



Investigation of near-surface structures using seismic refraction and multi-channel analysis of surface waves methods—a case study of the University of Lagos main campus

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Abstract

The need to use locations which are hitherto swamps or recreation centers to construct more building facilities that range from medium to huge structures within the University main campus informed the decision to embark on this study. Structures within the subsurface layers were investigated by analyzing the distribution pattern of some geophysical properties such as compressional wave (P-wave) velocity, shear wave (S-wave) velocity, and Poisson ratio. The near-surface layers were identified from the first break picks of P-waves velocities. Moreover, the dispersive capability of the surface wave produced S-wave velocity information that identified different geological structures based on the orientations of the lithological layer's rigidity. The P-wave velocities reveal three-layer structures of thicknesses between 3.0 m to 6.0 m and 2.0 m to 5.0 m for Layer 1 and Layer 2 respectively. These layers are in three categories of “Complex”, “Mild,” and “Simple” based on the distribution pattern of shear velocities. Poisson ratio analysis shows two categories of Topsoil/Lateritic layer of less than 2.0 m (thin) and between 2.0 m and 4.5 m (thick). Areas identified as “Complex” structure with thick Topsoil will require comprehensive foundation design than other areas especially when erecting huge building. Whereas, locations around the New Halls (NHs) may require simple foundation plan for building development compared to other areas since it is characterized by thin Topsoil and simple layer structure. The study will assist construction engineers with prior information of the structures of subsurface layers which thereby reduce time and cost of building development within the University campus.

Keywords P-velocity · S-velocity · Poisson ratio · Surface waves · Subsurface structures

Introduction

The seismic refraction method is based on the measurement of the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocities. Seismic energy is provided by a source (shot) located on the surface. Energy radiates out from the shot point, either traveling directly through the upper layer (direct arrivals), or traveling down to and then laterally along higher velocity layers (refracted arrivals) before returning to the surface. This energy is detected on the surface using a linear array (or spread) of geophones

spaced at regular intervals (Kearey et al. 2002). Beyond a certain distance from the shot point, known as the cross-over distance, the refracted signal is observed as a first arrival signal at the geophones. Observation of the travel times of the direct and refracted signals provides information on the depth profile of the refractors.

The application of seismic refraction method in subsurface layers investigation makes use of the velocity of seismic waves traveling through the subsurface that may have varying rock types of different degrees of compaction. Seismic energy in the form of compressional wave (P-wave) produced from a source at the surface and transmitted through the layers undergoes refraction at boundaries between media with contrasting acoustic impedances (Kearey et al. 2002; Ayolabi et al. 2009; Reynolds 2011). These seismic waves are eventually picked up by geophones planted at regular distance on the surface which record the times of arrival (Dobrin and Savit 1988; Adegbola et al. 2013; Mohd et al. 2016). Seismic

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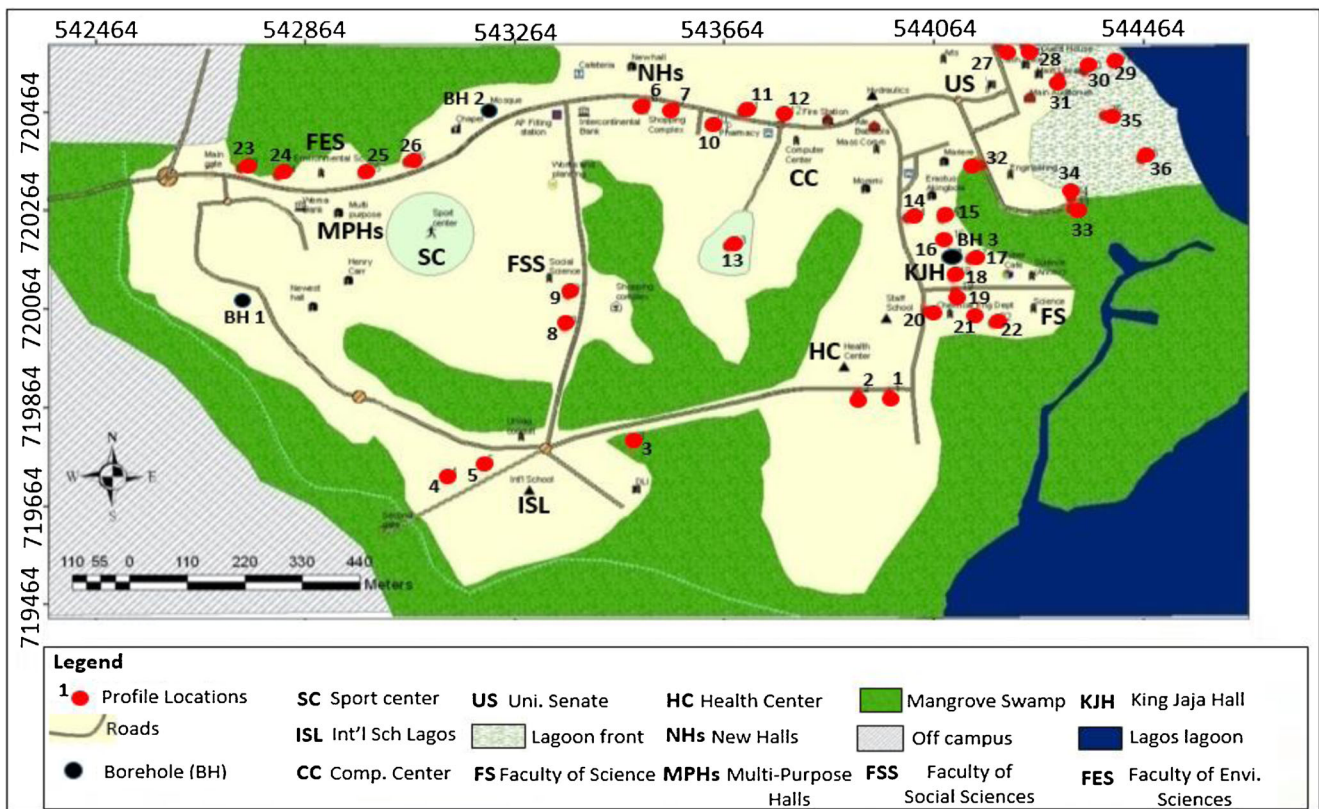


Fig. 1 Map of University of Lagos main campus showing locations of seismic data acquisition (red dots) and borehole locations (black dots)

refraction surveying uses this phenomenon in the determination of ground structures by observing the time it takes for seismic wave propagating through the subsurface to arrive

(Elsayed et al. 2014). Investigating the shallow subsurface conditions in sites with features such as channels, dams, roads, quarries, subways, and bridges using seismic refraction

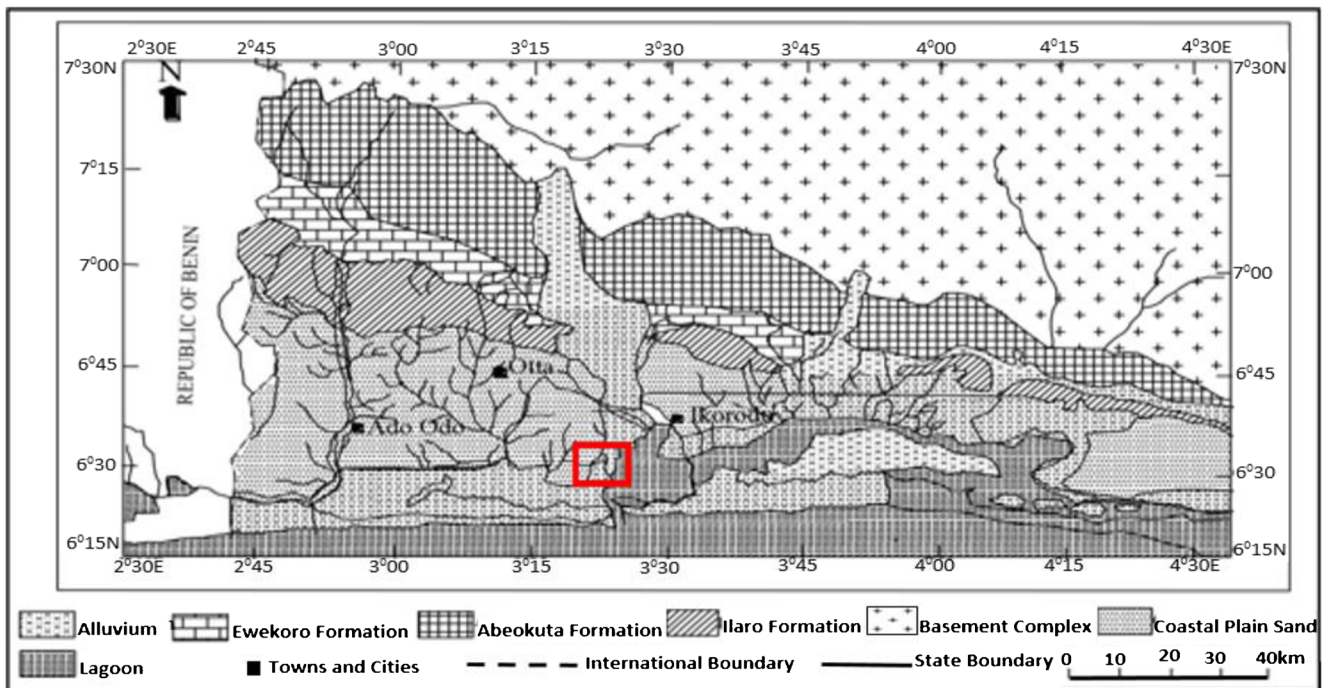


Fig. 2 Geologic map of Lagos and Ogun states (modified from Jones and Hockey 1964) showing location of the study area (red square)

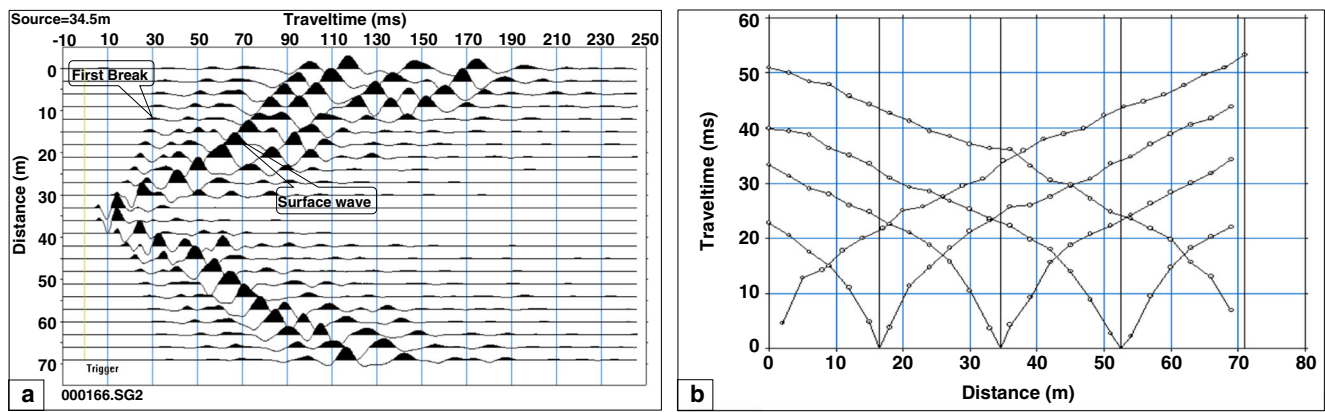


Fig. 3 a Seismic traces from split shot point (34.5 m) of profile 1. b Travel times versus distance plots for the five shot points on Profile 1

technique has shown reliable results (Hatherly and Neville 1986; Adegbola et al. 2013; Fkirin et al. 2016; Maunde and Bassey 2017). Moreover, the integration of refraction method with well log information helped to further determine properties of subsurface layers such as density, water saturation, and Poisson ratio (Sayed et al. 2012). Integration approach like this also helped to determine rock competency for engineering application such as excavation capability, depth to bedrock, crustal structure, and tectonics activities (Kilner et al. 2005; Varughese and Kumar 2011). Combining seismic refraction method with electrical resistivity imaging was used to investigate a dam site where the source and pathway of groundwater seepage were delineated (Sayed et al. 2012; Ronczka et al. 2017).

The refraction techniques depend on the propensity of near-surface wave velocities to increase with depths. This means that refraction methods are not sensitive to velocity

inversion where high velocity layer overlays low velocity layer (Kearey et al. 2002; Igboekwe and Ohaegbuchi 2011; Anomohanran 2013). It further implies that subsurface layer with inverted velocity will not be detected. Hence, construction made on such layer has high tendency to fail (Abidin et al. 2012; Ayolabi and Adegbola 2014). Therefore, to determine the structures of buried layers, S-wave velocity generated from the recorded surface waves which are the late arrivals high amplitude seismograms was analyzed through multi-channel analysis of surface wave (MASW) technique.

MASW is a non-destructive seismic method to evaluate thickness and shear wave velocity of the soil columns (Park et al. 1999). When seismic waves are generated on the earth surface, both body waves (P and S) and surface waves (e.g., Rayleigh, Love etc.) are produced. In theory, both surface wave types are predicted by the plane wave solutions of coupled elastic wave equation (Haskell 1953) as shown in Equations (1) and (2):

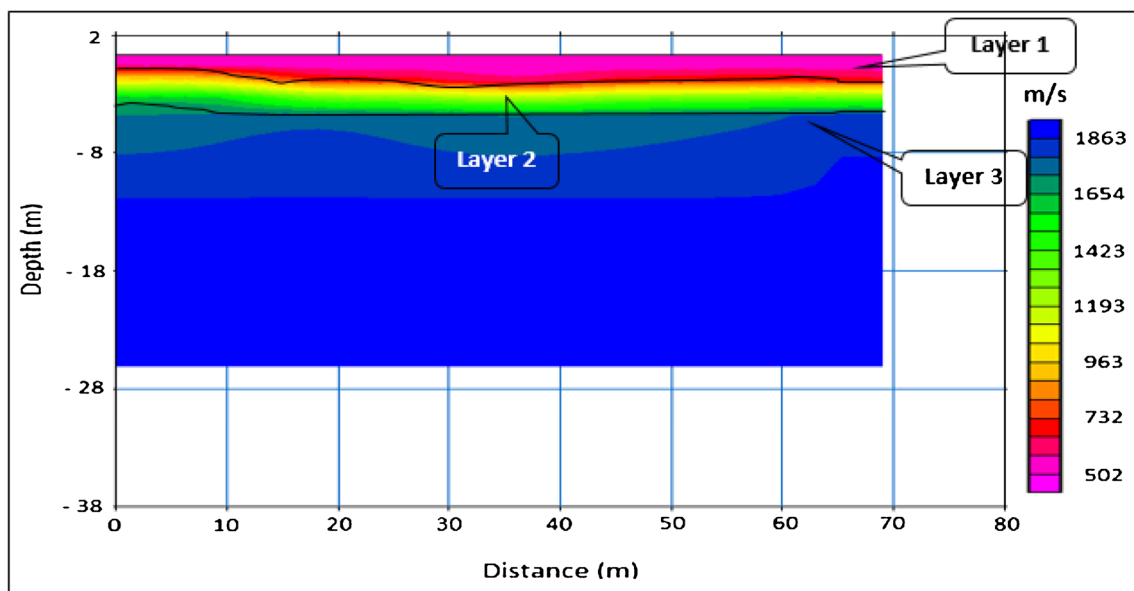
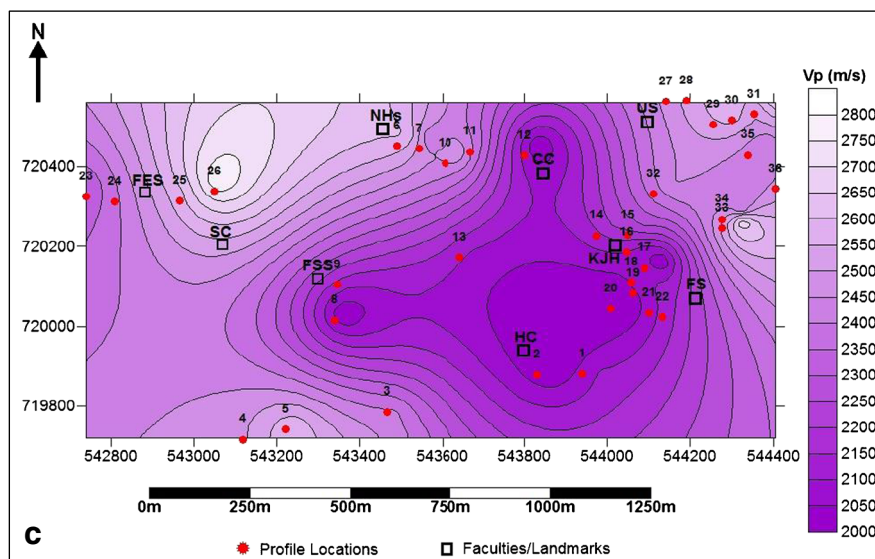
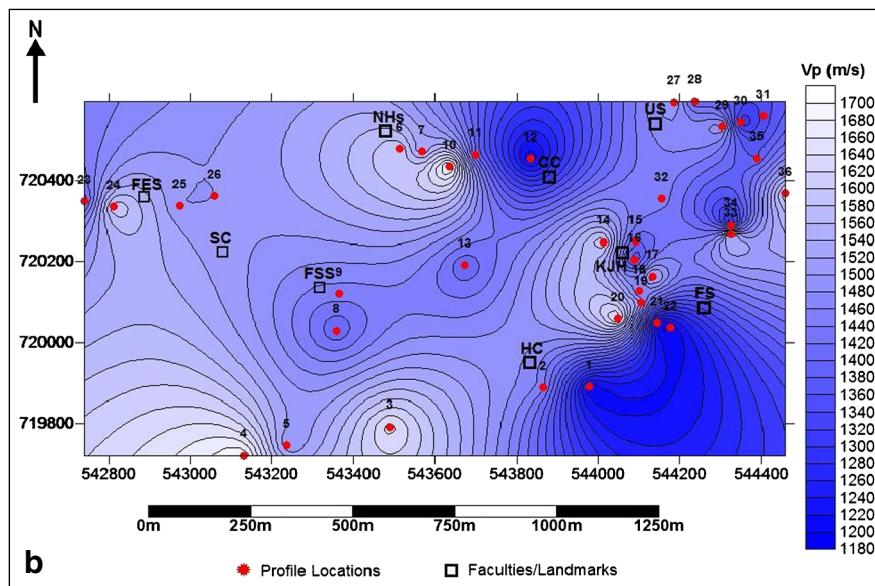
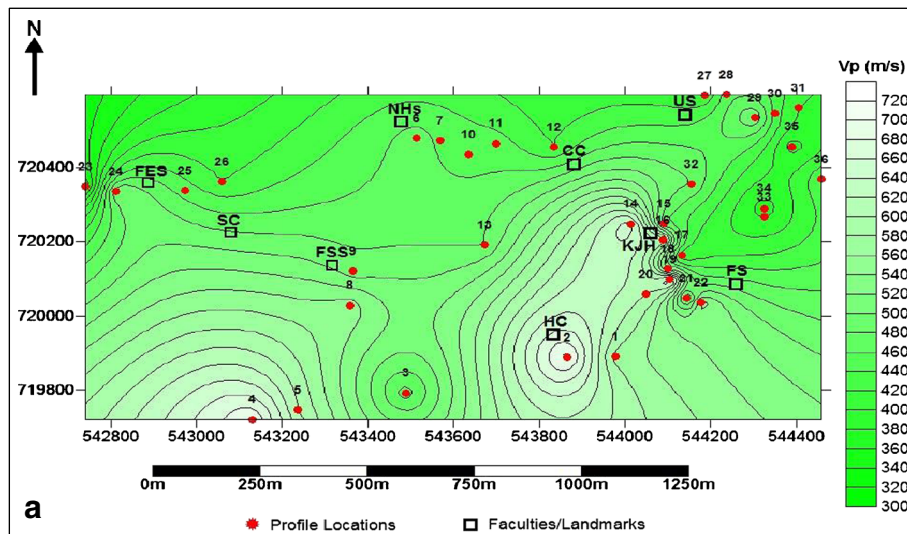


Fig. 4 P-wave velocity distribution of profile 1 showing vertical and lateral trends



◀ **Fig. 5** **a** P-wave velocity distribution of Layer 1 across the University campus. **b** P-wave velocity distribution of Layer 2 across the University campus. **c** P-wave velocity distribution of Layer 3 across the University campus

$$\frac{\partial^2 \psi}{\partial t^2} = V_s^2 \nabla^2 \psi \tag{2}$$

where Φ and ψ represent displacement potentials and V_p and V_s represent P- and S-wave velocities.

$$\frac{\partial^2 \Phi}{\partial t^2} = V_p^2 \nabla^2 \Phi \tag{1}$$

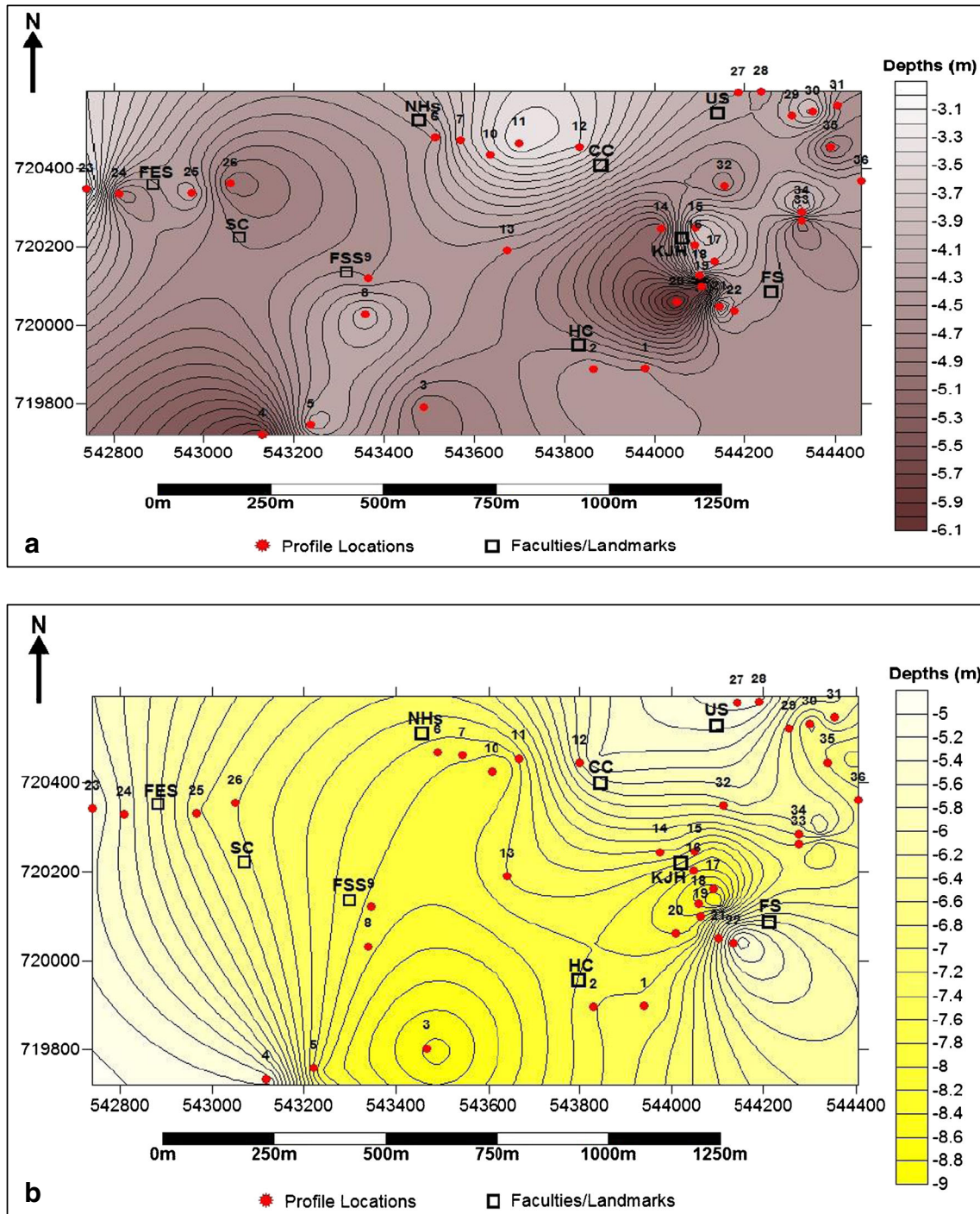


Fig. 6 **a** Depths map of Layer 1. **b** Depths map of Layer 2

Table 1 Summary of information from three borehole logs within the University campus

Borehole log (BH 1)		Borehole log (BH 2)		Borehole log (BH 3)	
Depths (m)	Lithology	Depths (m)	Lithology	Depths (m)	Lithology
0.0–4.1	Topsoil	0–2.0	Top soil	0.0–4.2	Silty clay
4.1–6.8	Sand	2.0–4.5	Silty clay	4.2–8.5	Sandy clay
6.8–16.4	Sandstone	4.5–8.2	Sandy clay	8.5–19.0	Fine sand
16.4–21.5	Sandy clay	8.2–15.8	Clayey sand	19.0–24.0	Sand
21.5–25.0	Clay	15.8–25.0	Fine sand	24.0–33.8	Gravel sand
25.0–27.0	Medium sand	25.0–28.5	Gravel sand		
27.0–32.5	Fine sand	28.5–35.5	Sandstone		

In the past few years, surface waves (ground roll) have been treated as troublesome noise masking the useful body wave signals (Garotta 1999). Most of the efforts have been made to attenuate it through data acquisition and processing techniques (Anstey 1986; Gurevich and Pevzner 2015; Kong et al. 2018). However, the dispersive property of surface waves that body waves lack, such that different wavelengths have different penetration depths and therefore, propagates with different velocities make it very useful (Park et al. 1997; Park et al. 1999; Schwenk et al. 2012). Analyzing the dispersion of ground roll, the near-surface S-wave velocity (V_s) profile can be obtained (Madun et al. 2016). However, the advantages of using the shear wave velocity field calculated from surface waves are not limited to the detection of anomalous subsurface materials. It also includes insensitivity to noise (ambient/cultural), ease of generating and propagating surface wave energy in comparison to body wave energy, and its sensitivity to changes in velocity (Park et al. 1999).

The need to expand and build new Faculties, Departments, Laboratories, Hostels, Staff quarters etc. has led to the use of some abandoned sites within the University of Lagos main campus for the construction of these facilities. Site locations which hitherto are plane field, recreation arena, car parks, soccer pitches, and swamps are now choice locations to erect medium scale to huge structures. This continuous desire to use abandoned sites for building construction informed the need for this study where the distribution of some basic subsurface geophysical properties such as compressional velocity, shear velocity, and Poisson ratio was determined. The distribution trends of these properties serve as useful information to geotechnical and construction engineers. This will assist in deciding the appropriate foundation

procedures to be adopted for the erection of different types of structures within the University main Campus.

Location and geology of the study area

The study area is located within the University of Lagos main campus as shown in Fig. 1. It lies approximately on latitude $6^{\circ}30'40''$ N and longitude $3^{\circ}24'52''$ E. It is bounded to the west by the Ogbe River and to the north, south, and major part of the east by the Lagos lagoon (Ayolabi 2004). It also lies in a marshland of vast mangrove and fresh swamps, surrounding a small and much deserted table land consisting of freshwater swamp, mangrove swamp, sandy plain vegetation, and rainforest (Lewis 1997). Lagos and its environs are located within the Dahomey Basin and it made up of the Benin formation (Miocene to Recent) and Recent alluvial deposits. Thick body of yellow (ferruginous) and white sands characterizes the Benin formation (Jones and Hockey 1964). The sands are friable, poorly sorted with shale intercalation, and sandy clay with lignite. Figure 2 is the geological map of Lagos and Ogun states, south west Nigeria showing the location of the study area indicated by the red square.

Methodology

Data acquisition

The field data acquisition procedure began with a reconnaissance survey to map out traverses (profiles) where data were

Table 2 Comparing layer thickness from the borehole logs and refraction survey results

	BH 1 (m)	Survey (m)	BH 2 (m)	Survey (m)	BH 3 (m)	Survey (m)
Layer 1 (m)	4.1	4.5	4.5	4.5	4.2	4.4
Layer 2 (m)	2.7	2.5	3.7	3.1	4.3	4.2

Table 3 P-velocities (V_p) for soils and rocks (Braja 2013)

Geo-material	Seismic velocity (m/s)
Topsoil	200–1000
Alluvium	500–2000
Compacted clay	1000–2500

acquired using a twenty-four channel seismograph of 10 Hz vertical geophone with 3 m spacing. In this study, thirty-six (36) profiles were mapped, spread around the University main campus as shown in the base map as big red dots. These red dots mark the center of the 71 m profile spread length. A sledge hammer (about 27 kg) and a thick/heavy metal plate of 33 cm × 21 cm × 5.5 cm weighing about 25 kg were used to generate the source energy needed for this near-surface investigation. The geophones were firmly planted along the profile into the ground while the first shot was done at zero meter (0.0 m) shot coordinate, 2 m away from the first planted geophone. On each profile, five shots were made at coordinates 0.0 m, 16.5 m, 34.5 m, 52.5 m, and 71.0 m. Three borehole data which were acquired prior to this study were used to substantiate the identified layers from this refraction survey.

Data processing

The first arrival events were picked for all profiles which were used to generate time-distance curves (T-X plot) for the five shots of each profile. Then, the relationships between time and distances helped to produce the P-wave velocity trends for all the profiles. Velocities and depths of the layers were determined from the velocity distribution trends. Moreover, the thickness of Layer 2 is the difference between the depth of Layer 1 and depth of Layer 2. Apart from the picked first arrivals, the high amplitudes but low frequency late arrivals which are mostly the surface waves (Kearey et al. 2002) were also analyzed. This horizontally traveling wave field was recorded by receivers (geophones) laid at the surface with spacing dx . They were

analyzed at different frequencies (f) for the phase velocities (V_f) based on the difference in the arrival times (Δt_f) of ground roll at two receivers as described by Equation (3).

$$V_f = \frac{dx}{\Delta t_f} \tag{3}$$

The analysis produces a set of data (f vs. V_f), the dispersion data, that were in turn passed into next step which is the inversion process. This process helped in the extraction of shear velocity from dispersion curves. The approach uses the least-squares algorithm inversion process as discussed by Park et al. (1997). Extracted shear velocities which were generated in 1-D were contoured using Surfer 8 to produce its 2-D model of shear velocities distribution within the near surface for all the profiles. Poisson ratio (σ) is an elastic property for rigidity determination (Sheriff 2002) and was estimated using the relation in Equation (4). “Seisimager” software which has packages like the Pickwin, Plotrefa, and WaveEq was used at different stages of data processing for picking first arrivals, P-velocity, and S-velocity analyses.

$$\sigma = \frac{V_p^2 - 2V_s^2}{2V_p^2 - V_s^2} \tag{4}$$

where V_p and V_s are the respective compressional and shear wave velocities.

Results and discussions

P-wave velocity analysis

The first break and surface wave arrivals are identified in Fig. 3a for 34.5 m shot point (coordinate) of Profile 1. Figure 3b is the T-X plot of the five shot points for Profile 1. These curves are sets of data pointing on approximately the same line; this represent time response from a

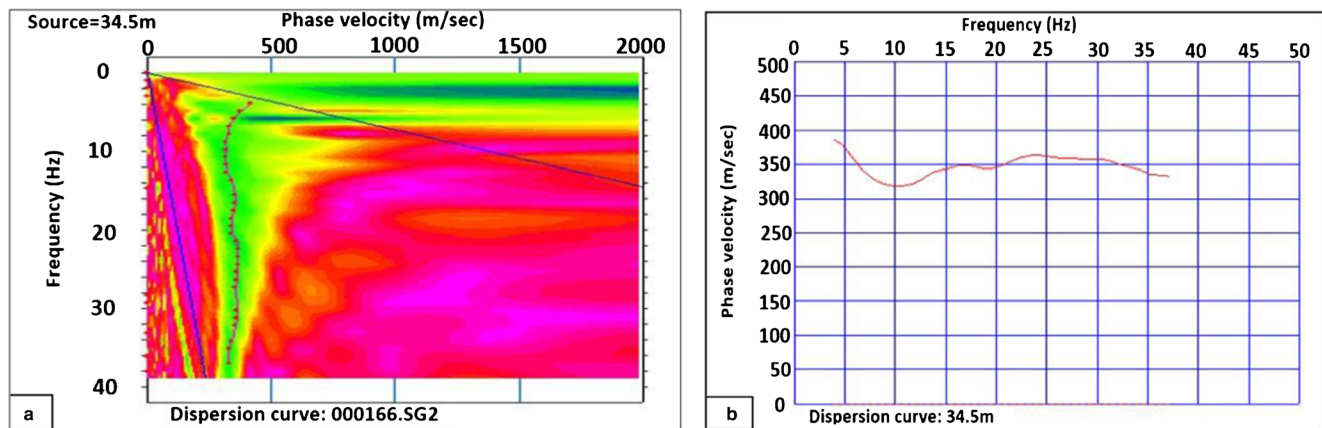


Fig. 7 a Trend of picked surface waves fundamental modes and b the dispersion curve

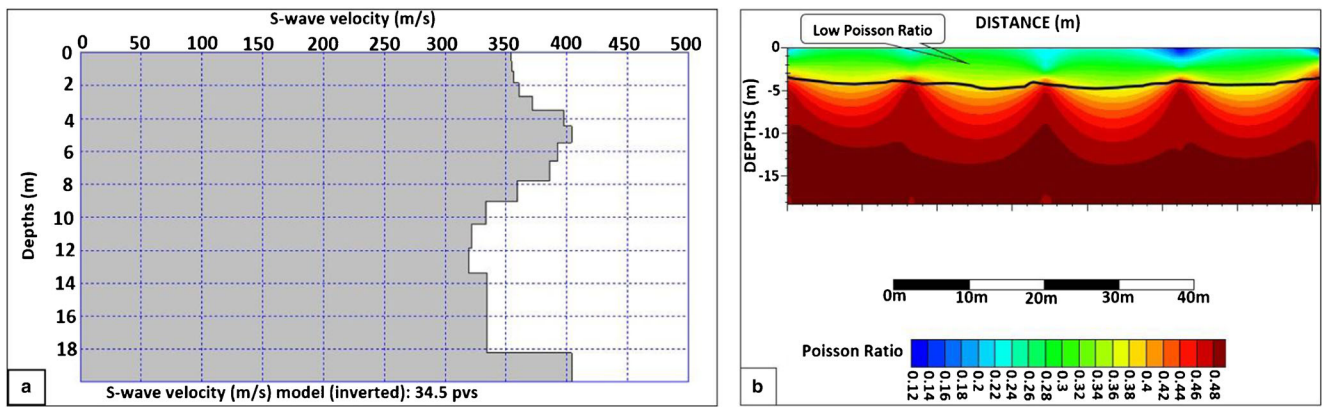


Fig. 8 a A one dimensional shear wave velocity trend and b Poisson ratio distribution across Profile 1

particular layer as described in Telford et al. (1990). This gives an indication of the numbers of geological layers present within the subsurface. Most of the surveyed profiles reveal mainly three layers refraction as illustrated in Fig. 4 which is a 2-D P-velocity distribution. Also, the P-velocity trend of each layer provides area understanding of this property. Figure 5 (a), (b), and (c) are the respective P-velocity distribution maps of Layer 1, Layer 2, and Layer 3 and the corresponding depths maps of the first two layers are presented in Fig. 6 (a) and (b). Full definition of the Faculties/Landmarks as illustrated in the P-velocities and Depths maps is presented in the base map of Fig. 1.

The Northern part of the University campus is predominantly characterized by low P-velocity between 300 and 460 m/s while the Southern part has increased velocity of 500 to 700 m/s as shown in Fig. 5a. This first layer (Layer 1) is seen to consist Topsoil and Silty clay of total thickness of about 4.5 m around the borehole (BH 2) location as revealed in Table 1 while thickness range from 3.6 to 4.8 m at the Northern section of the Campus. It could be as thick as 5.6 m in other parts of the surveyed area. Results from the borehole logs produced good correlation with results from the seismic refraction survey in

Layer 1 as shown in Table 2. Moreover, the P-velocity from the survey falls within the velocity range of Topsoil as described by Braja (2013) in Table 3.

In the second layer (Layer 2), the North East and South Eastern parts have P-velocities that range from 1240 m/s to 1480 m/s. Velocity increased between 1520 and 1680 m/s at the other parts as illustrated in Fig. 5b. The borehole logs (BH 1, BH2, and BH 3) in Table 1 reveal that the second layer is mainly Sand and Sandy clay with respective thickness of 2.7 m, 3.7 m, and 4.3 m from the borehole points. These showed comparable thicknesses with the estimations from the seismic survey (Table 2). It is further supported by Table 3 which shows that the velocity range is for Topsoil and Alluvium, an evidence of friable sediments. The thickness of the third layer with velocity of 1900 m/s and 2800 m/s cannot be determined by the refraction technique. It showed a relative low P-velocity around the center and at the South Eastern part of the University campus. This analysis implies that from ground surface to about 4.5 m deep especially around the boreholes are mainly Topsoil and Silty clay. These geo-materials portray weak compacted soil layer as described by Ayolabi and Adegbola (2014). It should be

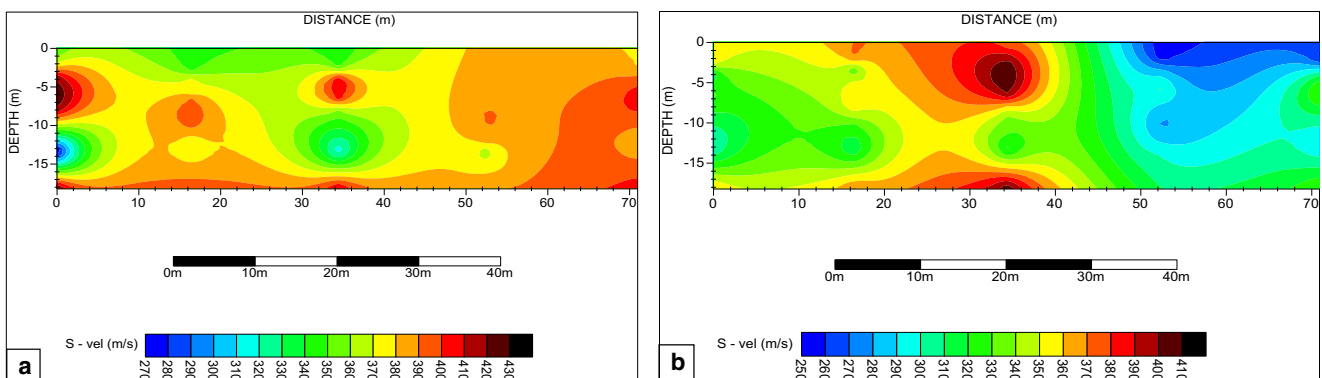


Fig. 9 “Complex” distribution pattern of shear velocity for Profile 20 (a) and Profile 30 (b)

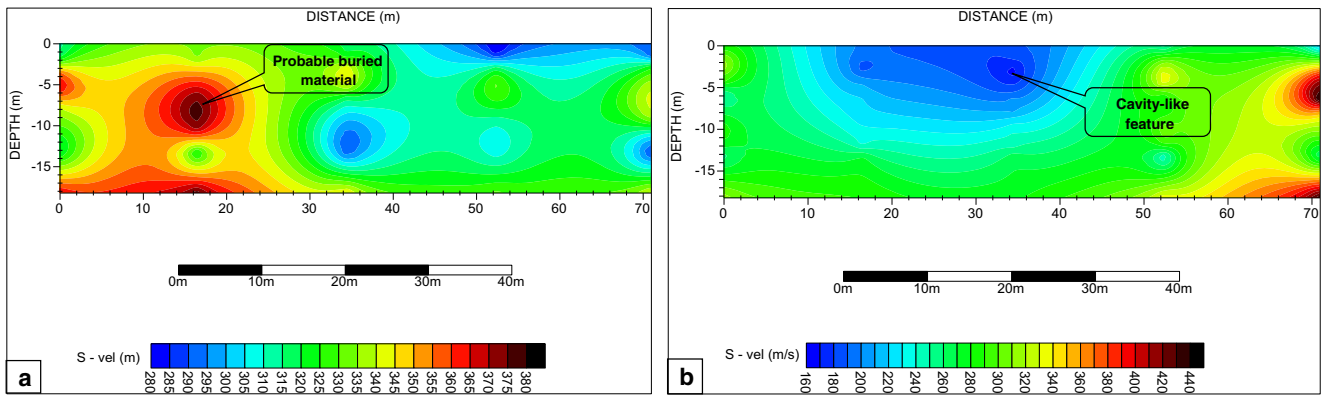


Fig. 10 “Mild” distribution pattern of shear velocity for Profile 11 (a) and Profile 27 (b)

excavated so as to expose the under laid relatively thick sand rich layer especially when considering erecting medium to gigantic structure.

Surface wave velocities analysis

The picked fundamental modes of the surface waves for dispersion analysis are shown in Fig. 7a and the dispersion curve is presented in a plot of phase velocity versus frequency which has displayed in Fig. 7b. This dispersive property is related to the vertical distribution of shear velocity within the subsurface as described in Dulaijan and Stewart (2007) and Adegbola et al. (2013). A 1-D distribution of shear velocity obtained from the analyzed surface wave is shown in Fig. 8a. On the other hand, the level of compaction/rigidity which has depicted by the Poisson ratio distribution for Profile 1 is illustrated in Fig. 8b. It shows that low Poisson ratio between 0.12 and 0.38 ties with the loosely packed Top soil of the first layer with an average thickness of 4.2 m for Profile 1. However, the shear velocity distribution of the five shots is presented in its 2-D format for better lateral interpretation of its trend as shown in Figs. 9, 10, and 11. The observed variation in the 2-D shear velocities reveals

different patterns resulting from the rigidity structure of the different layers within the near surface.

The results of the observed patterns in shear velocity trends for the 36 profiles are presented in three different categories depending on the complexity of the layer structure. These are the “Complex,” “Mild,” and “Simple” structures. Low Poisson ratio of less than 0.40 reveals two categories of thickness as shown in Table 4. These are thicknesses less than 2.0 m and when it is greater than 2.0 m but less than 4.6 m. This range of low Poisson ratio typifies the presence of Loose soils/ Laterites, Non-saturated clay, Sandy clay, and Silt as discussed in Sharma et al. (1990) and Essien et al. (2014). These links corroborate the results from borehole logs. The observed structures of the respective layers as described by the shear velocity distribution patterns and Poisson ratio trends are indicated by the mark “X” (Table 4). Low Poisson ratio at depths of less than 2.0 m characterized most of the investigated profiles. It implies that the shear wave produced low propagation velocity relative to the corresponding compressional wave which is an attribute of the presence of loose and lateritic soil.

Figure 9 (a) and (b) are the respective 2-D shear velocity distribution pattern illustrating “Complex” structural features.

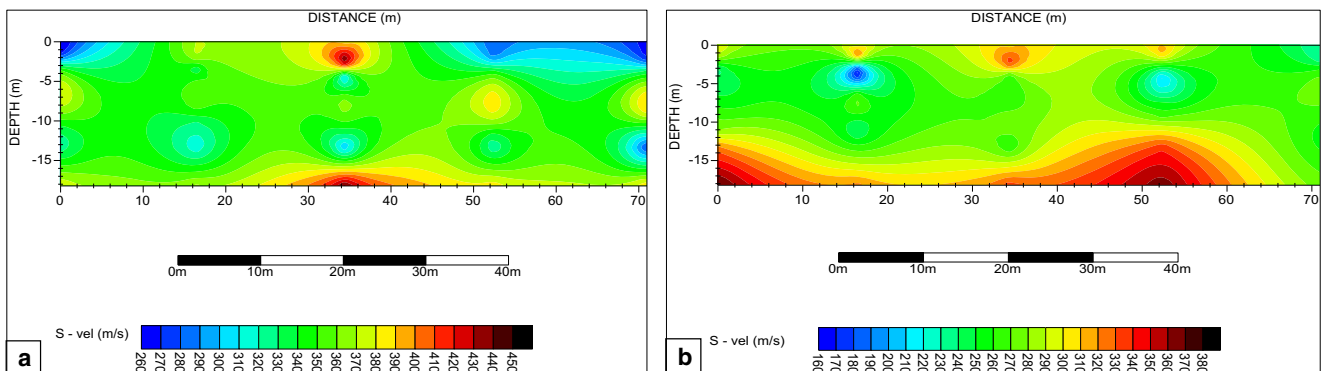


Fig. 11 “Simple” distribution pattern of shear velocity for Profile 13 (a) and Profile 23 (b)

Table 4 Shear wave velocities and Poisson ratio distribution patterns for all profiles

Profiles	Shear velocity structures			Average thickness of low Poisson ratio of less than 0.40	
	Complex	Mild	Simple	< 2.0 m	> 2.0 m and < 4.6 m
Profile 1		X			X
Profile 2		X			X
Profile 3		X		X	
Profile 4			X	X	
Profile 5		X		X	
Profile 6			X		X
Profile 7			X		X
Profile 8		X		X	
Profile 9			X	X	
Profile 10	X			X	
Profile 11		X		X	
Profile 12			X	X	
Profile 13			X	X	
Profile 14		X		X	
Profile 15		X		X	
Profile 16	X				X
Profile 17		X		X	
Profile 18			X		X
Profile 19			X		X
Profile 20	X				X
Profile 21		X		X	
Profile 22	X			X	
Profile 23			X		X
Profile 24			X	X	
Profile 25			X	X	
Profile 26	X			X	
Profile 27		X		X	
Profile 28			X	X	
Profile 29			X		X
Profile 30	X				X
Profile 31			X	X	
Profile 32			X	X	
Profile 33	X			X	
Profile 34		X			X
Profile 35		X		X	
Profile 36			X	X	

This suggests that the shear strength which determines the level of compaction of the lithologies is not horizontally stratified or rigidity varies significantly from point to point within the profile. It is therefore very important to take necessary precautions while designing foundation plan in this area. Figure 10 (a) and (b) represent “Mild” distribution of shear velocity while Fig. 11 (a) and (b) are illustrations of a typical “Simple” distribution pattern of shear velocity.

The features observed from the “Mild” structures are archetypal of the presence of high shear velocity (360–

380 m/s) which could be a result of a buried, well-compacted sediment (Fig. 10a). It can as well be the presence of buried pipe, cables, or drains due to human activities. Also, a cavity-like structure with low shear velocity (160–240 m/s) could indicate a region of poor compaction that possibly represents the presence of recent land fill sediments as shown in Fig. 10b. This may pose danger during huge engineering construction if not properly considered during foundation development design. Furthermore, in this type of scenario, a case of

velocity inversion within the subsurface may also occur. A “Simple” structural scenario shows gradual increase in velocities with depth from one layer to the next. In this case, simple foundation of minimal cost is required for both medium to massive building construction.

Moreover, the “Complex” structure observed from Profiles 20 and 30 also has thick lateritic Topsoil layers of between 2.0 and 4.5 m. Such areas are situated opposite the Health Center (HC), New Halls (NHs), and around King Jaja Hall (KJH). It is very important to deploy other geotechnical means such as Cone Penetrating Testing (CPT) in the foundation design around this area. Areas characterized by “Mild” structural complexities may not require compound foundation design plans as the “Complex” structures. Depending on the complexity of the subsurface structure as revealed by the patterns of shear velocity distribution and Poisson ratio trends, substantial foundation design plan may be required around areas like NHs, KJH, Faculty of Science (FS), Faculty of Environmental Science (FES), Swamps, and Lagoon front. However, strategic approach will be required in the foundation design and planning processes in areas with the “Mild” structural features than when the orientation of the layers rigidity is “Simple”.

Conclusion

Compressional and surface wave analyses for the detection of near-surface structures have been carried out in this study. The extracted shear wave velocities as a function of depth (up to 18 m) which revealed the near-surface rigidity anomalies complement and improve on the results from the compressional velocity analysis where depths of the identified layers hover around 8 m to 10 m. These further helped in determining the Poisson ratios which showed that some areas within the University main campus have thick but loose Topsoil layer. It is advised that this type of layer should be excavated before laying proper foundation especially for massive building construction. This study has revealed the different orientations of near-surface layers rigidity which can assist construction engineers in preparing the needed foundation designs. The results are laterally extensive and will help to reduce cost of acquiring many point source information within the University campus and areas with similar lithological setting. It may also help in reducing time of building project delivery.

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