geologica acta

Citation: Aka, M.U., Agbasi, O.E., Ibuot, J.C., 2024. Comprehensive seismic refraction analysis and 2-D geological modeling in Ini Local Government Area, Akwa Ibom State, Nigeria. Geologica Acta, 22.11, 1-11, I-IV.

Online ISSN: 1696-5728 DOI: 10.1344/GeologicaActa2024.22.11

Comprehensive seismic refraction analysis and 2-D geological modeling in Ini Local Government Area, Akwa Ibom State, Nigeria

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ABSTRACT

Seismic refraction methods are vital in geophysical investigations to reveal subsurface geological structures. This study focuses on the Ini Local Government Area, Akwa Ibom State, Nigeria, analyzing geological features beneath the surface, with emphasis on seismic velocities and layer thicknesses. The primary aim was to determine subsurface composition, identify geological disruptions, and develop 2-D subsurface models using seismic refraction data. Data were collected from forty locations using a Geometric ES 3000 12-Channel Seismograph, a Vulcan Sledge Hammer as the energy source, and geophones as detectors. The data were processed into Two-Way Time (TWT) graphs, and models were generated using strata modeling software. Three primary layers were identified: Layer 1 (topsoil) with lower seismic velocities (209-500m/s) and shallow depths (1-3m), Layer 2 (consolidated subsoil) with higher velocities (221-1210m/s) and greater depths (4-9m), and Layer 3 (bedrock) with the highest velocities (510-1700m/s) and depths (4.5-14.5m). Variations in seismic velocities and thicknesses highlighted geological instabilities. The V_P/V_S and Poisson's ratios provided insights into lithological variations. 2-D sections showed lateral variations and models revealed disruptions like faults. The study delineated three seismic layers, highlighting areas with suitable and unsuitable conditions for construction. This research's novelty lies in integrating seismic refraction data with advanced 2-D modeling, offering a comprehensive subsurface analysis crucial for construction planning and geological hazard assessment in Ini Local Government Area (LGA).

KEYWORDS **Seismic refraction. Geological modeling. Subsurface analysis. Seismic velocities. Geological discontinuities. Akwa Ibom State. Construction planning.**

INTRODUCTION

Geophysical data is an essential factor that must be considered while designing and constructing civil engineering structures, such as buildings, highways, and dams. This is because geophysical data is a crucial element that necessitates careful consideration during the entire procedure (Adewoyin *et al.*, 2021; Hasan *et al.*, 2020). More precisely, geophysical data is essential for ongoing actions, providing critical insights that inform and guide engineering decisions. During the site investigation phase, which occurs prior to the commencement of excavation and construction, it is customary to extensively utilize geophysical technology. This preliminary step is vital for ensuring the stability and safety of the proposed structures (Lin *et al.*, 2018).

Geophysical technologies are employed to ascertain the thickness of the overburden and to chart the subsurface conditions. One common method used is the resistivity technique. However, while employing this method, the depth of exploration is constrained by the array techniques utilized during data collection, such as resistivity sounding or resistivity imaging (Aka *et al.*, 2018; George *et al.*, 2010). The resistivity technique operates on the principle that as the depth of the subsurface increases, the amount of resistive material present also tends to increase. This method, although useful, imposes limitations on the maximum depth at which subsurface sections can be acquired, which can be a significant drawback in certain contexts (Doyoro *et al.*, 2021).

Given the constraints of the resistivity method, it is crucial to consider alternative approaches that can provide a more comprehensive understanding of subsurface conditions. The seismic method stands out as the most effective approach for obtaining a thorough and precise understanding of underground regions in terms of geophysical processes (Zhang and Curtis, 2020). This method provides a visual representation of the subsurface structure in both two-dimensional and three-dimensional forms, with a substantial level of detail. This comprehensive perspective offers a more in-depth analysis compared to the resistivity approach, which tends to provide a more shallow or superficial understanding. The inherent stability of the seismic method in a three-dimensional layout ensures the stability and reliability of the geographical section it enumerates, making it a highly reliable and safe procedure for application (Song *et al.*, 2019; Zhong and Yang, 2021).

The research undertaken by Ugwu (2008), Ayolabi *et al.* (2009) and Gabr *et al.* (2012) all support the effectiveness of the seismic method for geophysical investigations. Their studies have demonstrated the advantages of using seismic methods to achieve a more accurate and detailed understanding of subsurface conditions, which is crucial for the successful execution of engineering projects.

Due to ongoing expansion in Ini Local Government Area (LGA) of Akwa Ibom state, Niger Delta, Nigeria, a wide range of engineering activities, dredging operations, and construction projects are now underway. These projects are being implemented across the region, driven by the need for development and modernization. However, over the past few years, there have been recorded cases of construction disasters caused by structural failure (Igwe and Umbugadu, 2020). These calamities have led to the complete destruction of buildings and other structures, resulting in significant economic losses and, in some cases, loss of life. One of the primary reasons for these disasters is the insufficient link between construction companies and the subsurface geology of the region. This lack of understanding and communication has led to construction companies abandoning their work sites due to unforeseen geological challenges. The root cause of the problem lies in the inadequate assessment of subsurface conditions before the commencement of construction activities (Igwe and Umbugadu, 2020). This issue highlights the urgent need for a region-specific geological database that can provide valuable information about the subsurface conditions, enabling construction companies to make informed decisions and avoid potential hazards.

The creation of a region-specific geological database is highly sought after as a result of this need. Such a database would serve as a critical resource for identifying the most suitable areas for engineering constructions and overall regional development (Amadi, 2020). By providing detailed and accurate information about subsurface conditions, the database would help in mitigating risks associated with construction activities and ensure the stability and safety of structures. This task can be achieved with the aid of advanced geophysical technologies, particularly the seismic method, which offers a detailed and reliable understanding of subsurface conditions (Afegbua *et al.*, 2019).

Given these factors, it is crucial to conduct a thorough assessment of the subsurface conditions in the Ini Local Government Area of Akwa Ibom State, Nigeria. The aim of this study is to use Seismic Refraction Tomography (SRT) to establish a detailed geological database for the area. This comprehensive database will provide essential insights into subsurface characteristics, enabling construction companies and developers to make well-informed decisions, thereby minimizing the risks of geological hazards. By achieving these objectives, the study seeks to contribute to the region's safe and sustainable development, ensuring engineering projects are planned and executed with a high level of precision, safety, and environmental consideration.

GEOLOGY OF THE STUDY AREA

The Ini Local Government Area of Akwa-Ibom State, located within the coordinates of latitude 5°18'N – 5°16'N and longitude 7°39' – 7°53'E, as shown in Figure 1, features a diverse geological composition primarily consisting of clay, shale, and sandstone, as documented by Olugbenga and Christopher (2015). The shale in this area exhibits a bluish to dark gray coloration, characterized by its fissility and predominantly flat-lying orientation. As one moves upwards in the geological strata, the shale transitions into a mixture of clay and shale, ultimately resulting in light brownish-gray to reddish-brown clay. Observations from gullies reveal that the clay-shale sequence exceeds five meters in thickness, occasionally evolving into silty clay in localized areas. Notably, carbonized streaks of plant remnants are found within the dark gray shale, especially near the boundary between Akwa Ibom State and Abia State. Within the clay component, pebbles, boulders, and lenses of limestone are prevalent. Conversely, the sandstone, particularly in the Ebo, Okpoto, and Iwere areas of Ini Local Government Area, presents itself as predominantly massive, reaching depths of six to eight meters in certain exposures (Olugbenga and Christopher, 2015). This sandstone exhibits fine lamination, likely attributed to grading, interspersed with streaks of whitish clay (kaolin). Texturally, it registers as medium to coarse-grained, with a tendency towards fining upwards (Esu and Okereke, 2002).

The subsurface lithostratigraphic makeup of the area reveals the presence of the Akata Shales Formation, Agbada Formation, and the Benin Sands Formation. The outcropping units include the Imo Formation and the Ameki Group, which encompass formations such as Ameki, Nanka, Nsugbe, and Ogwashi – Asaba formations. The foundational stratum underlying the study area is the Imo Formation, characterized by thick clayey shale, fine-textured dark grey to bluish-grey shale, and intermittent sandstone bands (Ogbe and Osokpor, 2021). The geological makeup is defined by two predominant rock types: clay/shale and sandstone. Noteworthy occurrences include the massive sandstone formations at Odoro – Ikpe and Ikporom, distinguished by flaser beds featuring fine laminations and streaks of white clay. Texture-wise, the sandstone ranges from fine to very fine-grained, with variations in coarseness noted between locations such as Odoro-Ikpe and Ikporom (Onwuegbuchulam *et al.*, 2019). Geological records accentuate the prevalence of sandstones and limestones east of Nkari and Obotme, solidifying the composition of the study area primarily within the Benin Formation alongside the Bende – Ameki Group and Imo Shale Formation, as depicted in Figure 2.

The geological tapestry of Ini Local Government Area paints a rich tableau of varied rock formations and stratigraphic elements, shaping the contours of its landscape and underpinning the intricate interplay between geology and geography in the region's evolution and development. Understanding this complex geological framework is crucial for effective land use planning and resource management, which are vital for sustainable development in the area.

This geological complexity has significant implications for civil engineering and construction activities in the region. The prevalence of diverse rock types, ranging from clay and shale to massive sandstone formations, necessitates thorough geophysical investigations before embarking on any construction projects (Aka *et al.*, 2020). Geophysical data is crucial for designing and constructing civil engineering structures, such as buildings, highways, and dams. The data helps in understanding the subsurface conditions, thereby informing decisions related to foundation design, material selection, and construction techniques.

MATERIALS AND METHODOLOGY

The SRT data was collected from forty (40) locations within the study area using a Geometric ES 3000 12-channel seismograph. This device served as the primary recorder, with a Vulcan sledgehammer as the energy source and S and P geophones as detectors. In data acquisition, discrete shot records were generated and processed using the seismograph. The digitized first arrival data was compiled into Two-Way Time (TWT) measurements for a distance of 120 meters at varying geophone offsets.

A total of twenty (20) SRT datasets were obtained for forward and reverse triggering at 2.0-meter intervals, each covering a total length of 120 meters. The shot records were meticulously laid out and processed, ensuring the accuracy and reliability of the data. The time–distance graphs were plotted to evaluate the thickness and wave velocities of the geological layers. This involved analyzing the first arrivals of seismic waves to determine the depth and properties of subsurface features.

The true wave velocities of the first, second, and third geological layers were calculated using arithmetic and harmonic means. The arithmetic mean was used to assess the first and second seismic refracting velocities occurring in dipping formations. The harmonic mean was used to evaluate the third refraction layer's forward and reverse velocities.

$$V_{arithmtic} = \frac{V_1+V_2}{2} \qquad 1$$

$$V_{harmonic} = \frac{2}{\left(\frac{1}{V_{forward}}+\frac{1}{V_{reverse}}\right)} \qquad 2$$

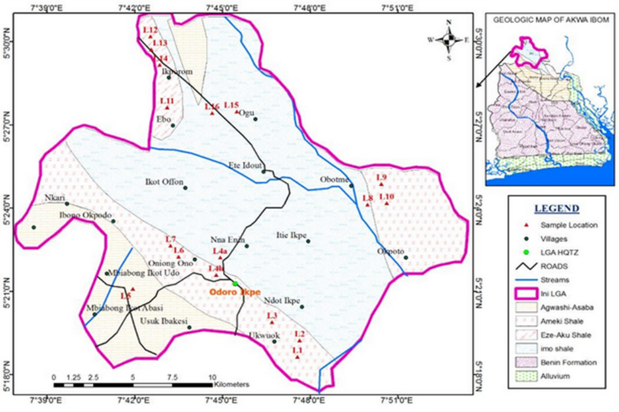

FIGURE 1. Geological map of the study area indicating sample locations.

Here, V_1 and V_2 are the velocities of the first and second layers, while $V_{forward}$ and $V_{reverse}$ are the forward and reverse velocities of the third layer.

After obtaining the thickness and wave velocity of the geological layers, the velocity data was filtered using the Discrete Fourier Transformation (DFT) implemented in MATLAB Software. This process helped in refining the data and reducing noise, thereby enhancing the clarity and accuracy of the seismic profiles.

The processed data was then used to create 2D geological models. The 2D model was generated using strata modeling software, providing a two-dimensional view of the subsurface. This model was crucial for understanding the layering and distribution of geological materials.

The 2D geological model was developed to assess geological discontinuities such as faults and fractures. This model offered a comprehensive view of the subsurface, allowing for the identification and analysis of structural features that could impact engineering and construction activities.

The following parameters were calculated based on the seismic data:

$$MeanV_p = \frac{1}{n}\sum_{i=1}^{n} V_{pi} \quad (3)$$

$$MeanV_s = \frac{1}{n}\sum_{i=1}^{n} V_{si} \quad (4)$$

$$Meand = \frac{1}{n}\sum_{i=1}^{n} d_i \quad (5)$$

$$\frac{V_p}{V_s} = \frac{MeanV_p}{MeanV_s} \quad (6)$$

$$\sigma = \frac{0.5\left(\frac{V_p}{V_s}\right)^2 - 1}{\left(\frac{V_p}{V_s}\right)^2 - 1} \quad (7)$$

The collected seismic refraction tomography data provided critical insights into the geological structure of the study area. By using a combination of forward and reverse triggering, arithmetic and harmonic mean calculations, and advanced processing techniques such as discrete Fourier transformation, the study was able to produce detailed 2D models of the subsurface. These models are invaluable for identifying geological features, assessing potential construction sites, and ensuring the safety and stability of engineering projects. The mean P-wave and S-wave velocities, depth measurements, V_p/V_s ratios, and Poisson's ratio further quantified the subsurface characteristics, contributing to a comprehensive understanding of the geological framework.

RESULTS

The analysis of the seismic refraction data collected from the Ini Local Government Area of Akwa Ibom State, Nigeria, has provided valuable insights into the subsurface geological structures. The summary of the seismic refraction parameters for various shot points is detailed in Table I (See Appendix). The interpretation of this data involved adjusting the arrival times and creating time-distance plots for the three identified layers, (see Figure A in Appendix). The thicknesses and velocity modeling were evaluated to illustrate the geological significance of the area.

The interpretation of seismic refraction data involves examining the arrival times of seismic waves at different geophone locations and creating time-distance plots for the identified layers. These plots help determine the seismic velocities, compressional velocities (V_P) and shear velocities (V_S) and the thickness of each layer. In the study area, three primary layers were identified at each shot point, with distinct seismic velocities and depths.

Layer 1 generally represents the topsoil and weathered material, with lower seismic velocities and shallower depths. At location L1, the V_P is 209m/s, and the depth is 1.8meters. Layer 2 typically corresponds to a more consolidated subsoil layer, with higher velocities and greater depths. For instance, at location L1, the V_P is 221m/s, and the depth is 5.5meters. Layer 3 often represents the bedrock or a highly compacted geological layer, with the highest velocities and depths. At location L1, the V_P for this layer is 510m/s, and the depth is 8.0meters.

The V_P/V_S ratios and Poisson's ratios (σ) provide additional insights into the subsurface materials. The V_P/V_S ratio helps in understanding the type of material present in the subsurface. For example, a lower V_P/V_S ratio often indicates softer, less consolidated materials, whereas a

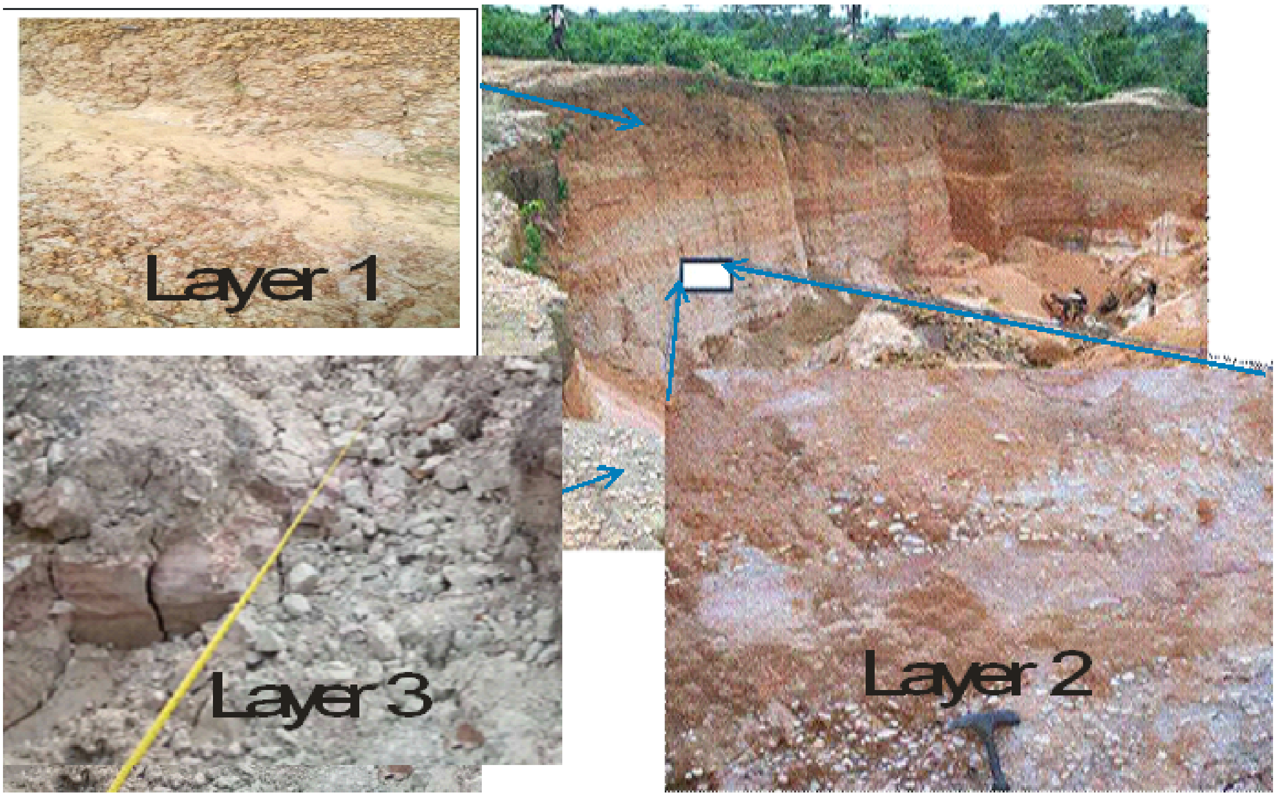

FIGURE 2. Lithology of the study area, illustrating the formation of three distinct layers.

higher ratio suggests harder, more compacted materials. Poisson's ratio gives information about the elastic properties of the material. A negative value of σ, as observed in several locations, indicates non-standard geological conditions or possible data anomalies.

2-D Geological Section

The 2-D geological sections, constructed using the velocity data, reveal the subsurface features and formations. These sections were divided into two segments based on the geophone stations. Figures 3 and 4 illustrate these sections, showing the stratification and lateral variation of the subsurface layers.

In Figure 3, the first layer, consisting of surface soil, shows a general eastward to westward gravitation, overlaying a layer of lateritic soil. This is followed by a third layer of silty clayey sediments. Figure 4 demonstrates a similar eastward to westward drift for the first layer, but with a more complex interaction between the second and third layers, suggesting disintegration and intrusion phenomena.

The variations in seismic velocities and layer thicknesses across the study area provide valuable information for geophysical and geological interpretations. The higher velocities observed in some locations, such as L20 (V_P of 1700m/s for layer 3), indicate the presence of dense, compacted bedrock, which could be of interest for construction and engineering projects. Conversely, areas with lower velocities and greater depths of weathered material may be more susceptible to ground movement and instability.

2-D Velocity Modeled Section

The 2-D velocity modeling was developed using refined seismic velocity data to identify geological disruptions, such as faults and fractures, evident in the 2-D geological sections of the subsurface. These models are essential for visualizing the continuity and discontinuities within the subsurface layers. By analyzing velocity anomalies, the locations and orientations of faults and fractures can be pinpointed, providing critical insights into geological stability and potential risks for construction projects. The 2-D models offer a detailed and accurate representation of the subsurface, enabling engineers and geologists to make informed decisions about site suitability and necessary precautions. Figures 5 and 6 illustrate the geological features captured by the 2-D models, underscoring the significance of advanced modeling techniques in geophysical investigations.

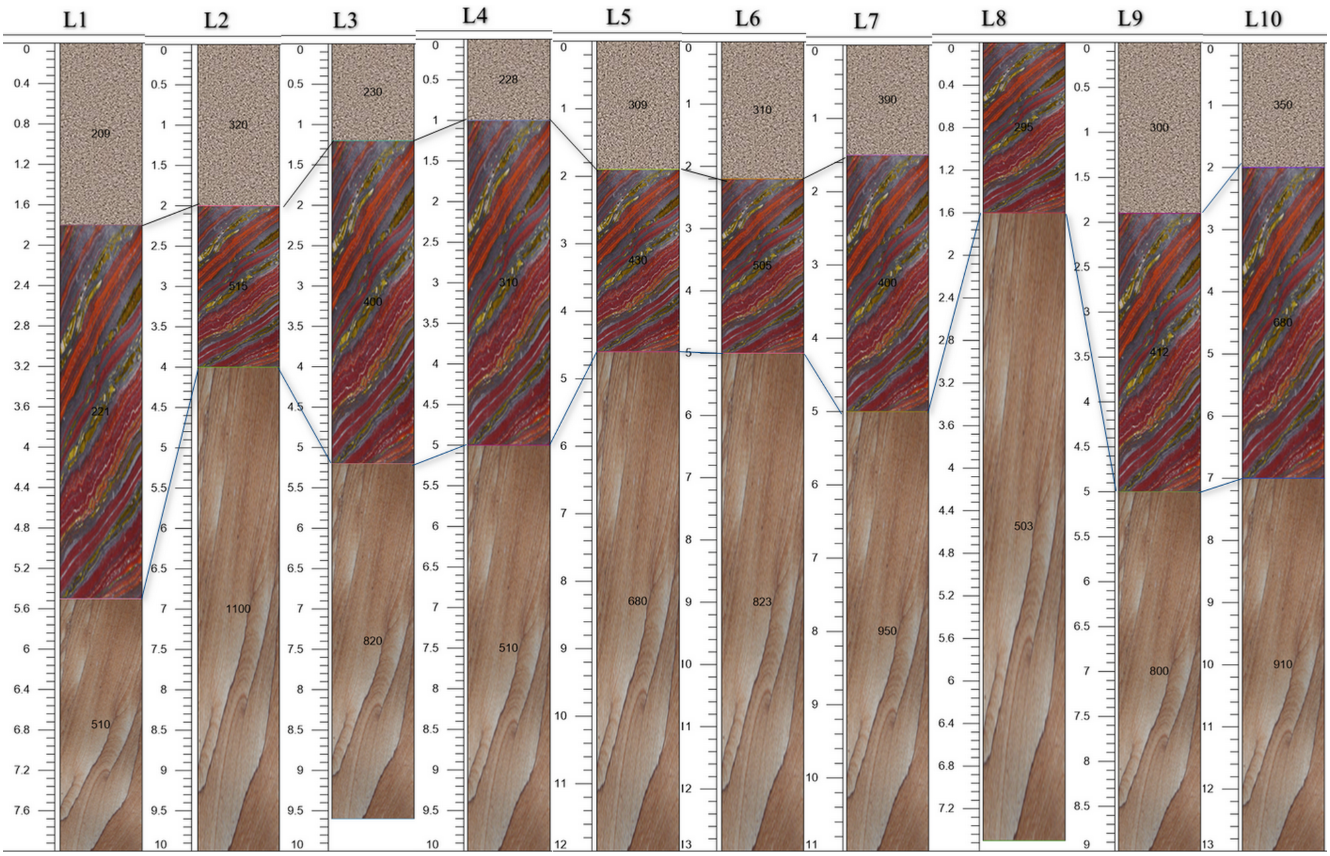

FIGURE 3. 2D geological cross-section for three layers at shot points L_1–L_{10}, illustrating subsurface geology of the area.

DISCUSSION OF RESULTS

The findings from this study delineate three distinct seismic refraction data layers (top, middle and bottom) across forty locations, using forward and reverse shooting techniques. Each layer's characteristics were identified through analysis of compressional and shear wave velocities, lithology discriminators, thickness, and porosity ratios, which provide significant insights into the subsurface geology of the Ini LGA.

The top layer exhibited compressional velocities (V_P) ranging from 209 to 500m/s and shear velocities (V_S) from 170 to 410m/s. The lithology discriminator (V_P/V_S) values ranged from 1.030 to 1.395, with thicknesses between 1.0 and 3.0 meters and porosity ratios from 0.029 to -6.958. This layer consists of irregular, loosely unstratified sand and gravel, low-density formations. Its coloration, ranging from gray to dark. The high variability in compressional velocities suggests a heterogenous composition, which includes loose, unconsolidated materials that are not suitable for heavy construction loads due to their low bearing capacity and high compressibility (Okewale, 2020).

The middle layer, with compressional velocities ranging from 221 to 1210m/s and shear velocities from 205 to 880m/s, showed lithology-discriminator values from 1.033 to 1.291. This layer had a thickness between 4.0 and 9.0 meters and porosity ratios from 0.268 to -6.963. It is characterized by residual soil from the A to E horizon, exhibiting properties of high strength, low compressibility, and low permeability. The rusty red to purple coloration of this layer indicates the presence of lateritic-clay material, which is often used in embankment construction and as backfill due to its stability and load-bearing properties (Okogbue *et al.*, 2020). This layer's high V_P and V_S values reflect its suitability for such applications, demonstrating a strong, compacted substratum.

The bottom layer's compressional velocities ranged from 510 to 1700m/s, with shear velocities from 490 to 1300m/s. Lithology-discriminator values ranged from 1.036 to 1.308, thicknesses from 4.5 to 14.5meters, and porosity ratios from 0.144 to -6.324. This layer is composed of sandy-clay material from the B, C, and R soil horizons. Notably, in locations 8, 14, and 19, a hidden layer formation was observed where the refractor did not produce first arrivals. This phenomenon, known as a blind zone, occurs

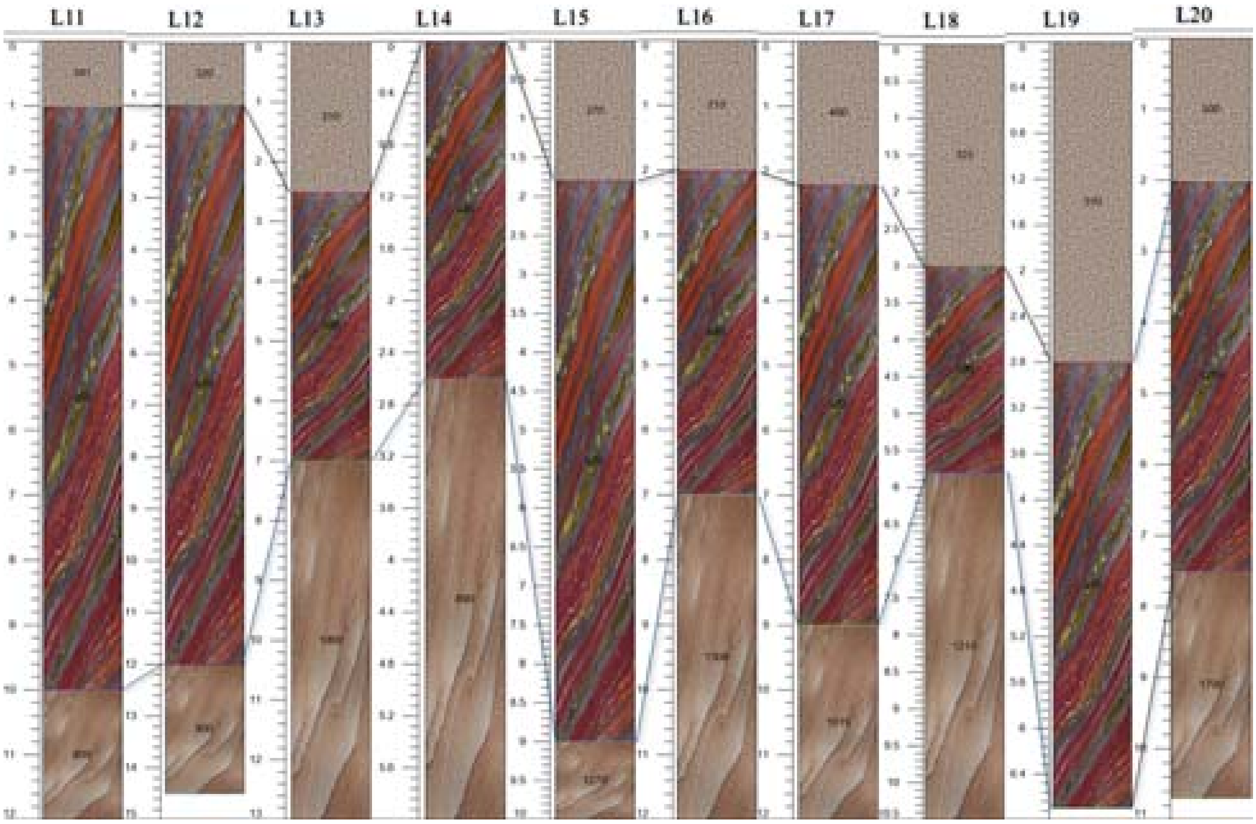

FIGURE 4. 2D geological cross-section for three layers at shot points L_{11}–L_{20}, illustrating subsurface geology of the area.

when a lower-velocity layer lies beneath a higher-velocity one, preventing critical refraction and thus no refraction energy returns to the surface. The presence of these blind zones suggests complex subsurface conditions that could pose challenges for geotechnical and structural engineering (Imeokparia and Falowo, 2019; Igwe and Umbugadu, 2020).

The bottom layer's material, including earthenware and stoneware clay, shows plasticity characteristics such as low strength, high compressibility, and high permeability. These properties make the layer prone to compaction, reducing pore spaces and potentially leading to the settling and movement of building foundations. This can result in cracking and damage to structures, highlighting the need for careful consideration in construction planning.

The lithology-discriminator's moderate variation across the layers indicates higher V_S values. Low values (less than 1.5) suggest clayey formations with air-filled soil, while the negative Poisson ratio indicates anisotropic soil properties with counter-intuitive compressibility characteristics. The significant changes in V_P, compared to the relatively stable V_S, point to variations in lithology, compressibility, and fluid content. These variations affect the seismic velocity, which is a function of the mechanical properties of the materials through which seismic waves propagate (Alhassan *et al.*, 2018).

These results show a range of velocities and soil characteristics comparable with those from earlier studies in the Niger Delta trough, (*e.g.* Ogagarue, 2007; Uko *et al.*, 1992). For instance, their studies reported velocity ranges of 500-517m/s for topsoil and 500-1730m/s for solidified layers, with thicknesses of 13.4-13.8meters and 2.9-4.5meters, respectively. These findings align with the current research, validating the observed trends in topsoil, laterite, and sandy-clay layers.

The 2D geological segments derived from seismic velocities indicate a sandy-clay porous material in the bottom layer, as shown in the velocity layers 1 to 10 and 11 to 20 in Figures 5 and 6. The 2D velocity model further enumerated the geologic discontinuities in the middle and bottom layers, identifying breaks in velocities at depths of 4.5 to 14.5meters near the surface. These discontinuities suggest vertical fault movements, impacting the shear strength of geological materials in the region.

Advances in geological modeling, particularly implicit modeling, have enhanced the visualization of subsurface

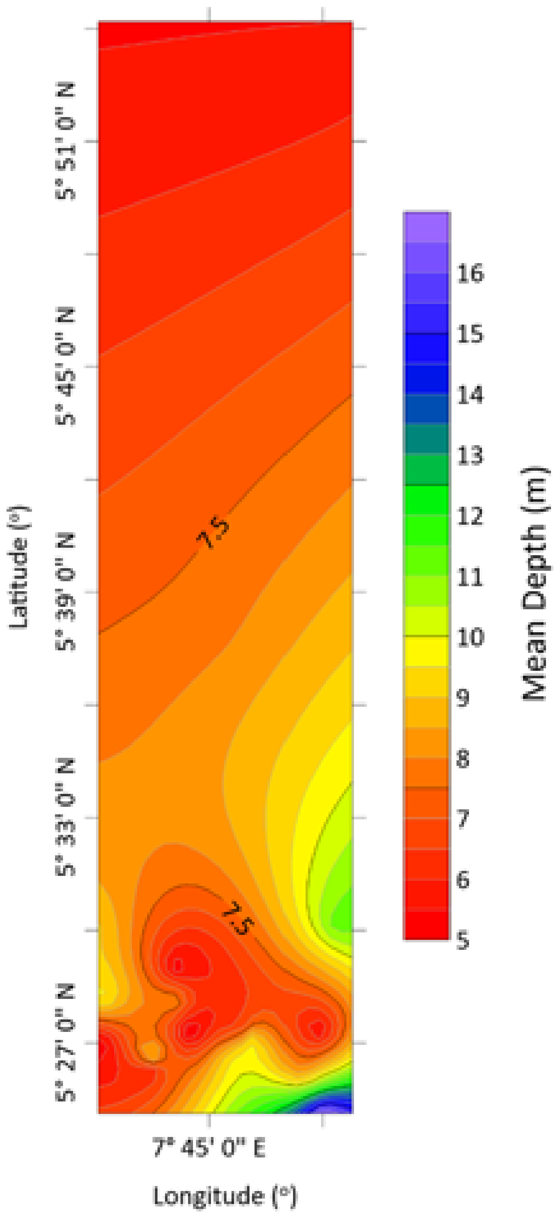

FIGURE 5. 2D depth model for layers $L_1 – L_{10}$ locations.

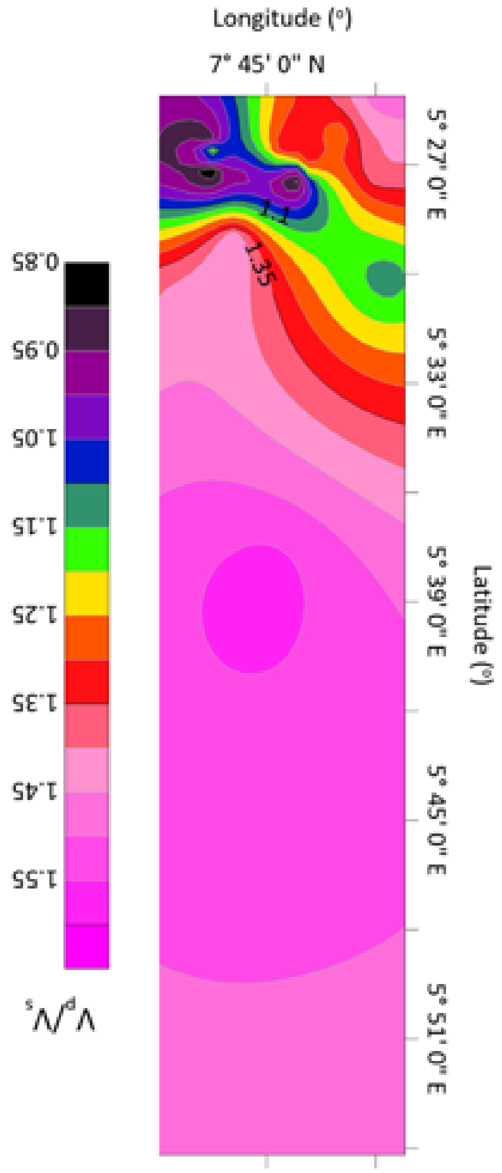

FIGURE 6. 2D velocity model for layers $L_{11} – L_{20}$ locations.

structures in 2D. This approach, as opposed to the traditional 2D sectional method, allows for the rapid incorporation of extensive datasets into the model, accounting for faults, unconformities, and lateral extents. The implicit modeling techniques used in this study facilitated a comprehensive understanding of the subsurface geology, revealing the fault through vertical movements of shear-strength geological materials in the region (Abraham and Alile, 2019).

The results from this study indicate that the bottom layer structures, characterized by relatively low seismic velocities and shallow depths, are predominantly composed of sandy-clayey material. These properties suggest that the bottom layers are unsuitable for heavy construction due to their low strength and high compressibility, as demonstrated by the seismic velocity of 510m/s at a depth of 8.0meters at location L1. Conversely, the middle layer's properties indicate good and saturated zones, making it more favorable for construction purposes. This detailed subsurface database provides valuable information for construction planning, geological hazard assessment, and other subsurface applications in the region.

CONCLUSION

The analysis of seismic refraction data from Ini Local Government Area, Akwa Ibom State, Nigeria, revealed significant subsurface geological structures. By adjusting arrival times and creating time-distance plots for three identified layers, the study provided essential insights into the area's geological features. The arrival times of seismic waves at different geophone locations allowed for determining seismic velocities (V_P and V_S) and the thickness of each layer.

Three primary layers were identified across the study area, each with distinct seismic velocities and depths. Layer 1, typically comprising topsoil and weathered material, exhibited lower seismic velocities and shallower depths. For instance, at location L1, the V_P was 209m/s, and the depth was 1.8meters. Layer 2, representing a more consolidated subsoil layer, showed higher velocities and greater depths, such as a V_P of 221m/s and a depth of 5.5meters at the same location. Layer 3, often corresponding to bedrock or a highly compacted geological layer, presented the highest velocities and depths, with V_P reaching 510m/s and a depth of 8.0meters at location L1. The V_P/V_S ratios and Poisson's ratios (σ) offered additional insights into the subsurface materials. The V_P/V_S ratio helped distinguish between softer, less consolidated materials and harder, more compacted ones. Poisson's ratio provided information about the elastic properties of the material, with negative values indicating non-standard geological conditions or potential data anomalies.

2-D geological sections, constructed using velocity data, illustrated subsurface features and formations. Stratification and lateral variation of the subsurface layers were highlighted, showing the drift of surface soil eastward to westward, overlaying lateritic soil and silty clayey sediments. These variations in seismic velocities and layer thicknesses provided crucial information for geophysical and geological interpretations. Higher velocities in certain locations indicated dense, compacted bedrock, important for construction and engineering projects. Conversely, areas with lower velocities and deeper weathered material layers may be more susceptible to ground movement and instability. 2-D velocity modeling was developed using refined seismic velocity data to identify geological disruptions like faults and fractures evident in the 2-D sections. This comprehensive three-dimensional model visualized continuity and discontinuities within subsurface layers, pinpointing the locations and orientations of faults and fractures. Analyzing velocity anomalies allowed for understanding geological stability and potential risks associated with construction projects. The 2-D models provided a detailed and accurate representation of the subsurface, enabling engineers and geologists to make informed decisions about site suitability and necessary precautions.

This study identified three distinct seismic refraction data layers (top, middle, and bottom) across forty locations using forward and reverse shooting techniques. The top layer, with compressional velocities (V_P) ranging from 209 to 500m/s and shear velocities (V_S) from 170 to 410m/s, indicated irregular, sand and gravel low-density formations. The middle layer, with V_P ranging from 221 to 1210m/s and V_S from 205 to 880m/s, exhibited properties of high strength and low compressibility, suitable for construction. The bottom layer, often indicative of bedrock or a highly compacted geological formation, exhibits seismic velocities of V_P ranging from 510 to 1700m/s and V_S from 490 to 1300m/s. This layer is primarily composed of sandy-clay material with high plasticity, making it susceptible to compaction and settling.The bottom layer, with V_P from 510 to 1700m/s and V_S from 490 to 1300m/s, comprised sandy-clay material with high plasticity, making it prone to compaction and settling. This detailed subsurface database provides valuable information for construction planning, geological hazard assessment, and other subsurface applications in the region.

It is recommended that further studies include a larger area of Ini Local Government to refine subsurface models and verify geological features more accurately. Implementing additional geophysical techniques, such as Ground Penetrating Radar (GPR) or Electrical Resistivity Tomography (ERT), can further enhance the understanding of subsurface complexities, contributing to safer construction and land-use planning in the region.

DECLARATION OF INTEREST

The authors declare that they have no known competing financial interests.

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APPENDIX

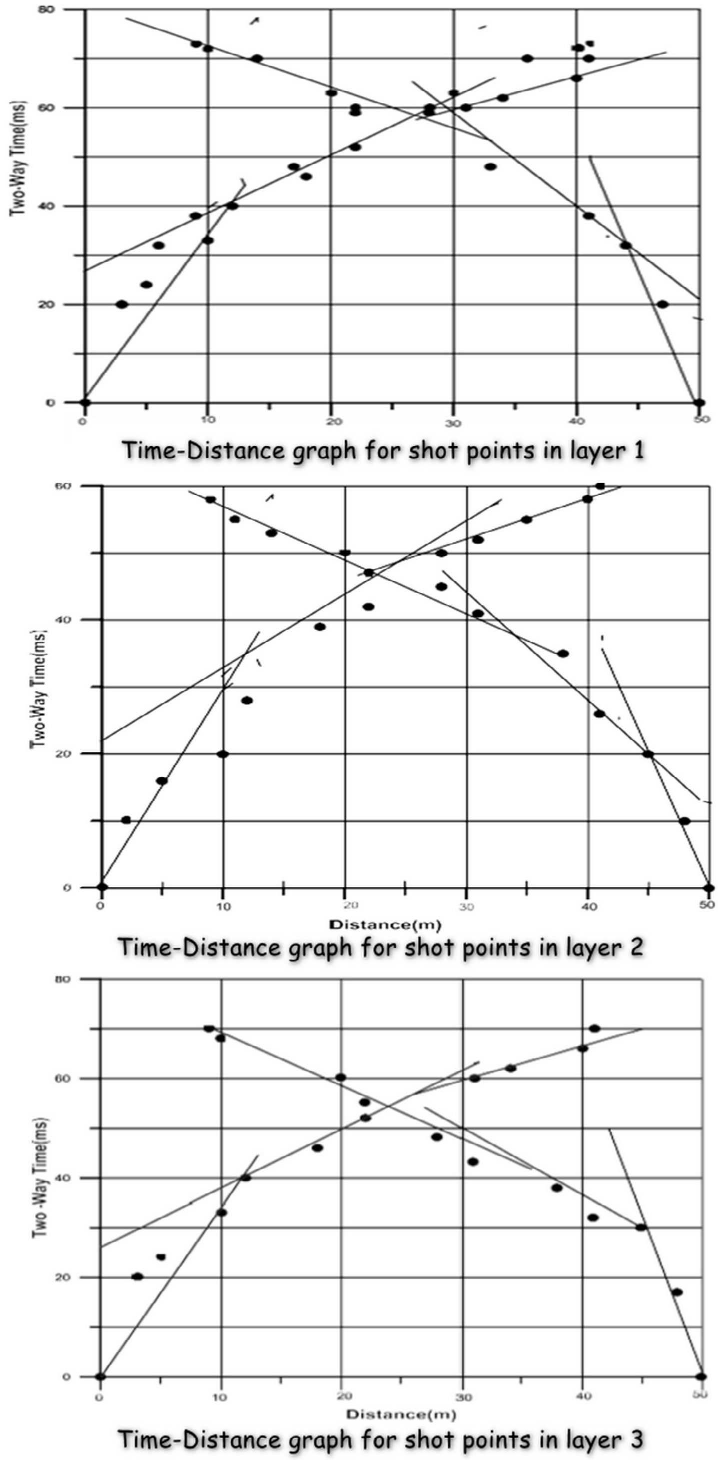

FIGURE I. Time-Distance graph for shot points.

TABLE I. Summary of seismic refraction parameters for shot points

Geophone Locations	Latitude (°N)	Longitude (°E)	Layers	Mean V_P (m/s)	Mean V_S (m/s)	Mean Depth (m)	V_P/V_S	σ
L1	5.4403	7.7236	1	209	170	1.8	1.229	-0.480
			2	221	205	5.5	1.075	-2.715
			3	510	490	8.0	1.041	-5.485
L2	5.4511	7.7019	1	320	300	2.0	1.067	-3.112
			2	515	470	4.0	1.096	-1.988
			3	1100	910	10.0	1.209	-0.583
L3	5.4689	7.7025	1	230	215	1.2	1.070	-2.950
			2	400	360	5.2	1.111	-1.635
			3	820	740	9.6	1.108	-1.695
L4	5.5011	7.7006	1	228	210	1.0	1.080	-2.506
			2	310	300	5.0	1.033	-6.963
			3	510	480	10.0	1.062	-3.406
L5	5.4186	7.8003	1	309	300	1.9	1.030	-7.709
			2	430	410	4.6	1.049	-4.482
			3	680	510	12.0	1.333	-0.144
L6	5.4358	7.7847	1	310	285	2.2	1.088	-0.144
			2	505	455	5.0	1.110	-1.654
			3	823	710	13.0	1.159	-0.957
L7	5.4517	7.7675	1	390	302	1.5	1.291	-0.250
			2	400	350	5.0	1.143	-1.132

TABLE I. Continued

Geophone Locations	Latitude (°N)	Longitude (°E)	Layers	Mean V_P (m/s)	Mean V_S (m/s)	Mean Depth (m)	V_P/V_S	σ
			3	950	816	11.0	1.164	-0.909
L8	5.6339	7.7517	1	295	240	1.6	1.229	-0.248
			2	503	485	7.5	1.105	-1.762
			3	-	-	-	-	-
L9	5.4689	7.7355	1	300	215	1.9	1.395	-0.029
			2	412	350	5.0	1.777	-0.027
			3	800	705	9.0	1.135	-1.235
L10	5.4833	7.7350	1	350	300	2.0	1.167	-0.881
			2	680	550	7.0	1.236	-0.447
			3	910	700	13.0	1.300	-0.225
L11	5.5017	7.8058	1	341	300	1.0	1.137	-1.207
			2	450	415	10.0	1.084	-2.356
			3	809	700	12.0	1.156	-0.987
L12	5.4522	7.7236	1	320	300	1.2	1.067	-3.112
			2	610	530	12.0	1.151	-1.039
			3	900	800	14.5	1.125	-0.212
L13	5.4550	7.7411	1	310	300	2.5	1.033	-6.953
			2	500	415	7.0	1.205	-0.606
			3	1060	990	13.0	1.071	-2.907
L14	5.4547	7.7642	1	340	310	2.6	1.097	-1.959

TABLE I. Continued

Geophone Locations	Latitude (°N)	Longitude (°E)	Layers	Mean V_P (m/s)	Mean V_S (m/s)	Mean Depth (m)	V_P/V_S	σ
			2	890	770	6.0	1.156	-0.987
			3	-	-	-	-	-
L15	5.4551	7.7994	1	370	310	1.8	1.194	-0.674
			2	820	760	9.0	1.019	-2.545
			3	1270	1000	10.0	1.155	-0.997
L16	5.9031	7.8133	1	210	190	2.0	1.105	-1.762
			2	885	701	7.0	1.148	-1.073
			3	1308	1110	12.0	1.189	-0.708
L17	5.4442	7.7239	1	400	350	2.2	1.143	-1.132
			2	572	380	9.0	1.505	-1.119
			3	1015	980	12.0	1.036	-6.324
L18	5.4441	7.7572	1	325	301	3.0	1.080	-2.506
			2	500	420	5.8	1.190	-0.702
			3	1210	950	10.5	1.274	-0.303
L19	5.4350	7.7906	1	310	290	2.8	1.069	-3.002
			2	910	815	6.7	1.117	-1.518
			3	-	-	-	-	-
L20	5.4355	7.8047	1	500	410	2.0	1.220	-0.524
			2	1210	880	7.5	1.235	-0.452
			3	1700	1120	10.7	1.518	-0.203