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Research Article

Subsurface Characterization Using Downhole Refraction Survey: A Case Study of the Niger Delta

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Abstract

This study addresses the critical role of downhole refraction as a method for assessing subsurface characteristics, particularly in areas facing challenges such as ground roll issues and weak reflection signals during seismic data acquisition. Focused on the Agudama, Kenfa, and Yenegwe settlements in the Niger Delta region, where frequent engineering structure collapses occur, the research aims to understand the depth and velocity of unconsolidated zones through downhole refraction. The study emphasizes the limitations of relying solely on uphole refraction and highlights the necessity of downhole methods for accurate velocity determination. The research employs various techniques, including borehole drilling, velocity measurements, and seismic pulse generation. The study's primary objectives include investigating the causes of engineering structure failures, proposing geophysical solutions, and contributing valuable insights into the geological context of the Niger Delta region. The fieldwork involved a comprehensive approach, combining reconnaissance surveys, downhole refraction studies, and the use of specialized equipment such as a Geometrics Stratavisor NZXP seismograph and explosives for seismic sources. The results of the downhole refraction survey reveal a double-layer velocity model in the research areas, indicating variations in weathered or unconsolidated layer thickness and velocities. The study establishes a relationship between elevation, weathered layer thickness, and velocities in both weathered and consolidated layers, offering valuable information for engineering considerations. The research concludes that the downhole refraction method is crucial for evaluating weathered strata properties and provides cost-effective subsurface information. The study recommends drilling below the weathered zone for seismic energy source placement, excavation depths for stable structures, and future investigations focusing on closely spaced data points and additional soil properties. These recommendations aim to enhance the safety and durability of structures in the study area, contributing to the understanding and mitigation of engineering structure failures in the Niger Delta region.

Keywords

Downhole Survey, Weathered Layer, Refraction Seismic, Drilling, Seismic Energy

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1. Introduction

The study focuses on downhole refraction as a crucial method for evaluating subsurface features, particularly in regions with ground roll issues and weak reflection signals during seismic data acquisition. Uphole and downhole refraction procedures are commonly employed to investigate low-velocity layers, providing valuable data for seismic reactivity and geology assessment [1-3]. The chosen study area, encompassing Agudama, Kenfa, and Yenegwe settlements, experiences frequent engineering structure collapses, motivating the need for downhole refraction to understand the unconsolidated zone's depth and velocity, contributing to ground roll and potential engineering challenges.

The limitation of obtaining near-surface data solely through uphole refraction, emphasizing the necessity of downhole refraction for accurate velocity determination was unraveled The uphole survey involves drilling boreholes and measuring velocities, providing essential information for interpreting seismic reflection data. The downhole method, involving sources near the surface and receivers down the hole, is presented as an effective alternative. Uphole or downhole study is defined as progressive sources at various depths in a borehole to determine the rate of near surface formation, unconsolidated thickness, and (sometimes) the variations of record quality with source depth or when line of geophones is sometimes placed in a 200-foot-deep hole to measure the upward movement times from a nearby, shallow source. [4-7]. A simplified diagram in figure 1, illustrates uphole survey results, including borehole lithology, field layout, and time-depth and interval velocity displays.

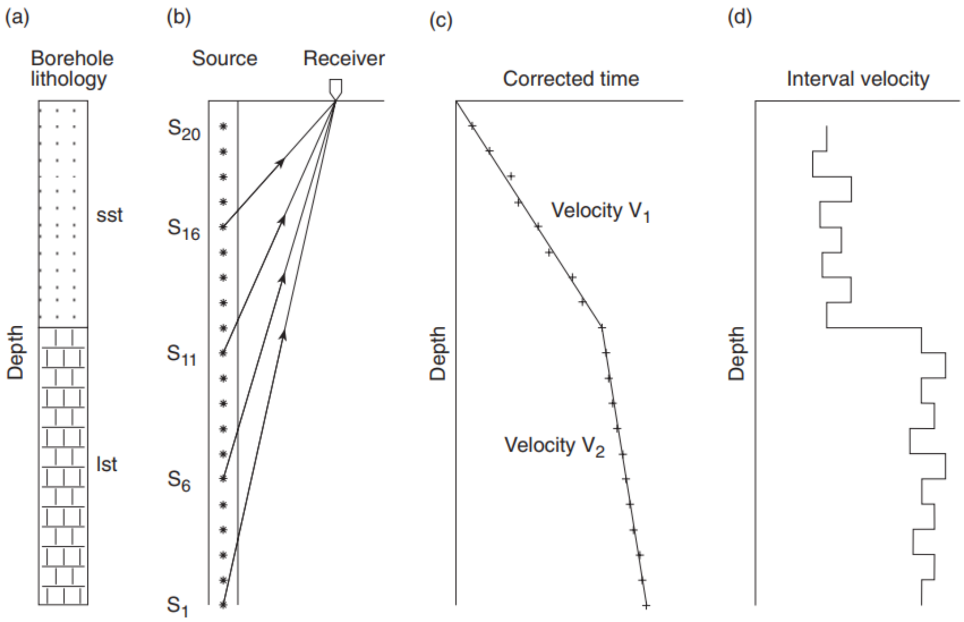

Figure 1. *Uphole survey displays with the receiver at the surface: (a) borehole lithology; (b) field layout with one receiver location and 20 source levels identified; (c) time–depth display; (d) interval velocity display.*

The escalating rate of engineering structure failures prompts the need for geophysical investigations. The study aims to identify the fundamental causes of these failures and proposes solutions from a geophysical perspective. The primary aim is to explore the root cause of engineering structural collapse using a geophysical approach and suggest long-term solutions. Objectives include establishing an uphole refraction survey, generating seismic pulses, examining layer characteristics during wave propagation, determining wave speed through different thicknesses, and assessing the depth of weak or worn layers.

This research comprehensively examines various techniques in downhole refraction seismic data gathering, encompassing conceptualization, implementation, and ecological implications. It aims to identify potential causes of engineering structure collapse and propose relevant solutions. The write-up underscores the significance of downhole refraction in understanding subsurface conditions, particularly in regions prone to engineering challenges. It emphasizes the complementary roles of uphole and downhole surveys in providing accurate data for geological interpretation and seismic analysis. The study's focus on the Niger Delta contributes valuable insights into the geological context of the region, enhancing the understanding of engineering structure failures and proposing geophysical solutions.

Location, Physiography and Geology of the study area

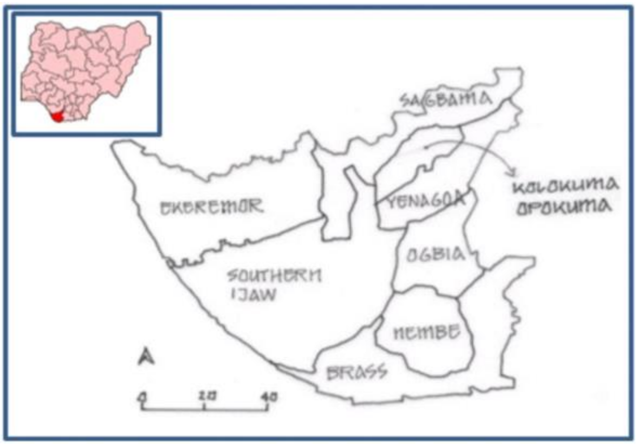

Figure 2. The location map of Bayelsa State [15].

The research area, situated in the uplands of Bayelsa State, covers Agudama, Kenfa, and Yenegwe settlements. Borehole identity numbers and locations coordinates are specified as 1298/5491, 1375/5491, and 1452/5491, with coordinates of 445333.913 Easting and 105501.130 Northing, 445325.864 Easting and 113200.747 Northing, and 445325.864 Easting and 113200.747 Northing, respectively. Figure 2 depicts the location of Bayelsa State.

The Niger Delta, situated at the West African continental margin, formed during the Cretaceous continental break-up, characterized by a triple junction [8, 9]. Extending across the Niger Delta Province, it has prograded southwest from the Eocene to the present, generating depobelts, marking the delta's most active region [10]. Encompassing an area of 300,000 km^2, with sediment volume and thickness exceeding 500,000 km^3 and 10 km, respectively, these depobelts constitute one of the world's largest regressive deltas [11-13]. The delta sequence, with Tertiary clastics up to 12 km thick, is categorized into three lithostratigraphic units: marine claystones and shales, sandstone-siltstone-claystone alternations, and alluvial sands [1, 10].

The Benin Formation in the research area is primarily composed of large, porous, freshwater-bearing sandstone with shale interbeds, a Miocene to recent continental deposit [14, 15]. Major growth-fault trends in the Delta create structural and stratigraphic belts called depobelts, holding hydrocarbons in high-quality sandstone reservoirs [10, 16].

2. Materials and Methods

The fieldwork commenced with a reconnaissance survey, including geographical feature observations. A downhole refraction study was conducted to assess weathered section thickness, zone velocities, and travel time within layers. GPS recorded site coordinates. Materials used encompassed a water pump, drill equipment, explosives, geophones, hydrophones, and a Geometrics Stratavisor NZXP seismograph. Boreholes, 66m deep, were drilled at different locations using the flush drill technique. Water injection softened the earth, aiding drilling and supporting the drill bit's circulation. Cut lithologies were collected at 3m intervals to enable soil profiling. Table 1 details shot points' positions, coordinates, elevations, and drilled and logged depths.

Table 1. Downhole statistics summary of the study area.

S/N	Shot Points Position	Coordinates		Elevation (m)	Drilled Depth (m)	Logged Depth (m)
		Easting	Northing			
1	DWH 1(1298–5491)	445,333.91	105,501.13	3.145	66	60
2	DWH 2(1375–5491)	445,325.56	109,351.23	7.088	66	60
3	DWH 3(1452–5491)	445,325.86	113,200.75	7.487	66	60

Logging Process

Drilled holes were partially logged, covered with plastic pipes, and filled with water to account for potential backfilling. A 1.5m energy source hole, 3m from the logging hole, was bored. Semi-automated rotary drilling employed manually rotated drill stems, with water and drilling mud stabilizing and flushing cuttings. Logging utilized water-resistant cables, marine rope, and hydrophones at various depths. Geometrics Stratavisor NZXP, an efficient seismograph, facilitated data acquisition, complemented by 6mm-cap explosive detonators as seismic sources and a 10Hz hydrophone receiver. The entire process was meticulously recorded on a data sheet and stored on diskette or tape for future use, allowing for trace adjustments to suit specific presentation needs.

3. Results

In the study area, downhole refraction data was effectively collected. Lithological records were collected at depths ranging from 0 to 66 m during this acquisition. Tables 2 to 4 show the field record sheets.

Table 2. Field lithological report of downhole drilling at Agudama town.

Shot Point ID	**SL 1298**	**SP 5491**
Coordinate	Easting	Northing
	445,333.91	105,501.13
Drilled Depth	66m	
Depth Logged	60m	
Time of Drilling (GMT +1)	Start Time	End Time
	8:55 am	2:15pm
Location	Agudama Town	
S/N	Depth (m)	Formation
1	2	Overburden
2	3	Fine-grained sand
3	6	Fine-grained sand
4	9	Fine-grained sand
5	12	Fine-grained sand
6	15	Fine-grained sand
7	18	Clay
8	21	Clayey Sand
9	24	Clayey Sand
10	27	Sandy Clay
11	30	Sandy Clay
12	33	Medium-grained sand
13	36	Medium-grained sand
14	39	Medium-grained sand
15	42	Medium-grained sand
16	45	Fine-grained sand
17	48	Fine-grained sand
18	51	Fine-grained sand
19	54	Fine-grained sand
20	57	Medium-grained sand
21	60	Coarse-grained sand
22	63	Coarse-grained sand
23	66	Coarse-grained sand

Note: SL = Source line; SP = Shot point; ID = Identity

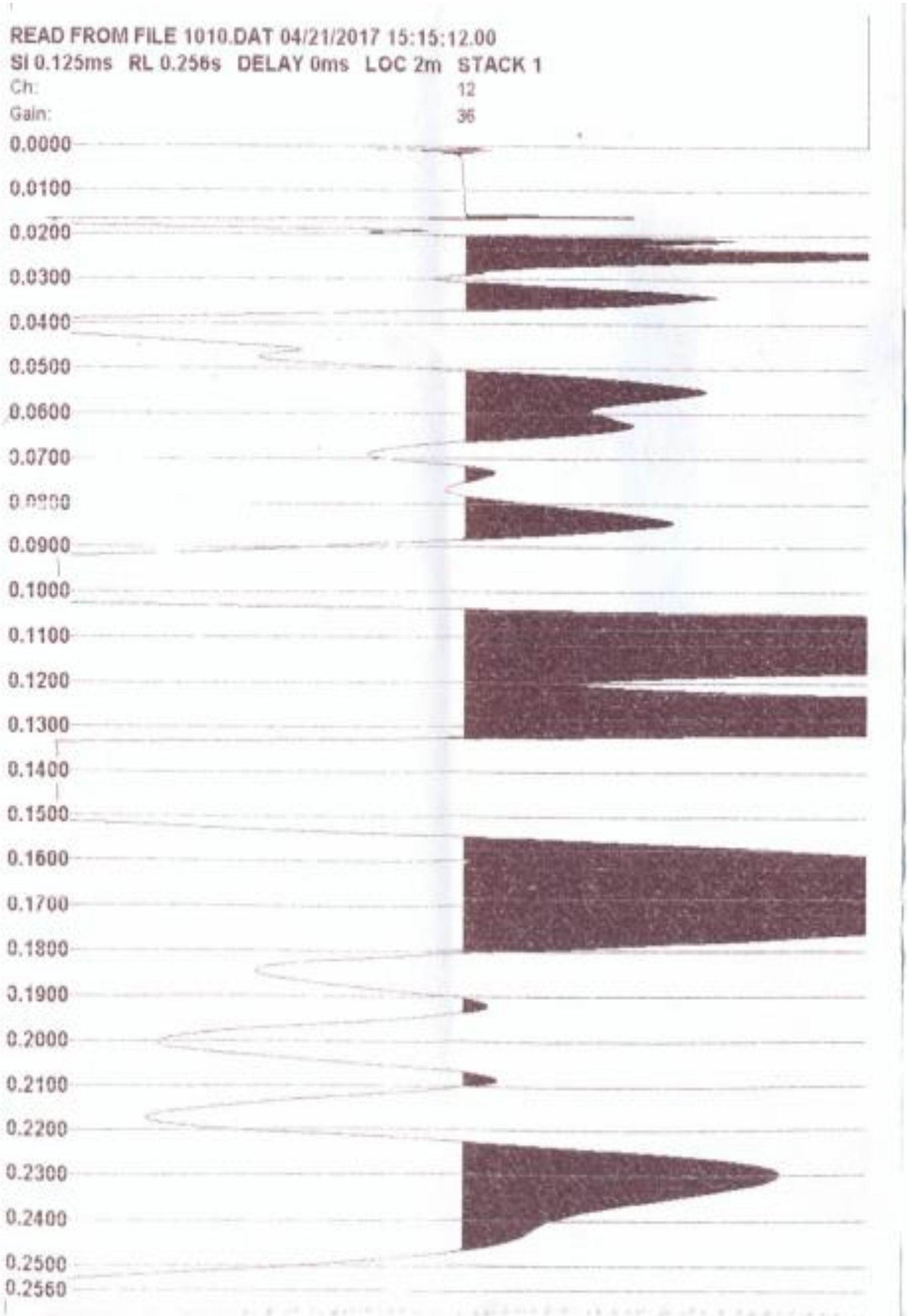

***Figure 3**. Selected monitor record of seismic wave arrival at Agudama Community shot point location.*

***Table 3**. Field lithological report of downhole drilling at Kenfa town.*

Shot Point ID	SL 1375	SP 5491
Coordinate	Easting	Northing
	445,325.56	109,351.23
Drilled Depth	66m	
Depth Logged	60m	
Time of Drilling (GMT +1)	Start Time	End Time

Shot Point ID	**SL 1375**	**SP 5491**
	9:05 am	1:15pm
Location	Kenfa Town	
S/N	Depth (m)	Formation
1	2	Clayey sand
2	3	Clay
3	6	Clay
4	9	Clay
5	12	Fine-grained sand
6	15	Fine-grained sand
7	18	Fine-grained sand
8	21	Fine-grained sand
9	24	Fine-grained sand
10	27	Fine-grained sand
11	30	Medium-grained sand
12	33	Medium-grained sand
13	36	Medium-grained sand
14	39	Medium-grained sand
15	42	Medium-grained sand
16	45	Fine-grained sand
17	48	Fine-grained sand
18	51	Fine-grained sand
19	54	Fine-grained sand
20	57	Medium-grained sand
21	60	Coarse-grained sand
22	63	Coarse-grained sand
23	66	Coarse-grained sand

Table 4. *Field lithological report of downhole drilling at Yenegwe town.*

Shot Point ID	**SL 1375**	**SP 5491**
Coordinate	Easting	Northing
	445,325.86	113,200.75
Drilled Depth	66m	
Depth Logged	60m	
Time of Drilling (GMT +1)	Start Time	End Time
	11:10 am	3:14pm
Location	Yenegwe Town	
S/N	Depth (m)	Formation

Shot Point ID	SL 1375	SP 5491
1	2	Silt
2	3	Clay
3	6	Clay Sand
4	9	Sandy clay
5	12	Fine-grained sand
6	15	Fine-grained sand
7	18	Fine-grained sand
8	21	Fine-grained sand
9	24	Fine-grained sand
10	27	Fine-grained sand
11	30	Medium-grained sand
12	33	Medium-grained sand
13	36	Medium-grained sand
14	39	Medium-grained sand
15	42	Medium-grained sand
16	45	Fine-grained sand
17	48	Fine-grained sand
18	51	Fine-grained sand
19	54	Fine-grained sand
20	57	Medium-grained sand
21	60	Coarse-grained sand
22	63	Coarse-grained sand
23	66	Coarse-grained sand

The course of the data processing, we specifically select the time corresponding to the time of first break for each shot. This time of first break signifies the time for first deflection to the left by signal trace. Its significance lies in its crucial role in the interpretation of downhole data. Figures 3, 4, and 5 are selected samples of signature printouts derived from the downhole refraction seismic survey conducted at three distinct test locations.

The study utilizes near-surface depth models, employing selected first break times and a cross-plot of defined hydrophone positions and time, crucial for processing downhole refraction data. The first break time, determined by the initial signal deflection, is manually compared to seismograph-selected data to ensure coherence and eliminate inaccuracies. Data processing with Udysys geophysical software produces cross-plots of trip times and depth for boreholes, facilitating the creation of velocity and thickness contour maps. Surfer 12 is employed to model low-velocity and consolidated layers, while additional models compare elevation to weathering thickness in relation to borehole placement. Thorough examination of these graphs informs precise interpretations, enhancing the understanding of subsurface conditions.

The presented data below illustrates the processed results derived from the raw measurements of the downhole refraction survey. Tables 5 to 7 depict the original readings obtained from the three downhole surveys conducted.

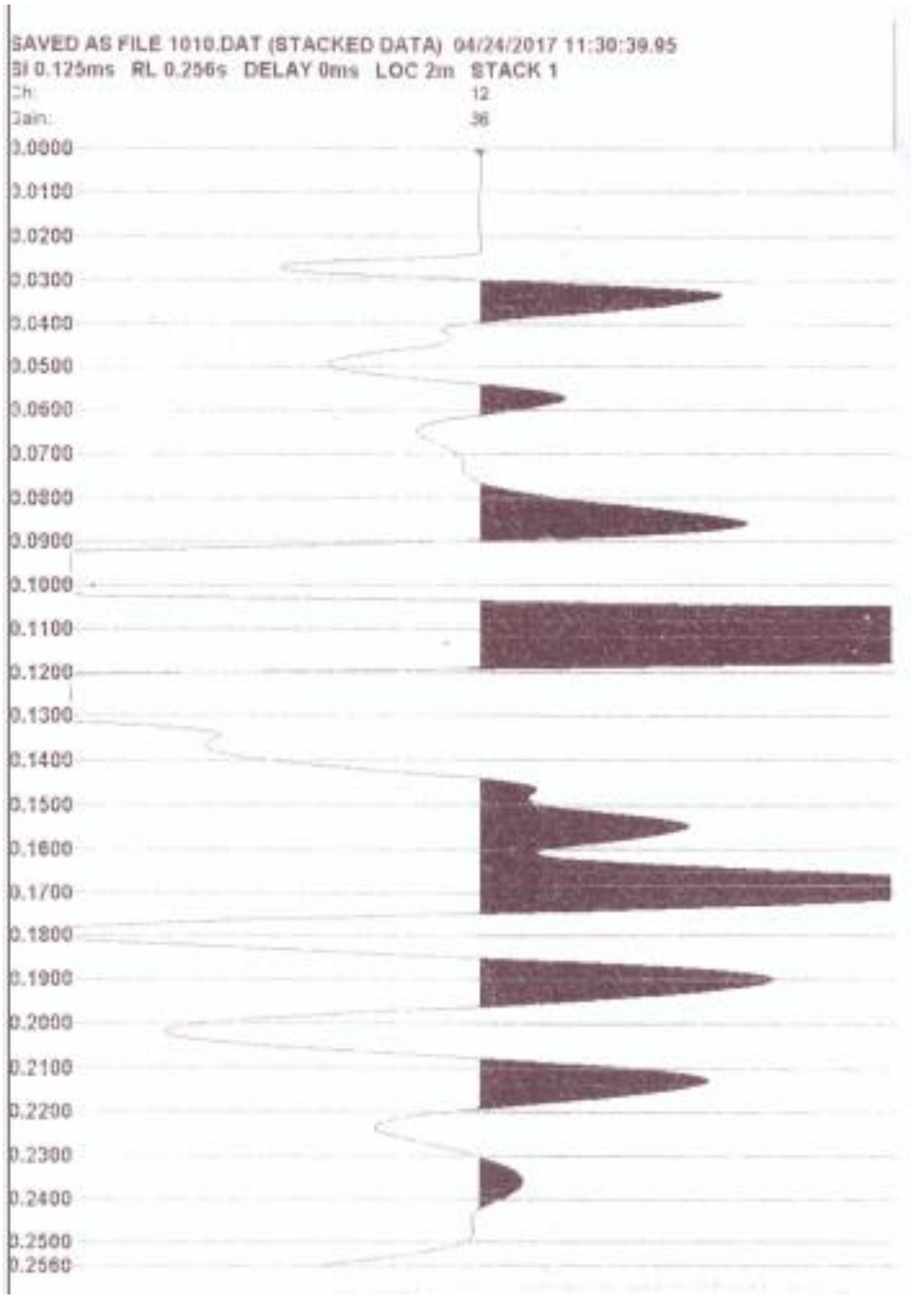

***Figure 4.** Selected monitor record of seismic wave arrival at Kenfa community shot point location.*

***Table 5.** Data for uphole position at Agudama (SL1298, RL 5491).*

Channel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Depth (m)	3	5	7	9	12	15	18	21	24	27	30	33	36	39	42	45	50	55	60
Tm (ms)	2	4	4.5	5.5	8	10	11	12	14	17	18	20	22	23	25	26	28	31	35
Tc (ms)	0.9	3.3	4.2	5.3	7.8	9.9	10.9	11.9	13.9	16.9	18	20	22	23	25	26	28	31	35
Ts (ms)	2.3	4.7	5.6	6.7	9.3	11.3	12.3	13.3	15.4	18.4	19.4	21.4	23.4	24.4	26.4	27.4	29.4	32.4	36.4

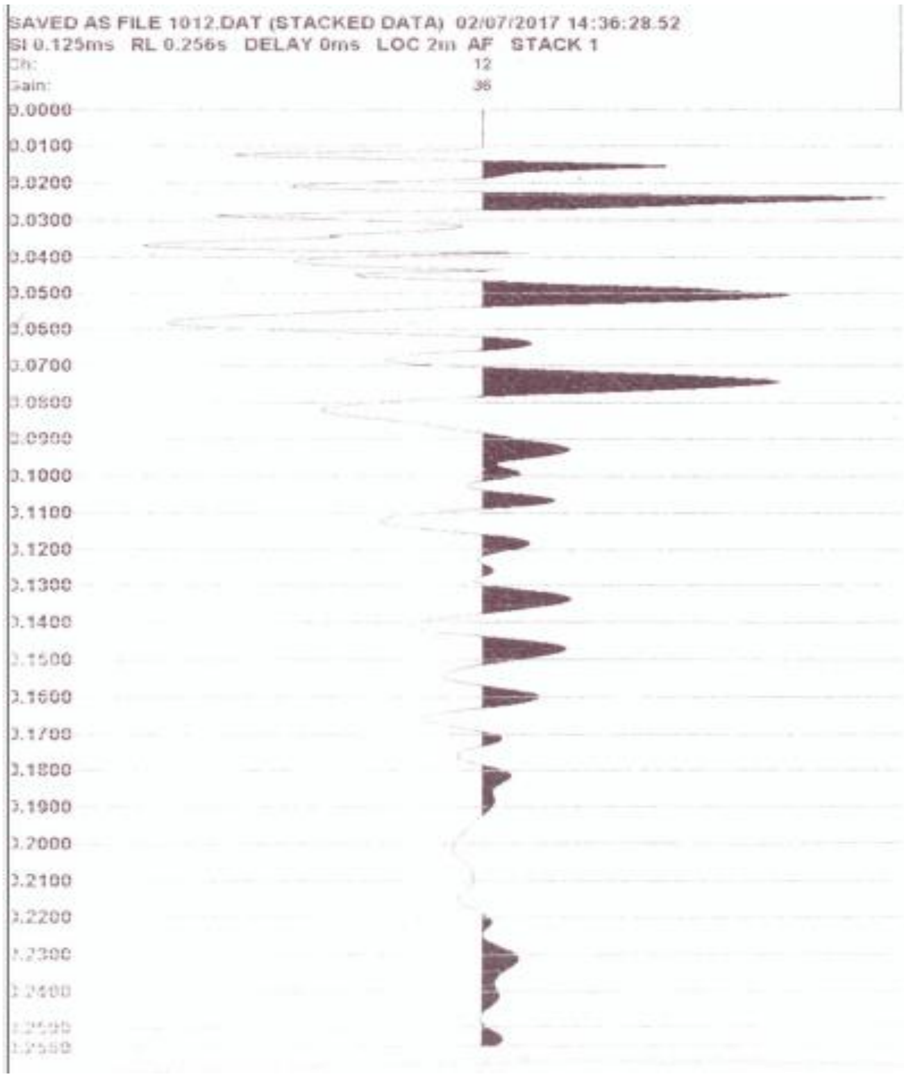

Figure 5. *Selected monitor record of seismic wave arrival at Yenegwe Community shot point location.*

Table 6. *Data for uphole position at Kenfa (SL1375, RL 5491).*

Channel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Depth(m)	3	5	7	9	12	15	18	21	24	21	30	33	36	39	42	45	50	55	60
Tm (ms)	9.5	12	13	15	17	18	20	21	23	24	26	21.5	30	31	33	34.5	37.5	40	43
Tc (ms)	4.2	10	12.1	14.4	16.7	17.8	19.8	20.9	22.9	23.9	25.9	27.4	29.9	31	33	34.5	37.5	40	43
Ts (ms)	11	16.1	18.8	21.1	23.4	24.5	26.6	27.6	29.6	30.6	32.7	34.2	36.1	37.7	39.1	41.2	44.2	46.1	49.7

Table 7. *Data for uphole position at Yenegwe (SL1452, RL 5491).*

Channel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Depth(m)	3	5	7	9	12	15	18	21	24	21	30	33	36	39	42
Tm (ms)	5	6.5	9	10	12	14	15.5	17	19	20	22	24	26	27	29
Tc (ms)	2.2	5.4	8.4	9.6	11.8	13.8	15.4	16.9	18.9	19.9	21.9	24	26	27	29

Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ts (ms)	5.8	8.9	11.9	13.2	15.3	17.4	18.9	20.4	22.5	23.5	25.5	27.5	29.5	30.5	32.5

Note: Tm =measured time; Tc = Offset corrected time; Ts= Surface corrected time; Corrected Depth dc= Depth (Rec)—Depth (Sou); Tc= Tm * (dc/ sqr(offset^2+ dc^2); Ts= Tc—Tc(0)

Utilizing a time-depth graph, qualitative interpretation was conducted to establish a model for the weathering layer and its associated values. The illustrated time-depth curves in Figures 6 to 8 provide a visual representation of this process. The data presented in Table 8 consistently supports a double-layer model.

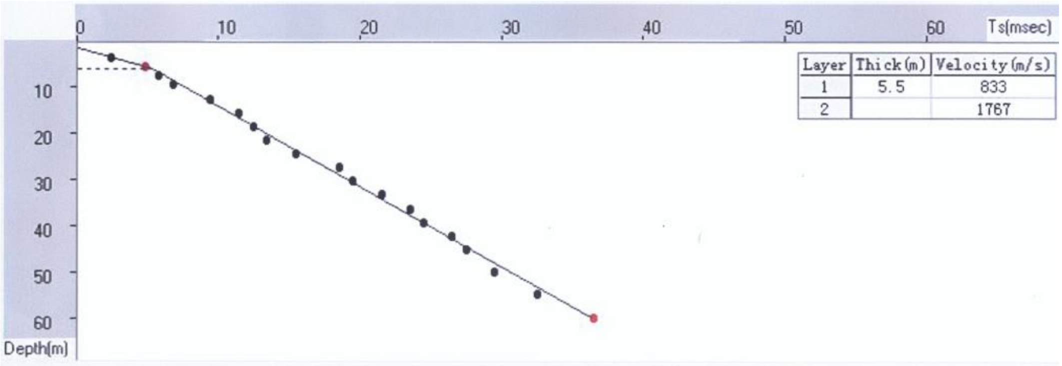

Figure 6. *Travel time versus depth curve for borehole at Agudama community (SL 1298, RL 5491).*

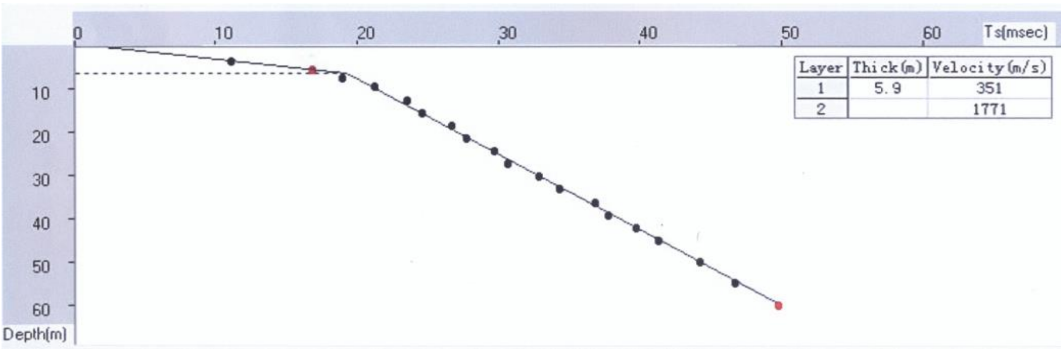

Figure 7. *Travel time versus depth curve for borehole at Kenfa community (SL 1298, RL 5491).*

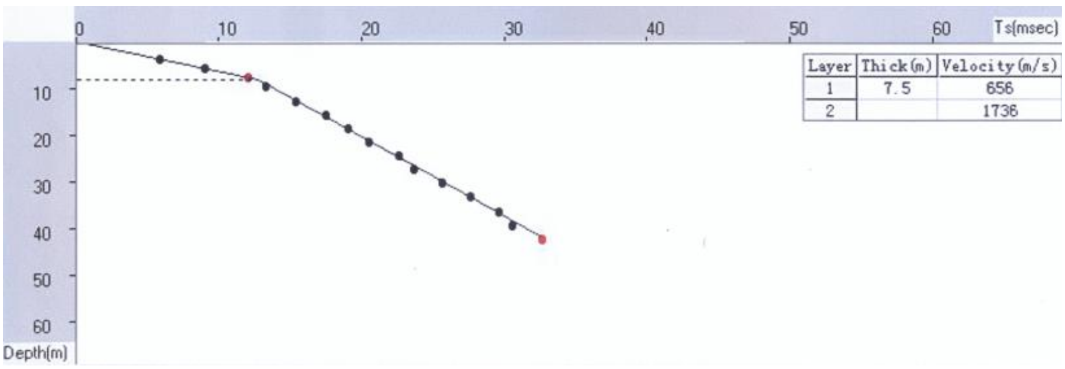

Figure 8. *Travel time versus depth curve for borehole at Yenegwe community (SL 1452, RL 5491).*

Table 8. Results of processed downhole data for all boreholes.

S/N	Shot Points Position	Coordinates		Elevation (m)	Weathered Layer		Consolidated Layer
		Easting	Northing		Thickness (m)	Velocity, V1 (m/s)	Velocity, V2 (m/s)
1	DWH 1(1298–5491)	445,333.91	105,501.13	3.145	5.5	833	1767
2	DWH 2(1375–5491)	445,325.56	109,351.23	7.088	5.9	351	1771
3	DWH 3(1452–5491)	445,325.86	113,200.75	7.487	7.5	656	1736

DWH = Downhole

4. Discussions

Figures 9 to 12 present the 3D representation of velocities in the weathered and consolidated layers, along with the thickness of the weathered zone and corresponding elevations at the study sites. The interrelationships among these variables are graphically depicted in Figures 13 to 16.

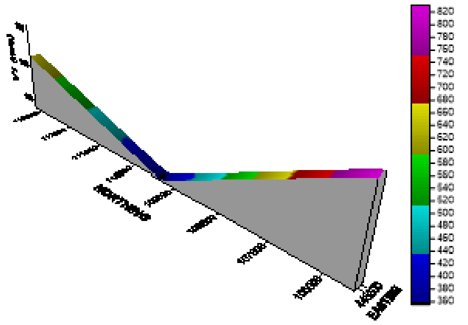

Figure 11. 3D weathered layer velocity plot of the study area.

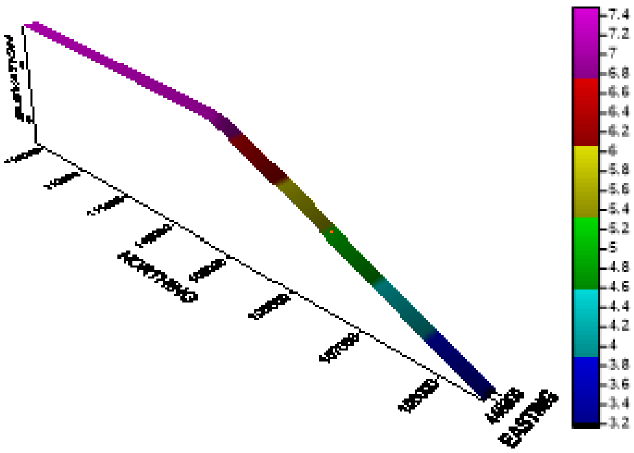

Figure 9. 3D Elevation contour of the study area.

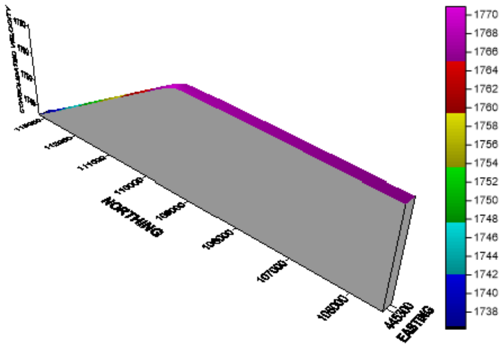

Figure 12. 3D consolidated layer velocity plot of the study area.

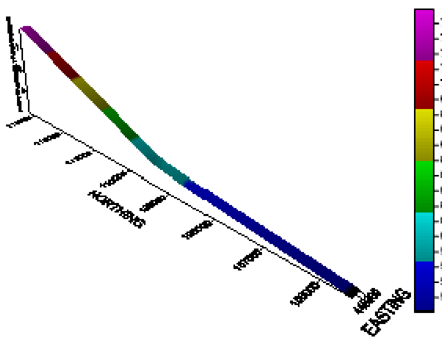

Figure 10. 3D Weathered Layer thickness plot of the study area.

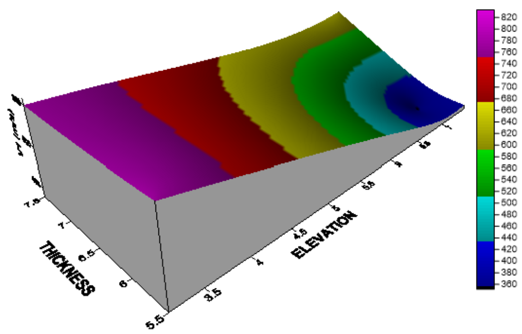

Figure 13. Elevation, weathered Thickness and weathered layer velocity 3D plot.

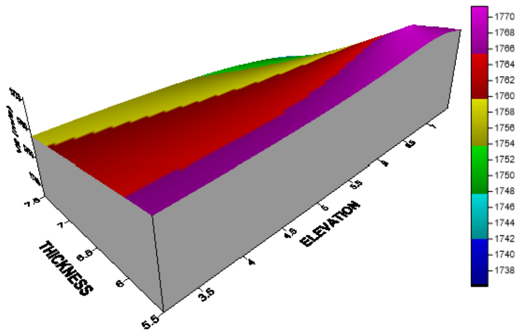

Figure 14. *Elevation, weathered Thickness and consolidated layer velocity 3D plot.*

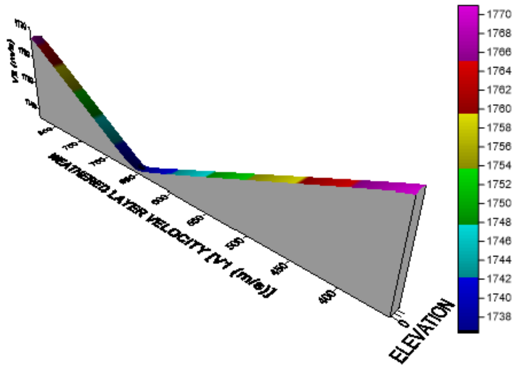

Figure 15. *Elevation, weathered layer velocity and consolidated layer velocity 3D plot.*

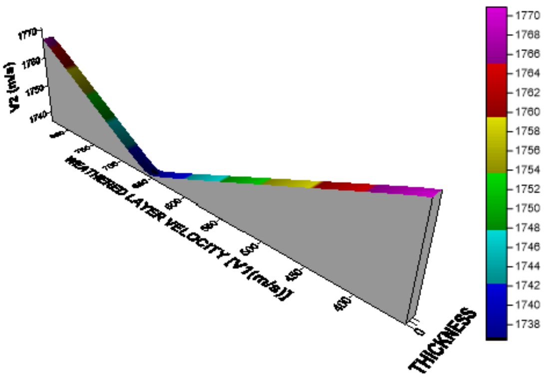

Figure 16. *Weathered layer thickness, weathered layer velocity and consolidated layer velocity 3D plot.*

The downhole refraction survey results reveal a prominent double-layer velocity model in the research areas, as depicted in Figures 6 to 8. The worn layer thickness varies from 5.5m to 7.5m, with an average of 6.3m, and the corresponding unconsolidated zone velocity ranges from 351 to 833 m/s, averaging at 613.3 m/s. In the consolidated zone, velocities range from 1,736 to 1,771 m/s, with an average of 1,758 m/s. Figures 9 and 10 illustrate that Agudama has the smallest elevation and weathered layer thickness, indicating less excavation during engineering work. Kenfa exhibits the highest consolidated layer velocity and the lowest weathered layer velocity among the three locations. Figure 13 shows a linear relationship between elevation, weathered layer thickness, and weathered layer velocity, indicating higher velocity in areas with elevated elevation and weathered layer thickness. Consolidated layer velocity, as shown in Figure 14, is highest in areas with moderate elevation and worn layer thickness. Figures 15 and 16 reveal that consolidated layer velocity is lowest at the greatest elevation and maximum weathered layer thickness, suggesting an inverse relationship in these areas. The findings suggest that elevation and weathered layer thickness influence the velocities of the weathered and consolidated layers differently across the research locations.

5. Conclusions

The study effectively employs the downhole refraction geophysical method to investigate the behavior of weathered zones in the research region, focusing on weathered layer thickness and velocities in weathered and consolidated layers. Results from three drilling sites reveal an average weathered zone thickness of 6.3m and velocities ranging from 351 to 833 m/s in weathered layers, and 1736 to 1771 m/s in consolidated layers. The strong velocity contrast border between weathered and consolidated zones suggests that structures founded on consolidated zones are more resilient, potentially reducing the high rate of structural collapse in the area.

The study concludes that the downhole refraction method is crucial for evaluating weathered strata properties, providing cost-effective and valuable subsurface information. Weathered layer velocity, elevation, and thickness are directly related, while consolidated layer velocity inversely correlates with elevation and weathered layer thickness.

6. Recommendation

Based on the findings, the study recommends drilling below the weathered zone to bury explosive used as source of seismic energy before detonation for quality reflection seismic data acquisition to minimize attenuations and ground rolls. For construction of high-rise structures, highways, and bridges, a minimum 15m excavation below foundations is advised to ensure stability on consolidated layers. Future studies should focus on closely spaced data points for better-defined subsurface information. Investigating additional soil properties supporting durable structures using various geophysical and geotechnical approaches is encouraged. Geochemical investigation of soil within the transition zone is recommended to understand chemical properties, guiding material selection for construction to prevent adverse reactions and potential harm. These recommendations aim to enhance the safety and durability of structures in the study area.

Abbreviations

Tm: measured time
Tc: Offset corrected time
Ts: Surface corrected time
Corrected Depth
DWH: Downhole
SL: Source line
SP: Shot point
ID: Identity

Author Contribution

Onwubuariri, Chukwuebuka Nnamdi conceptualized and designed the research under the supervision of Anakwuba, Emmanuel Kenechukwu. Agoha, Chidiebere Charles, Egwuonwu, Emmanuel and Ugochukwu, Joseph reviewed existing literature and data. Onwubuariri, Chukwuebuka Nnamdi, Osaki, Lawson Jack and Mgbeojedo, Tochukwu Innocent interpreted the result under the supervision of Anakwuba Emmanuel Kenechukwu. All the authors contributed to writing the research draft, read and approved the final manuscript.

Ethics Approval

The paper reflects the authors' research and analysis in its complete and truthful manner.

Data Availability

The data set used will be made available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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