm$ □$_A(f)] = f_0 \pm 5\%$	|0.01617| < 0.05	OK
□$_f$<□(f_0)	0.58123 < 1.79688	OK
□□□□	0.2144 < 1.58	OK

Threshold values for □$_f$ and □$_A$(f_0)					
Freq. range [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
□(f_0) [Hz]	0.25 f_0	0.2 f_0	0.15 f_0	0.10 f_0	0.05 f_0
□(f_0) for □$_A$(f_0)	3.0	2.5	2.0	1.78	1.58
log □(f_0) for □$_{logH/V}$(f_0)	0.48	0.40	0.30	0.25	0.20

Appendix 2: The SESAME, 2005 guidelines

Max. H/V at 20.53 ± 3.72 Hz (in the range 0.0 - 64.0 Hz).			
Criteria for a reliable H/V curve [All 3 should be fulfilled]			
$f_0 > 10 / L_w$	20.53 > 0.50	**OK**	
$n_c(f_0) > 200$	12318.8 > 200	**OK**	
□$_A$(f) < 2 for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5$Hz **□$_A$(f) < 3 for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5$Hz**	Exceeded 0 out of 986 times	**OK**	
Criteria for a clear H/V peak [At least 5 out of 6 should be fulfilled]			
Exists f^- in $[f_0/4, f_0]$ | $A_{H/V}(f^-) < A_0/2$	14.219 Hz	**OK**	
Exists f^+ in $[f_0, 4f_0]$ | $A_{H/V}(f^+) < A_0/2$	41.438 Hz	**OK**	
$A_0 > 2$	3.95 > 2	**OK**	
$f_{peak}[A_{H/V}(f) \pm$ □$_A(f)] = f_0 \pm 5\%$	|0.18122| < 0.05		**NO**
□$_f$<□(f_0)	3.72075 < 1.02656		**NO**
□$_A$(f_0) <□(f_0)	0.2864 < 1.58	**OK**	

Threshold values for □$_f$ and □$_A$(f_0)					
Freq. range [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
□(f_0) [Hz]	0.25 f_0	0.2 f_0	0.15 f_0	0.10 f_0	0.05 f_0
□(f_0) for □$_A$(f_0)	3.0	2.5	2.0	1.78	1.58
log □(f_0) for □$_{logH/V}$(f_0)	0.48	0.40	0.30	0.25	0.20