Application of Holisurface Technique in MASW and HVSR Surveys for Site Characterisation at Ewoyaa, Ghana*

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Abstract

Over the past six years, exploration activities for lithium deposit have been conducted in Ewoyaa and its surrounding communities in the Central Region of Ghana. As part of the Environmental Protection Agency's policies governing mining activities, it is substantially recommended to analyse the possible effects of blasting activities on the integrity of buildings in the area. In order to achieve this, site investigation was undertaken to classify the *in-situ* materials based on their dynamic properties and quantify their response capabilities to seismic waves. Multichannel Analysis of Surface Waves (MASW) and seismic microtremor data for obtaining Horizontal to Vertical Spectral Ratio (HVSR) were acquired and analysed using the HoliSurface technique. The results from the Holisurface active MASW method were used to characterise the subsurface materials based on the Euro Code 8 (EC 8) for seismic response site classification for soil as a criterion, while the HVSR method to ascertain the level of vulnerability of the site to seismicity. The 3-component geophone was utilised within the holisurface framework for recording surface waves in both active and passive modes. The Vs_{30} values recorded at sites L100 and L300 were 299 m/s and 269 m/s, respectively, whereas site L200 recorded a Vs_{30} value of 1271 m/s. Thus, L100 and L300 belong to class C; moderate to dense subsurface materials while L200 falls in class A; rocky subsurface materials based on the Eurocode 8 seismic site classification for soils. The Vs values further helped to compute elastic moduli that revealed the competence of the survey areas, especially site L200. The study areas recorded natural peak frequencies ranging from 2.06 to 4.88 Hz, natural peak periods between 0.20 and 0.49 seconds and the vulnerability index (Kg) values from 0.30 to 6.34; depicting that Ewoyaa is a seismically safe area. It can therefore be inferred from the results of this study that the survey area is generally resilient, competent, and resistant to future blasting activities from mining.

Keywords: Site Characterisation, Shear Wave Velocity, Site Response, Microtremor Analysis, Vulnerability

1 Introduction

Invasive mechanical methods including the standard penetration test (SPT), dynamic cone penetration test (DCPT), etc., are commonly applied to evaluate near-surface engineering features of soils for geotechnical site characterization (Tokeshi *et al.,* 2013). Invasive procedures are not applicable for all geotechnical site characterisation surveys, especially in site investigations that involve very large areas (Bard *et al.,* 2010; Foti and Passeri, 2018). As a result, covering huge areas of inquiry using these methodologies is time-consuming and very expensive (Lane, 2009). When vast amounts of earthworks are necessary, the evaluation of the on-site stress field along a 2-D profile using seismic approaches, without any disruption produced from direct borehole drilling methods, is crucial (Matthews *et al.,* 1997; Donohue *et al.,* 2013).

The depth of investigation in applying invasive techniques is shallow. These methods also require coring and drilling of boreholes, which in effect tend to cause disturbances to the intrinsic conditions of the soil materials at the site (Bell, 2013).Non-invasive geophysical methods are employed as either a substitute to decipher the ground conditions and properties of the site or as a complement to make a comparison between the results obtained from both the invasive techniques and the non-invasive techniques.

Recently, non-invasive 1-D and 2-D array-based surface wave methods, such as Spectral Analysis of Surface Waves (SASW), Multichannel Analysis of Surface Waves (MASW), Multi-channel Simulation with One Receiver (MSOR), Refraction Microtremor (ReMi), and others, are more efficient than traditional invasive mechanical techniques for geotechnical site investigations in terms of scope of application, time efficiency, cost, and other extra manual activities such as drilling of boreholes which affect the intrinsic conditions of the soil materials (Tokeshi *et al.,* 2013; Jafri *et al.,* 2018).

One of the most reliable non-destructive geophysical techniques is the multichannel analysis of surface waves (MASW), which may be used to assess the site class for geotechnical and civil engineering purposes as well as to provide near-surface shear wave velocity (V_S) profiles (Dikmen *et al.,* 2010).The seismic wave velocity varies with the fundamental mechanical properties, such as Poisson's ratios, shear modulus, etc. of subsurface materials. Thus, well-established correlations between shear wave velocity (Vs)and many other geotechnical parameters such as shear modulus, bulk modulus, young's modulus, bulk density, and

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Poisson's ratio among others have been used for site characterisation purposes (Balgari *et al.,* 2018). This establishes the relevance of Vs in geotechnical and seismologic studies, thus making the MASW methodologies very useful in these fields (Lin *et al.,* 2004; Picozzi *et al.,* 2009; Balgari *et al.,* 2018).

The MASW is classified into two categories as active MASW and passive MASW (HVSR microtremor method). Depending on whether the MASW data is active or passive, the depth that may be reached varies from a few tens of meters (active) to a few hundred meters (passive) (Park *et al.,* 2007; Salas-Romero *et al.,* 2021; Gosar *et al.,* 2008). By integrating active and passive data, the frequency regime gets broadened, allowing for higher resolution and deeper information from the location (Park *et al.,* 2005; Foti *et al.*, 2018).

The basis for MASW is the dispersive behaviour of Rayleigh and Love waves, which propagate by means of a layered media with frequency-dependent velocities (Park *et al.,* 2007). The active MASW produces a 2D pseudo-shear-wave velocity (Vs) section of the subsurface by interpolation of 1D shear-wave velocity profiles. To define a site's V_S soil profile, the method detects wave movements on the earth's free surface, measures the phase velocity dispersion curve and inverts it using a hypothetical model (Jafri *et al.,* 2018; Moura *et al.,* 2012; Adamo *et al.,* 2021).

Setchell *et al.,* (2016) used non-invasive geophysical techniques to establish a three-dimensional (3D) model for their site investigation in Southern Asia and attested that the geophysical methods are quick (time-efficient) in covering large survey areas per day (up to 1km) compared to the conventional drilling techniques. Tokeshi *et al.* (2013) made joint use of both active and passive seismic techniques for their site characterisation and concluded that the non-invasive methods permitted the assessment of the shear wave velocity ground profile in a time-efficient and less expensive manner; in contrast to the boring methods. Thus, stating that the non-invasive approaches are reliable in estimating the shear velocity ground profile.

The ground motions observed during seismic events or geohazards are greatly influenced by the local soil conditions (Chauhan *et al.,* 2019). According to Tropeano *et al.* (2018), the terrain, thickness and type of overburden are the main determinants of ground motion intensity. Site response parameters (natural ground frequency and amplification) derived from site response analyses deploying HVSR (micro-tremor data) is one of the popular techniques of seismic hazard evaluation and micro zonation (Pudi *et al.,* 2021). These parameters depend on local surface geology and ground soil conditions and help to identify regions that are vulnerable to damage due to an earthquake event (Govindaraju and Bhattacharya, 2012; Roy and Sahu, 2012; Chieffo and Formisano, 2019).

The HVSR has been effectively utilised in site response studies by Chauhan *et al.,* (2019) and for the determination of liquefaction potential of site materials by El Hilali *et al.,* (2021). The method provides the amplification factor and the natural frequency of the subsurface materials, which are then used to evaluate the vulnerability index (Kg) of the soils in response to seismic events. Amplification factors and natural ground frequency at a site are used to assess the possible impacts of high-risk seismic activities such as intense and prolonged blasting or an earthquake (Picozzi *et al.,* 2009). Also, zones with natural frequencies less or equal to 2.0 Hz are prone to higher to mild amplification and are more vulnerable as compared to those above 2.0 Hz (Chauhan *et al.*, 2019).

The extensive exploration work for lithium at Ewoyaa and its surrounding communities has necessitated a comprehensive investigation that will provide knowledge on the nature of subsurface materials that underlay the communities in close proximity to the concession. This investigation should be able to characterise the site with respect to potential blast impacts when mining activities commence.

This study, therefore, employed non-invasive geophysical techniques to characterise three sites at Ewoyaa by obtaining the site categorisations using EC8.This comprises the geotechnical properties of the subsurface materials as well as the vulnerability indices of the sites in response to failure and possible damage on structures within the surrounding areas, since mining activities such as blast-induced tremors are highly anticipated.

2 Resources and Method Used

2.1 Study Area

Ewoyaa is located in the Mfantsiman Municipality of the Central Region of Ghana. It is situated 4.55 km north of Saltpond and about 5.5 km southwest of Mankessim. Ewoyaa can be found at latitude 5°14'21"N and longitude 1°03'44"W. The Mfantsiman Municipality covers about 660 km^2 of the 10,826 km^{2}total land area of the Central Region. The Ewoyaa community however occupies just about 0.06 km^{2}of the Mfantsiman Municipality, representing 6.10% of the total area of the municipality. Ewoyaa shares borders with Anokye to the east, Afrengwato the west, and Krofu to the north. Fig.1 shows the location of Ewoyaa; the study area and the distribution of the survey traverses.

2.2 Geology of the Area

The geology of the survey area consists of the Birimian Super group, a volcano-sedimentary basin of the Proterozoic age in the western part of Ghana as shown in Fig. 2. The rocks are mainly basin-type granitoid rich in biotite (micas) (Klemd, 2002), which range in composition from intermediate granodiorite often medium grained to felsic leucogranites often coarse to pegmatoidal grain size (Atlantic Lithium, 2020). These rocks intrude the Birimian metasedimentary rocks such as greywacke, phyllites, etc., causing them to metamorphose to schist marked by garnet, mica, and staurolite and weathered at some locations within the area (Karikari *et. al.*, 2021; Tay *et al.*, 2017). Present also are the later pegmatites that intrude the granitic rocks and other rocks in the areaand occur generally as sub-vertical dykes with two dominant trends: either striking north-northeast (Ewoyaa Main) and dipping sub-vertically to moderately southeast to east-southeast or striking west-northwest (Abonko, Kaampakrom and Ewoyaa Northeast) dipping sub-vertically northeast (Atlantic Lithium Limited, 2020)**.**

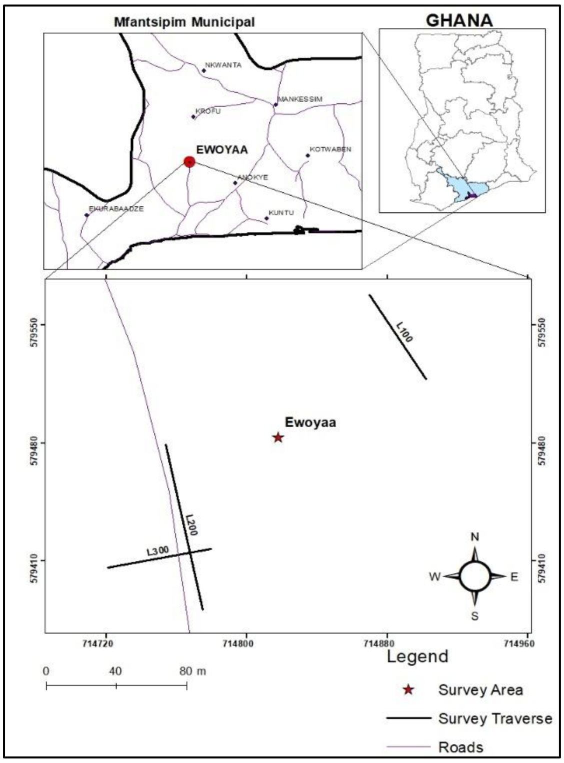

Fig. 1 Location Map of the Study Area and Survey Traverses

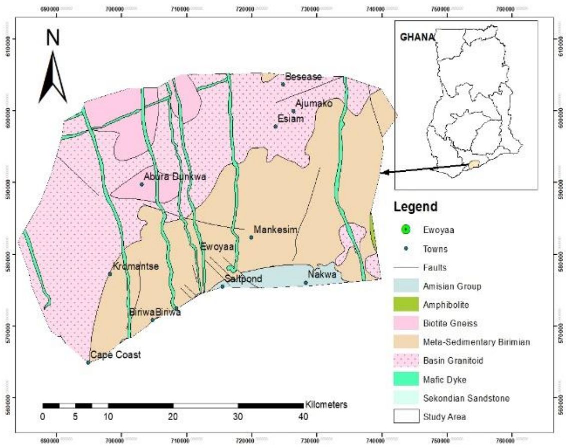

Fig. 2 Geological Map of the Area

The pegmatite intrusions observed in the Birimian are spodumene-rich pegmatites, which are lithium-bearing pyroxene (Filip *et al.*, 2006). There are two main types of pegmatites found there: the barren pegmatites with no mineralization, and spodumene-bearing pegmatites with mineralization of lithium. There are also numerous massive quartz veins found in the area, which can be attributed to the presence of intrusions in the area (Atlantic Lithium Limited, 2020)

2.3 Methods

The main methods used in this research include the HoliSurface Technique for Active MASW surveys and passive microtremor HVSR analysis.

2.4 Data Acquisition

2.4.1 HoliSurface Technique for Active MASW Data Acquisition

The HoliSurface (HS) integrated system is a small device made to function well while saving time, space, and energy. This indicates that you can easily operate alone using the HS system. For instance, the seismograph and source are in the same location when recording data for the HoliSurface technique (active seismic), whereas the 3C geophone is at a specific distance (offset). After the first set of stack shots, the field technician can proceed without having to repeatedly switch between the source and the recording system as is necessary with other acquisition systems by immediately checking the data's quality on the monitor (Holisurface, 2019).

The active method is one involving the generation of energy in the form of vibrations by striking a sledgehammer on a strike plate. This was done by first placing the plate horizontally on the ground and producing 10 stacks; thereafter placing it vertically in a shallow pit enough for the plate to fully sit and stacking. This is carried out on the face of the plate such that the energy generated moves parallel along the traverse of the survey, hence data for Rayleigh and Love waves were obtained respectively. Two separations of spread cable were used:120 m and 60 m, depending on the availability of space.

The Holisurface technique was used in this seismic data acquisition process where a 4.5Hz 3C geophone, which is capable of picking data for three components of surface waves (Fig. 3) is fixed at the end of the spread length. This is done by connecting the spread cable to the geophone via its connector. The rule of thumb here is that in the active mode, the arrow indicated on the geophone (i.e. radial component) which points to the north-seeking direction is to be aligned in the direction of the traverse towards the trigger source. It is also required that the bubble is centred, and the geophone is well-levelled and stable on the ground. This sensor is well-fixed to the ground just behind the area the shots were made (Fig. 4a). After the connection, the strike plate is placed flat lying on the ground, where the sensor is positioned such that, it points towards the plate. In this case, Rayleigh waves are generated, and the data is then collected.

2.4.2 Passive (HVSR) Data Acquisition

One of the most effective methods for determining the fundamental or resonant frequency (Fr) of soft deposits is the HVSR technique (El-Hussain *et al.*, 2013; Pazzi *et al.*, 2016; Ryanto *et al.*, 2020).The technique is based on the detection of microtremors, which are characterised by low energy and amplitude levels (Okada and Suto, 2003). The technique establishes the spectral ratio between the horizontal (H) and vertical (V) components of motion recorded using a properly calibrated 3-component (3C) geophone at a single station (Cartiel *et al.*, 2006; Lermo and Chavez-Garcia, 1993). The HVSR approach introduced by Nakamura (1989) is one of the geophysical passive methods that has gained the most traction in recent years due to its efficiency in terms of both cost and time.

The vital parameters to fix before the passive acquisition are the sampling rate and the acquisition time (or length) which depend on the stratigraphy of the site. In this work, the sampling rate was fixed at 8 ms - 125 Hz and the acquisition time (or length) was 20 minutes. A delay period of 2 seconds was used together with the activation of the gain for proper amplification of seismic waves. The 3C geophone was configured to be in line with the magnetic North pole of the Earth and well placed on the ground such that the bubble is centred. On each traverse, the data was acquired at the midpoint and at the end of the traverse. Fig. 4(b) depicts the passive data acquisition modes employed in this survey.

2.5 Data Processing

The software used for processing both the active MASW and passive HVSR data are the HoliSurface and win MASW software, respectively.

2.5.1 HoliSurface (Active MASW) Data Processing

The HoliSurface technique for MASW data processing entails three steps: loading the raw data (seismic waveforms) from the storage medium onto the software interface, the development of dispersion curves, and the inversion of dispersion data to produce shear wave velocity profiles. The objectives of the data processing stage are to determine the dispersive properties of the site and the inversion of the horizontal (radial and transverse) and vertical components, which is aimed at determining the subsurface Vs model. The procedure is similar to that used by Dal Moro *et al.*(2018).

The data processing for the acquired active seismic data begins with raw field data preparation to obtaining dispersion images and picking of dispersion curves to extracting the shear wave velocity profiles after the inversion process. At the early stages of the processing, the dispersion analysis is carried out. The main goal of dispersion analysis is to pick a dispersion curve, which is then used in the inversion process to determine the shear wave velocity (Vs) profile (Beaty *et al.*, 2002; Dal Moro *et al.*, 2007).

Before carrying out the dispersion analysis, the recorded active field data (offset versus time plot) was loaded on to the software (Holisurface®). The excess unwanted traces in the data were cleaned leaving the relevant signals. Since the focus is Rayleigh waves, the Rayleigh wave: group velocity spectra option was selected. The maximum time limit at which useful data was obtained was identified (i.e. not more than 1.2 s for all traverses). Major signals were then selected whereas minor insignificant signals were zeroed.

To generate the group velocity spectra of the Rayleigh, the minimum and maximum frequency were initially fixed. Fig. 5 shows the offset versus time field traces and the resulting group velocity spectra. From velocity spectra obtained in the dispersion process, the dispersion curve is then determined (i.e. the overlapped synthetic model). The shear wave velocity profiles were then extracted after this inversion step

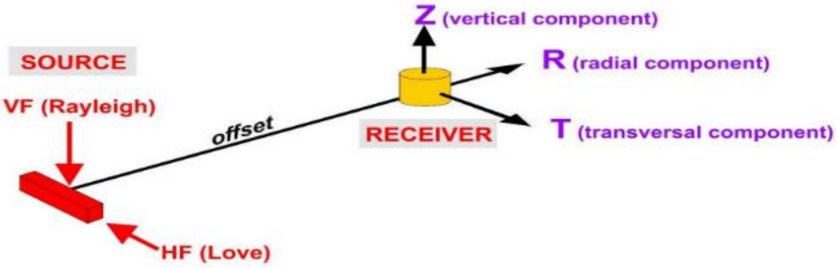

Fig. 3Typical Acquisition Setup Depicting the Various Components of Surface Waves(Dal Moro, 2015)

Fig. 4 (a) Active Data Acquisition Methods (b) Passive Data Acquisition

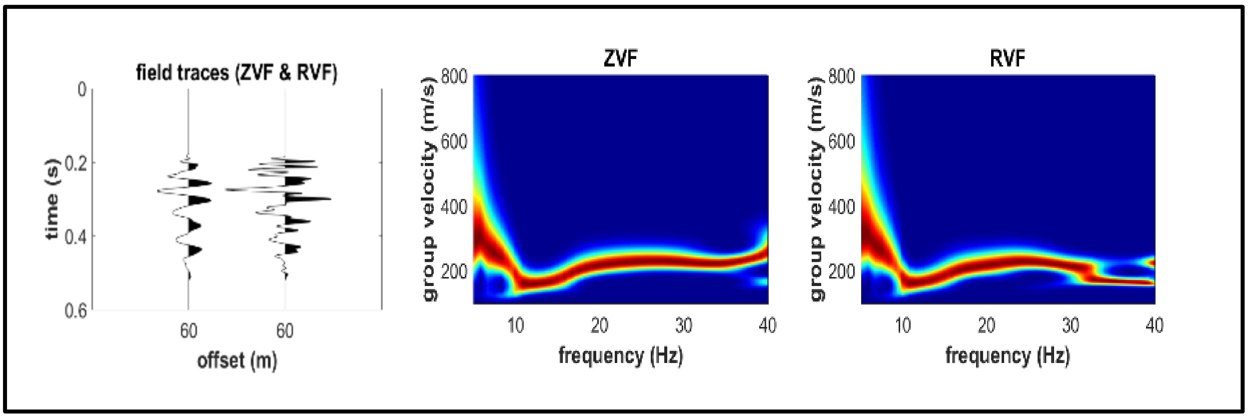

Fig. 5 (a) Seismic Traces for Vertical (ZVF) and Radial (RVF) Components (b) Group Velocity Spectra for the Rayleigh Waves

3.2.2 HVSR Computations

The recorded microtremor data at each survey location were processed using the win MASW software with underlying principles proposed by Nakamura (1989; 2000). During the data processing, intensive artificial disturbance signals were removed using a bandpass filtering of 0.01–20 Hz. After which a Fast Fourier Transform (FFT) was used to obtain the amplitude spectra of the two horizontal (NS and EW) and one vertical (Z) components for each window. The soil transfer function (T) was estimated using the spectral ratio of the horizontal (Hf) and vertical (Vf) components of the recorded data. In which Hf is the spectral combination of north-south (HNS) and east-west (HEW) horizontal components (Bard &SESAME Team, 2004). Out of this function, the fundamental frequency (F_g) and amplification factor (A_g) of the soil deposit were derived for each point.

$$T = \frac{H_f}{V_f} \quad (1)$$

The ground vulnerability index (K_g) parameter enables the easy quantification of the level of the possible damage that could occur in a soil deposit which is subjected to cyclic stress, such as earthquake or intense blasting. The ground vulnerability index (K_g) was calculated based on Nakamura and Takizawa (1990):

$$K_g = \frac{A_g^2}{F_g} \quad (2)$$

3.3 Empirical Theories Employed

The various theories that were employed to carry out the research are presented in this section. The dynamic engineering properties within the top 30 m of the layers of the subsurface as well as the vulnerability index for all HVSR sites were computed by the following relationships.

$$V_{s,30} = \frac{30 \text{ m}}{\sum_{i=1}^{n} \frac{d_i}{V_{s,i}}} \quad (3)$$

$$\rho = \alpha Vs^{\beta} \quad (4)$$

$$Vp = Vs\left(\frac{1-\mu}{0.5-\mu}\right)^{0.5} \quad (5)$$

$$G = \rho * Vs^2 \quad (6)$$

$$E = 2G(1+\mu) \quad (7)$$

$$K = \frac{E}{3(1-2\mu)} \quad (8)$$

$$\mu = \frac{Vp^2 - 2Vs^2}{2(Vp^2 - Vs^2)} \quad (9)$$

$$K_g = \frac{A^2}{f_o} \quad (10)$$

Where:

n = number of layers of the Vs profile up to 30 m
d_i = thickness
V_{si} = shear wave velocity of each layer respectively
α = 0.52
β = 0.2 (Anbazhagan *et al.*, 2016)
Vp = P-wave velocity
μ = Poisson's ratio and
G = shear modulus
ρ = bulk density
E = Young's modulus
Kg = seismic vulnerability index
A = amplification factor of the site and
f_o = peak natural frequency (Nakamura, 1997)

3 Results and Discussion

3.1 Multichannel Analysis of Surface Waves (MASW)

The active Multichannel Analysis of Surface Waves (MASW) technique was applied to estimate shear wave velocity (Vs) for subsurface materials as part of geotechnical site investigations. This was to evaluate the stiffness and other dynamic engineering properties of near-surface materials in the study area.

Figs. 6, 7, and 8 represent results for the joint inversion of Rayleigh waves (vertical and radial components); velocity spectra with the dispersion curve as well as the shear wave velocity profile for all survey lines (L100, L200 and L300 respectively). The summary of the site classification based on the average shear wave velocity within the top 30 m (Vs_{30}) and the relevant dynamic geotechnical parameters is shown in Table 1.

From the vertical profile of the shear wave velocity (Vs) for L100 (Fig. 6), the top layer (surface to 4m) had an average of 275 m/s, which reduced to around 180 m/s when a relatively weak layer was encountered at a depth of 4 to 7 m. The shear wave significantly increased to 385 m/s at a depth range of 8 to 24 m, signifying a very consolidated soil deposit, after which there was a lower velocity layer encountered with 270 m/s; similar to the properties of the uppermost layer. Information from drilling logs on the traverse show that L100 is underlain by completely weathered schist with a very thick overburden. The overburden has moderate density which suggest a moderate competence.

In Fig. 7, it can be seen that the shear wave velocity increases progressively from layer to layer with respect to depth. The first layer to a depth of 9.4 m recorded a very high Vs of 822 m/s indicating a layer of well compacted soil to weathered rocks, while the Vs for the next major layer (9.4 to 21 m) was 1591 m/s. This further increased to 1900 m/s between 21 and 36 m and further to the bedrock beyond 36 m with a V_s of 2650 m/s.Geological logs show that L200 is underlain by pegmatite intrusive rock which is slightly weathered, hence a shallow overburden and rocky subsurface materials; suggesting that the site is very competent.

The third traverse, L300 (Fig. 8) recorded Vs for the top 4.4 m layers to range from 233 to 372 m/s, which depict soils with medium density. The next layer was a relatively low velocity layer with Vs of 152 m/s from 4.4 to 9.4 m, signifying a poorly densified to weak layer; however, the next two layers from 9.4 to 15.5 m and 15.5 to 25 m recorded 251 m/s and 416 m/s shear wave velocity values respectively, which depicts a moderately densified soil stratum and a much competent soil layer respectively. The fifth layer recorded a Vs of 299 m/s to a 40 m depth. L300 is underlain by completely weathered schist with a very thick moderately dense overburden, suggesting a moderately competent material.

Traverses L100 and L300 had Vs_{30} of 299 m/s and 269 m/s respectively within the range of 180-360 m/s and are classified C using the Eurocode 8 soil classification for seismic sites. These areas thus consist of thick layers of moderate to dense soil. However, L200 with Vs_{30}value of 1271 m/s is classified as A under the EC 8. This class is described by geological formations made of rock or other rock-like materials, with very shallow weak materials near the surface. The thin overburden material overlying the rocky subsurface indicates higher resistance to ground vibrations or cyclic stress.

The Vs_{30} relates to the soil rigidity or stiffness, and this is depicted in Fig. 9, such that shear modulus or rigidity (Gs) increases as the Vs for each of the soil layers within the stratigraphy from the surface to a depth not more than 30 m.

Similar to the results obtained for the Vs_{30}, the geotechnical parameters computed for the upper 30 m; thus, Shear modulus (G_{30}), Bulk density (ρ_{30}), Young's modulus (E_{30}) and Bulk modulus (K_{30}) reported for these three sites show moderate elasticity moduli for L100 and L300, whereas L200 had very high elasticity moduli (Table 1). The shear modulus values depict the level of resistance of the subsurface materials to shear stress impacts; the young's modulus provided information on the strength of the soils/rocks to withstand tensile stress impacts; whereas the bulk modulus reveals the ability of the subsurface materials to overcome compressive stress impacts; and finally, the bulk density informs on the level of denseness or competence of the soils or rocks at a site. With respect to all these geotechnical parameters, it can be inferred that the L200 site has the highest capacity to withstand and resist seismic impacts. However, sites L100 and L300 possess average abilities to resist such impacts.

3.2 Horizontal to Vertical Spectral Ratio (HVSR)

Peaks of the horizontal to vertical spectral ratio have shown to be reliable predictors of the resonance frequency of low-impedance surface layers (Pazzi *et al.,* 2016). Amplification factors and natural ground frequency at the location are used to assess or represent the impacts, identifying locations with high seismic risk during an earthquake (Picozzi *et al.,* 2009).

The site response parameters that were derived from the HVSR curves (Figs. 10, 11 and 12) of the study area are presented in Table 2. The amplification (H/V ratio) factor at the site ranges between 1.15 and 5.50 and indicate minimal seismic impedance contrast due to the thin sedimentary layer overlying the competent bedrock. The geology of the study area comprises of mainly competent rocks and highly compacted soil materials hence do not amplify ground motions significantly.

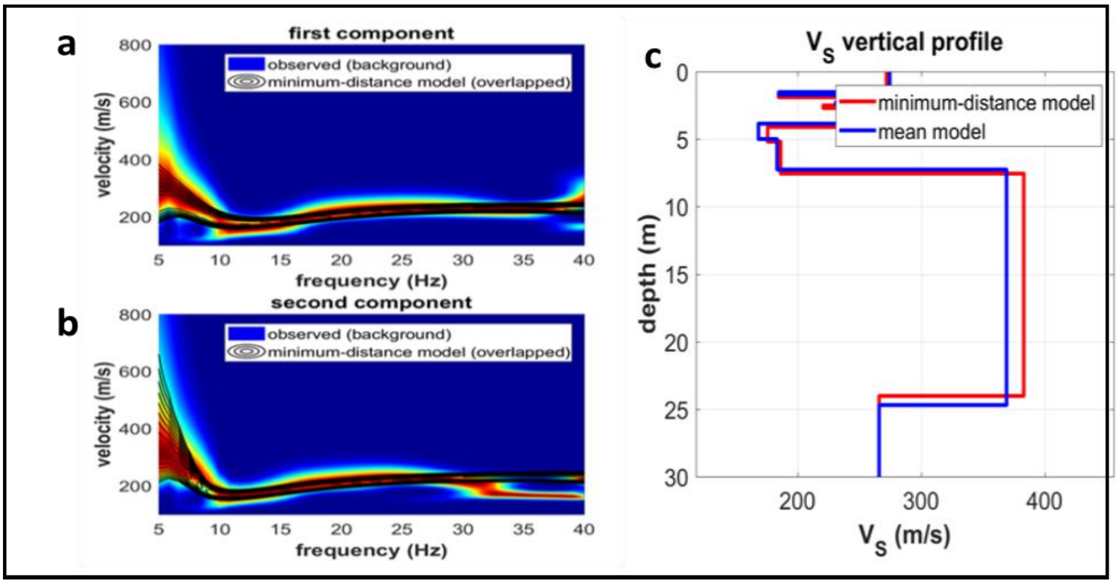

Fig. 6 Joint Inversion of Rayleigh Waves Showing Velocity Spectra for (a) Vertical Component (Z) (b) Radial Component (R) and (c) Shear Wave Velocity Profile for L100

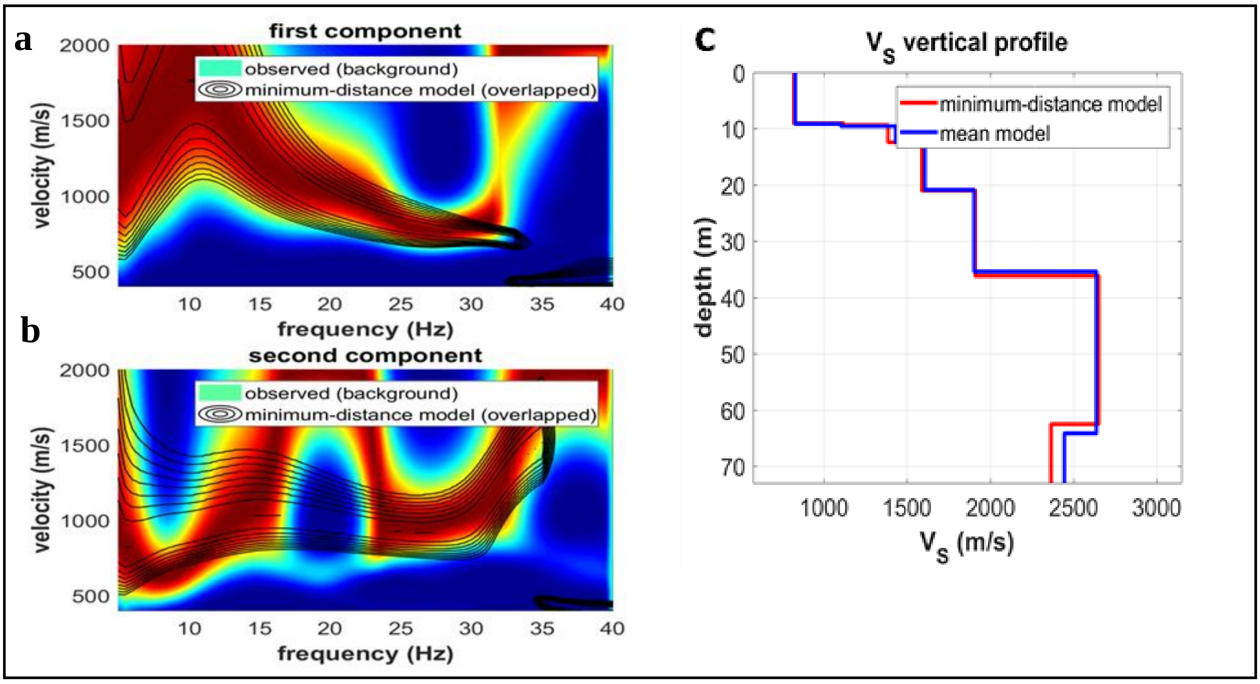

Fig. 7 Joint Inversion of Rayleigh Waves Showing Velocity Spectra for (a) Vertical Component (Z) (b) Radial Component (R) and (c) Shear Wave Velocity Profile for L200

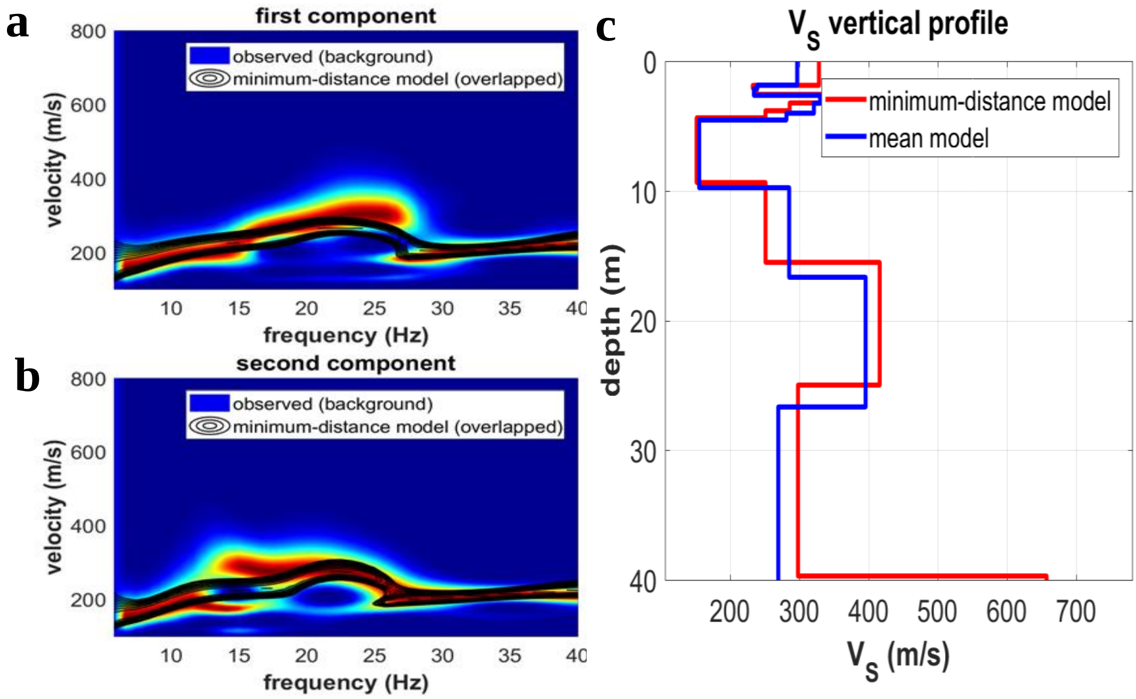

Fig. 8 Joint Inversion of Rayleigh Waves Showing Velocity Spectra for (a) Vertical Component (Z) (b) Radial Component (R) and (c) Shear Wave Velocity Profile for L300

Table 1 Site Category Determination Based on Vs, 30 model and dynamic engineering properties

MASW Line	Vs_{30} (m/s)	Shear Modulus, G_{30} (MPa)	Bulk density, ρ_{30} (kg/m^3)	Youngs Modulus, E_{30} (MPa)	Bulk modulus, K_{30}(MPa)	Site Class
100	299	145.37	1626.06	375.06	297.67	C
200	1271	3508.52	2171.86	9192.31	8063.43	A
300	269	115.20	1592.04	306.44	300.43	C

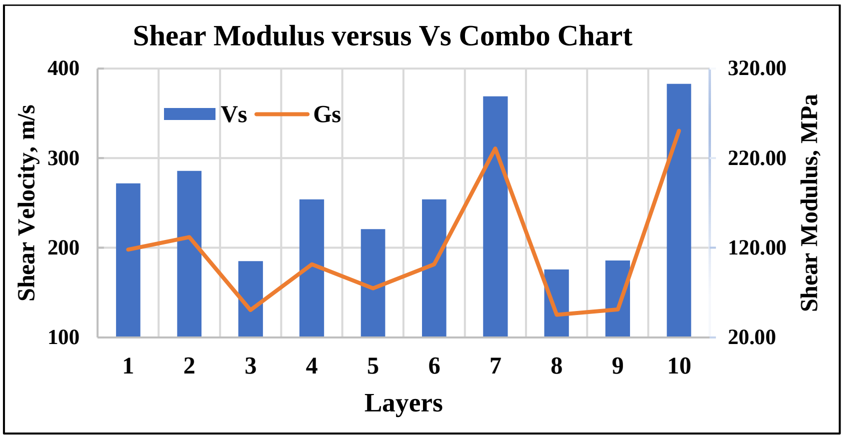

Fig. 9 Relationship Between Shear Wave Velocity and Shear Modulus

The minimum and maximum natural peak frequencies for the study area are 2.06 Hz and 4.88 Hz, respectively. Zones with natural frequencies less or equal to 2.0 Hz are prone to high seismic amplifications and are more vulnerable as compared to those above 2.0 Hz (Chauhan *et al.*, 2019).In this regard, it can be said that all three sites have high resistance to seismic amplifications, thereby not vulnerable seismic impacts.

The minimum and maximum natural peak periods for the site are 0.20 seconds and 0.49 seconds, respectively. These short periods indicate that when seismic shocks occur, it would be dissipated quickly within a period of less than 0.5 seconds, hence, its effects would not be felt for a longer period.

The vulnerability index (K_g) values for the study area ranges from0.30 to 6.34. The K_g is used as an indicator to the extent of vulnerability of a site and the structures *in situ* in the event of a cyclic stress impact. For a site to respond to seismic events that could impose hazard or destruction on buildings and other structures, the K_g values must be greater than 20 (Nakamura, 1997). The higher the K_g value, the greater the tendency for the site to experience varying levels of destruction, including the collapse of structures (Rezaei and Choobbasti, 2014;Chauhan *et al.*, 2019).The results obtained from this study establishes that no significant impacts of blasting will be experienced in the catchment area due to the envisaged mining activities.

With special reference to Figure 13, it can be deduced that among the HVSR site response parameters presented, the ground amplification factor (A_g) has a direct correlation with the vulnerability index (K_g). Thus, sites with greater A_g values have high K_g values.

Table 2 Site Response Parameters and Vulnerability Index for the Study Area

MASW Line	HVSR Site	H/V Ratio	Peak Frequency (Hz)	Natural Period (s)	Vulnerability index, K_g
L100	1	1.21	4.88	0.2	0.3
	2	5.5	4.77	0.21	6.34
L200	1	3.5	2.26	0.44	5.42
	2	1.72	2.06	0.49	1.44
L300	1	1.15	3.38	0.3	0.39
	2	1.32	3.56	0.28	0.49

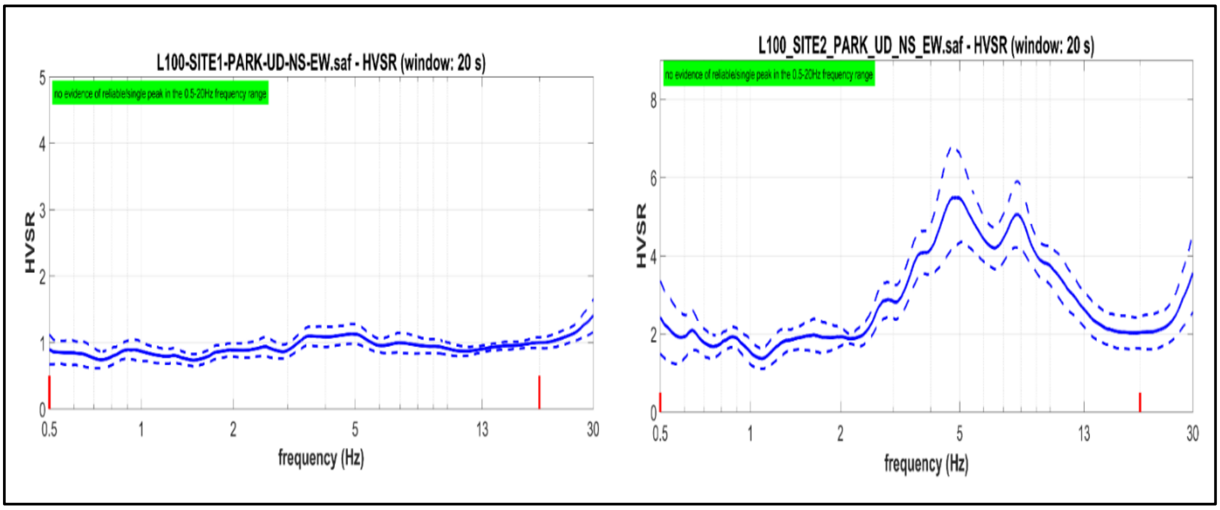

Fig. 10 Horizontal-to-Vertical Spectra Curves on L100

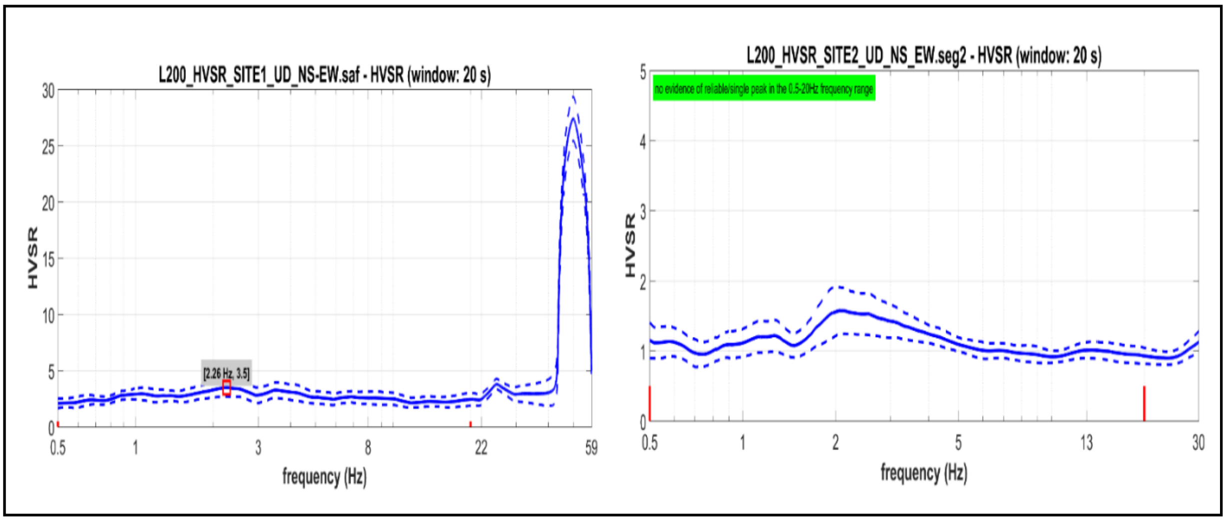

Fig 11 Horizontal-to-Vertical Spectra Curves for L200

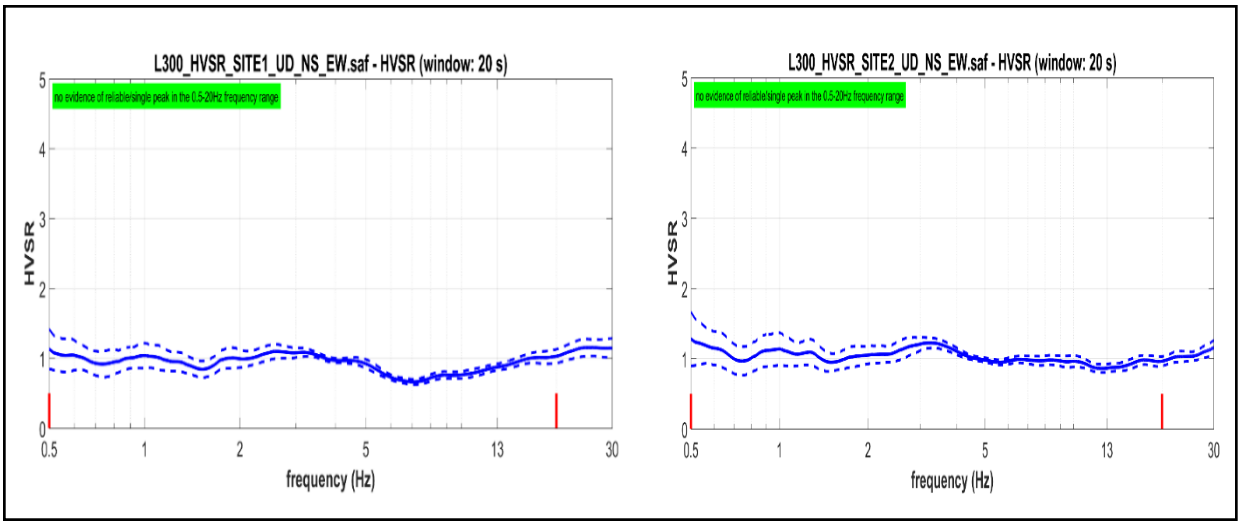

Fig. 12 Horizontal-to-Vertical Spectra Curves for L300

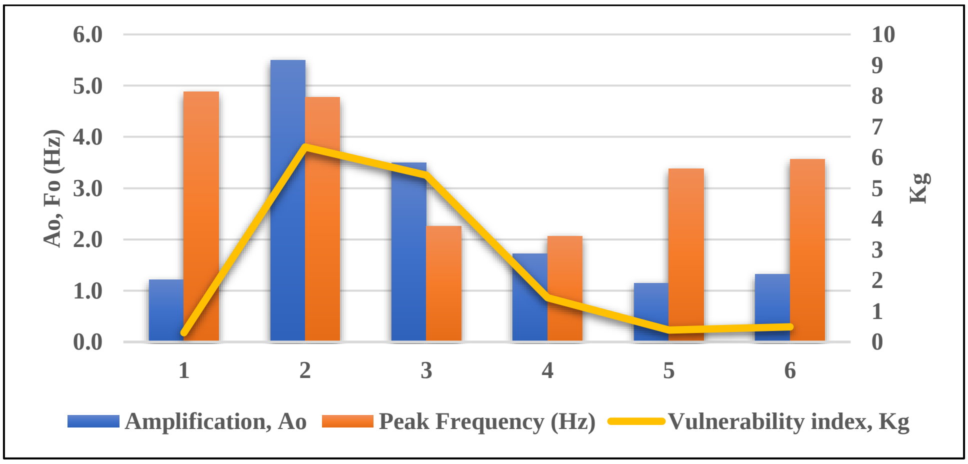

Fig. 13 Relationship between the Site Response Parameter

4 Conclusions and Recommendation

4.1 Conclusion

Generally, the shear wave velocities obtained at the three sites yielded site characteristics that prove that the area is competent and will withstand any seismic event. The Vs30 values recorded at sites L100 and L300 were 299 m/s and 269 m/s, respectively. Since these values fall within the range of 180-360 m/s, the sites are classified as C with respect to the Eurocode 8 seismic site classification for soils. This shows that the areas consist of thick layers of moderate to dense soil. Site L200 recorded a Vs30 value of 1271 m/s, therefore, the site is classified A using the EC 8. Thus, the dominant geological formations at this site are rock or other rock-like materials, with very shallow weak materials near the surface. The shallow thickness of the overburden material overlying the rocky subsurface suggests greater resilience to cyclic stress or ground vibrations.

Shear modulus (G_{30}), bulk density (ρ_{30}), young's modulus (E_{30}), and bulk modulus (K_{30}) computed for the upper 30 m and reported for these three sites show moderate elasticity moduli for L100 and L300, whereas L200 had very high elasticity moduli. These results have a similar trend as those obtained for the Vs30.

The study areas recorded the lowest and highest natural peak frequencies to be 2.06 Hz and 4.88 Hz, respectively. This means that none of the three locations is vulnerable to seismic impacts due to their strong resistance to seismic amplifications. The natural peak periods also recorded in the study area range between 0.20 and 0.49 seconds. This suggests a brief timeframe and a small amount of amplification as a result of seismic hazards or events. This means that seismic shocks would diminish swiftly, in less than 0.5 seconds, after they occur.

The vulnerability index (K_g) values, which provide an indication of the level of safety or vice versa of a site with respect to seismic impacts, were low for the survey area. This ranged from 0.30 to 6.34. The survey area can thus be said to be generally safe, stable, and secure should blasting and other ground disturbing activities be carried out at the Ewoyaa concession.

4.1 Recommendation

In the event of an earthquake or a tremor having the same frequency as the natural frequency, resonance will occur, resulting in amplification of seismic waves in the area. If this resonance frequency is the same or close to that of the buildings/structures in the area, then the destruction of properties is highly assured. It is therefore recommended that future studies at this site should include frequency measurements of the building at the site. This would go a long way to inform decision makers on the best way forward.

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