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Empirical Geophysical Analysis of Unconsolidated Layer and of its Implication: Case Study of Gbaran Field, Niger Delta

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Abstract

This study investigates the weathered layer parameters of the Gbaran (OML 28) field in the Niger Delta using uphole refraction. 57 boreholes were bored and logged to study stratum components and characteristics. Weathered layer thickness ranges from 15.1m to 4.3m, with an average unconsolidated layer thickness of 6.9105m. Most of the unconsolidated stratum is silt or clay. This stratum has seismic wave velocities from 299 to 997m/s, averaging 697.14m/s. Consolidated stratum velocities average 1742.58m/s, ranging from 1551 to 1925. Subsurface refraction surveys were conducted at numerous locations, drilling and logging 57 boreholes. The acquisition plan included flushing drilling, cut lithology sampling, and logging from 0 to 60 metres. The velocities and thicknesses measured for each uphole site distinguish worn and cemented layers. Weathered layer thickness shows geological formation-influenced variations. Weathered layer velocity is 299–997m/s lower than consolidated layer velocity. Consolidated layer velocity is 1551–1925 m/s. Weathered layer thickness, velocity, and consolidated layer velocity are examined, focusing on thickness-velocity relationships. The recommendations include foundation design, construction methods, water management, geotechnical research, seismic design, monitoring, and geotechnical specialist coordination. Seismic refraction surveys can characterize underlying material variations and aid engineering design and risk assessment in the Niger Delta's dynamic geology.

Keywords: *Uphole; Seismic refraction; Gbaran; Weathered Layer; Hydrophone; Consolidated Layer.*

1. Introduction

The exploration of unconsolidated layers through refraction seismic methods holds significant importance in various fields such as seismic data acquisition, engineering practices, and agricultural applications [1-2]. Unconsolidated layers represent loosely packed or poorly compacted soil strata typically located at or near the surface. These layers are predominantly composed of materials such as overburdens, silts, clays, laterites, and fine-grained sands [3].

Unconsolidated soil refers to soil that has not undergone substantial pressure or compression to alter its physical attributes significantly [1,4]. Such soil maintains loose particle arrangements, allowing for easy movement of water, air, and roots, making it favorable for agricultural activities. Key characteristics of unconsolidated soil layers include:

- **Particle arrangement:** These soils exhibit loose particle arrangements, where sand, silt, and clay particles are not tightly packed, enabling the free movement of essential elements for plant growth.
- **Porosity:** Unconsolidated soils generally possess higher porosity, providing increased volume of pore space for water retention and transmission.

- **Permeability:** The loose structure of unconsolidated soil results in good permeability, allowing water to flow more freely compared to compacted soils.
- **Erosion and settlement:** These soils are susceptible to erosion caused by wind or water transport, as well as settlement due to external loading, posing challenges for construction activities.
- **Foundation considerations:** Construction on unconsolidated soil necessitates careful attention to prevent issues such as differential settlement, which can impact the stability of structures.
- **Geotechnical engineering**: Understanding the properties of unconsolidated soil is vital for geotechnical engineering, aiding in assessments of soil stability and behavior through various tests.
- **Natural processes:** Unconsolidated soil layers are often prevalent in areas undergoing natural processes like weathering and deposition, such as riverbanks, floodplains, and coastal regions.

It is crucial to recognize that the characteristics of unconsolidated soil can vary significantly based on factors like soil composition, environmental conditions, and geological history. Engineers and geologists rely on such analyses to make informed decisions regarding land use, construction practices, and environmental management, emphasizing the significance of ongoing research in this field [5].

2. Location and geology of the study area

The Gbaran Field in Bayelsa State, Nigeria, was formed during the Holocene epoch of the quaternary period through the accumulation of sedimentary rocks in the lower delta plain. The most prominent geological characteristic of the field is the sedimentary alluvium [2]. Across the field, one can observe abandoned beach ridges. The abundance of tributaries in the Niger River plain indicates the ongoing presence of significant geological transformations. The Gbaran Field is situated at a longitude of 4.7836° N and latitude of 5.8600° E. According to Nyananyo [6], the Niger Delta is the delta with the highest population on Earth. As per the research conducted, it is ranked as the second-largest globally and holds the title of being the largest in Africa [4,7-8]. The wetland portions of the region cover approximately 5,400 to 6,000 km² out of its total size of 7,000 km². These wetlands are known for hosting the world's largest mangrove forest [6,8]. In addition, it includes various distinct natural areas such as lowland rainforests, freshwater swamp forests, barriers, and coastal ridges [6,8]. The geographical coordinates of the research area can be observed on the maps depicted in Figures 1 and 2.

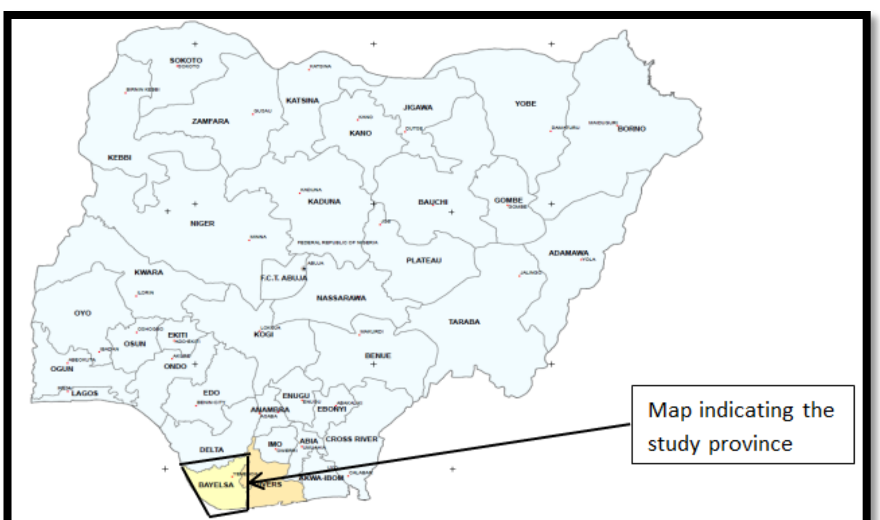

Figure 1. Map showing the study province of Gbaran field.

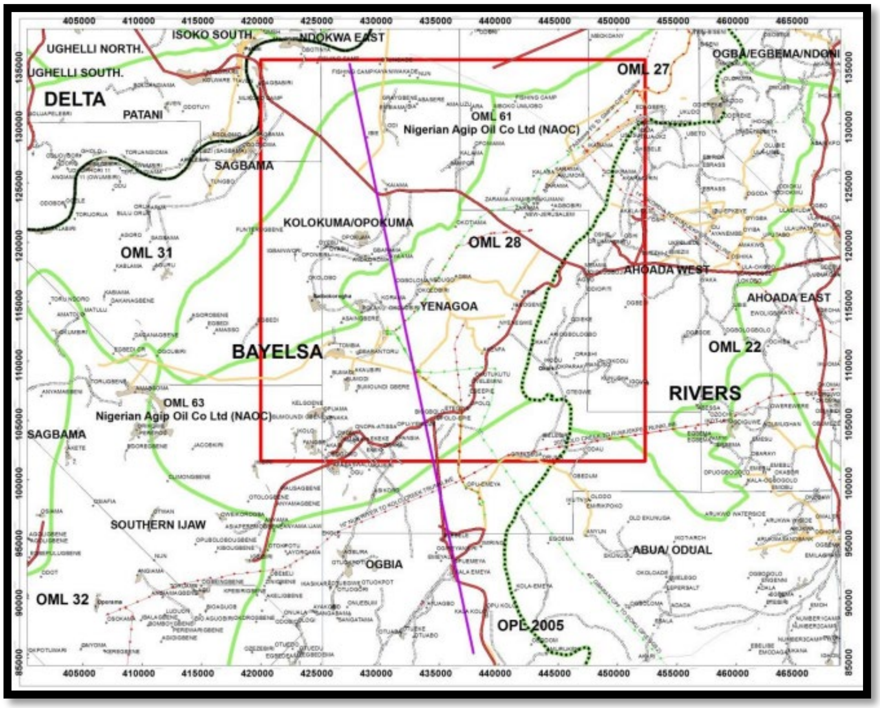

Figure 2. Diagram indicating the Gbaran field (OML 28).

The Gbaran Field predominantly consists of two soil types: inceptisol aquepts, characterized by their youth, shallow depth, and poor drainage, and sulfaquepts, which are acid-sulfate soils [9-10]. Variations in the field's physical properties help identify different soil units, although certain types are more prevalent than others [11-13]. Soil distribution within the area includes:

- High levees feature soils such as sands, sandy loam, loamy sandy, and silty loamy.
- Lower regions are covered by red silty, clay loamy, or fine-grained soils.
- Meander belt soils exhibit a more uniform texture compared to higher elevations.
- Silted river belt soils, including peat for clay and waterlogged soils, are commonly found along dormant creeks and streams.
- Basin soils, like sandy loams and silty clay loams, remain saturated for extended periods annually.
- Transition zone soils, affected by both saltwater and freshwater floods, consist of silt and sandy silt, with some areas showing potassium deficiency, particularly in sandy soils with medium to fine grains.

The Gbaran Field's landscape comprises floodplains, coastal beaches, barrier beaches, and tidal flats, with notable features such as lagoons and cliffs [5]. Positioned between the upper and lower delta plains of the Niger Delta, the field generally exhibits low-lying terrain, with a slight elevation increase across the wide plain and a drop in elevation downstream.

3. Methodology

A preliminary survey of the area was carried out as part of the field work, during which notes were taken about the geographical features. In order to ascertain the weathered layer depth, geological zone velocities, and observed passage times through the layers, a subsurface refraction survey was executed at multiple locations. We used a GPS device to record the coordinates of the places of interest to document their geographical positions [14].

3.1. Acquisition flow

57 downhole locations had 66-m boreholes dug. Flush drilling was used to drill these holes. The pit was regularly pumped with water to soften the ground for drilling. The drill bit rotates freely inside the ground while cutting sediments with its support weight. Ground cuttings are

washed into the mud pit for evacuation. As the hole deepened, cut lithology samples were taken every 3 m. Samples were taken to profile soil vertically at shot points. As lithologies alternate with depth, velocity fluctuations are obvious. Not all drilled holes are logged. This allows for backfilling. We installed plastic pipes and filled the drilled holes with water before logging. The energy source hole, where explosive caps or detonators are concealed, was 1.5 m deep and 3 m from the hole to be logged. Semi-automated rotary drilling was used. This drilling method flushes cuttings by manually rotating drill stems with the swivel head arm and pumping water into the hole. A mixture of bentonite, EZ mud, and water stabilises the hole and flushes sediment cuttings to the top. Well-calibrated water-resistant conducting electric cable and maritime rope with distinct hydrophone sites were used for logging. The order of logging depths is 0, 1, 3, 5, 10, 15, 20, 25, 30, 40, 50, 60 m. Acquisition was done using a fast, accurate Geometrics Stratavisor NZ1 light-weight signal booster seismography. This procedure also used 6 mm cap explosive detonators (seismic source), a 10 Hz hydrophone receiver, a calibrated cable and marine rope, and a 24-V rechargeable battery. Data sheet and diskette tap were used to record field occurrences and store them.

4. Results and discussions

A total of 57 boreholes were dug only to obtain refraction data (uphole) in the GBARAN (OML 28) region. The objective of this inquiry is to ascertain the exact thickness of the weathered layer, which negatively affects the acquisition of reflection seismic data and also provides a significant obstacle to the execution of engineering projects. Both weathered and consolidated layer velocities were estimated. Moreover, according to the characteristics of the weathered layer and the composition of the materials, they are most suitable for agricultural activities, particularly for growing plants. Table 1 presents the precise position and corresponding results acquired from uphole data collecting. According to this investigation, OML 28 was found to consist of two separate layers: the weathered layer and the consolidated layer. The differentiation between these layers is based on their variation in velocity, with just two velocity models being identified.

Table 1. Uphole statistics summary of the study area.

S/N	Location (borehole points)	Coordinate		Elevation (m)	Weathered layer report	Consolidated layer report	
		Easting	Northing		Thickness (m)	VelocityV1 (m/s)	Velocity V2 (m/s)
1	UPH 01 (1760 - 5491)	445324.8430	128599.9190	7.3670	5.7	742	1779
2	UPH 02 (1683 - 5491)	445325.5910	124752.0190	8.6540	7.5	779	1755
3	UPH 03 (1606 - 5491)	445325.6430	120901.4530	7.2870	5.9	500	1739
4	UPH 04 (1529 - 5491)	445325.8340	117051.0950	7.9970	5.6	571	1749
5	UPH 05 (1452 - 5491)	445325.8640	113200.7470	7.4870	7.5	656	1736
6	UPH 06 (1375 - 5491)	445325.5600	109351.2330	7.0880	5.9	351	1771
7	UPH 07 (1298 - 5491)	445333.9130	105501.1300	3.1450	5.5	833	1767
8	UPH 08 (1760 - 5414)	441475.6870	128601.0590	7.0310	5.7	769	1710
9	UPH 09 (1683 - 5414)	441475.8070	124753.1700	3.6690	4.3	833	1727
10	UPH 10 (1606 - 5414)	441450.0000	120900.5000	8.7570	6.7	546	1760
11	UPH 11 (1529 - 5414)	441475.5260	117051.6660	8.0120	8.1	782	1758
12	UPH 12 (1452 - 5414)	441450.0000	113200.5000	6.6000	6.9	591	1598
13	UPH 13 (1375 - 5414)	441475.9080	109352.5090	6.8700	5.0	500	1733
14	UPH 14 (1298 - 5414)	441475.4570	105499.3630	5.8060	9.4	766	1636
15	UPH 15 (1914 - 5337)	437625.1840	136299.8170	8.6900	7.5	730	1691
16	UPH 16 (1837 - 5337)	437625.6060	132451.5090	6.7440	6.3	833	1734
17	UPH 17 (1760 - 5342)	437875.8430	128601.4480	7.9780	6.2	714	1723
18	UPH 18 (1683 - 5337)	437625.6700	124751.3860	7.8510	9.0	569	1736
19	UPH 19 (1606 - 5337)	437625.5440	120901.4610	5.3560	5.6	714	1750
20	UPH 20 (1529 - 5337)	437625.7420	117050.6160	5.0520	9.7	918	1643
21	UPH 21 (1452 - 5337)	437625.5010	113200.9680	5.3400	5.6	833	1775
22	UPH 22 (1375 - 5337)	437625.8000	109351.4000	7.1240	6.7	833	1551
23	UPH 23 (1298 - 5351)	438325.8000	105501.4000	7.1258	6.0	952	1778
24	UPH 24 (1914 -5260)	433650.3510	136301.2120	10.3430	7.3	950	1762

S/N	Location (borehole points)	Coordinate		Elevation (m)	Weathered layer report	Consolidated layer report	
		Easting	Northing		Thickness (m)	VelocityV1 (m/s)	Velocity V2 (m/s)
25	UPH 25 (1837 - 5260)	433750.8990	132451.1380	9.0680	7.3	714	1762
26	UPH 26 (1760 - 5260)	433751.4430	128601.8100	9.4130	5.9	408	1716
27	UPH 27 (1683 - 5260)	433750.8110	124751.3130	7.0950	5.2	714	1760
28	UPH 28 (1606 - 5260)	433750.5710	120901.7220	4.8210	9.1	738	1701
29	UPH 29 (1529 - 5260)	434050.7000	117051.3510	8.2300	8.2	571	1700
30	UPH 30 (1452 - 5260)	433748.1270	113198.8940	6.0480	4.8	714	1746
31	UPH 31 (1375 - 5260)	433750.9360	109348.8240	4.9810	4.9	714	1769
32	UPH 32 (1298 - 5260)	433750.7880	105501.8330	6.4100	5.1	714	1754
33	UPH 33 (1914 - 5183)	429928.6200	136301.4400	9.4280	9.9	898	1675
34	UPH 34 (1837 - 5183)	429925.8240	132451.4110	9.9390	15.1	973	1657
35	UPH 35 (1760 - 5183)	429925.7910	128601.3930	8.9960	8.6	997	1722
36	UPH 36 (1683 - 5183)	429926.0090	124751.1290	7.8350	9.1	869	1712
37	UPH 37 (1606 - 5185)	425000.7870	120901.3540	7.3080	5.8	299	1865
38	UPH 38 (1529 - 5183)	429900.7420	117050.9610	4.9400	5.0	833	1755
39	UPH 39 (1452 - 5183)	429900.6650	113202.0750	6.0580	6.7	851	1775
40	UPH 40 (1375 - 5183)	429952.0570	109353.5810	5.2090	6.1	833	1753
41	UPH 41 (1298 - 5183)	429951.1060	105500.7220	6.0540	5.7	526	1730
42	UPH 42 (1837 - 5106)	426050.8700	132451.3830	7.1590	9.8	757	1746
43	UPH 43 (1760 - 5106)	426050.5560	128601.6500	6.0450	5.2	476	1806
44	UPH 44 (1683 - 5106)	426050.8620	124752.3000	6.5640	5.7	556	1787
45	UPH 45 (1606 - 5106)	426051.1110	120900.5340	8.3750	6.2	556	1895
46	UPH 46 (1529 - 5106)	426051.0500	117050.6710	4.6350	6.3	714	1745
47	UPH 47 (1452 - 5106)	426050.9070	113352.7160	5.1940	7.1	671	1736
48	UPH 48 (1375 - 5106)	426050.2220	109352.1310	2.8810	10.0	714	1750
49	UPH 49 (1297 - 5106)	426075.0000	105450.5000	6.5400	6.0	513	1753
50	UPH 50 (1837 - 5029)	422198.6730	132450.5500	6.8180	6.1	488	1755
51	UPH 51 (1760 - 5029)	422201.4160	128602.8790	6.1690	6.2	513	1757
52	UPH 52 (1683 - 5029)	422200.8810	124750.8350	5.5330	7.6	666	1799
53	UPH 53 (1606 - 5029)	422200.7920	120901.1680	3.7790	6.9	909	1925
54	UPH 54 (1529 - 5029)	422200.1090	117049.1750	3.4290	7.9	553	1813
55	UPH 55 (1452 - 5029)	422200.3740	113200.7840	6.5470	6.3	392	1749
56	UPH 56 (1375 - 5029)	422200.5660	109351.9060	6.5580	7.9	701	1647
57	UPH 57 (1298 - 5029)	422200.8610	105500.4660	3.6620	6.6	927	1751

To facilitate the collection of refraction data, the research area was divided into seven sections, with each section containing at least seven uphole placements. Swaths 7 and 6 comprise seven uphole positions each, whereas Swaths 5, 4, and 3 comprise nine uphole positions apiece. Swaths 2 and 1 each comprise eight uphole spots.

The analysis of the obtained refraction data from all 57 boreholes throughout the 7 swaths indicated a consistent two-layer model for the whole research area. The uppermost layer known as weathered or unconsolidated layer is composed of loose or low velocity material, while the layer beneath it, known as consolidated layer is made up of compacted material. The mean duration for the occurrence of the first break among the 57 obtained data points is 9.31 milliseconds. The term "first break" refers to the first deflection of seismic signal towards the left. It is equivalent to the time of signal arrival. The analysis or interpretations were conducted using Udysys software.

4.1. Weathered layer thickness analysis

The eroded or loosely packed layers are primarily found in the uppermost layers of soil. The weathered layer in this study predominantly comprises overburdens, loose lateritic soil, and fine and medium-grain sand, exhibiting variations based on the location and geological formations found in the investigated area. The regions impacted by weathering are commonly known as low-velocity layers or zones. This phenomenon occurs when seismic waves propagate at a reduced velocity in loose zones compared to densely compacted regions. This is due to the fact that sound or energy propagates more rapidly in a compacted medium than in a loose medium. The research indicates that the mean unconsolidated thickness of the study region is 6.9105m, with the maximum and minimum unconsolidated thickness within the analysed area measuring 15.1m and 4.3m, respectively. The hue orange in Figures 3 and 4 represents places with a substantial amount of weathered thickness. Regions with a moderate thickness of weathered material are represented by green areas, whereas regions with a low thickness of weathered material are represented by blue areas. Figure 5 depicts a vector diagram that showcases the distribution of weathering thickness. Locations with low thickness indicate areas of arrow convergence, whereas locations with high worn thickness indicate areas of arrow divergence. The upper limit of the weathered layer's thickness is located between the easting coordinates of 430,000 and the northing coordinates of 130,000 to 135,000, as depicted in Figures 3 and 4.

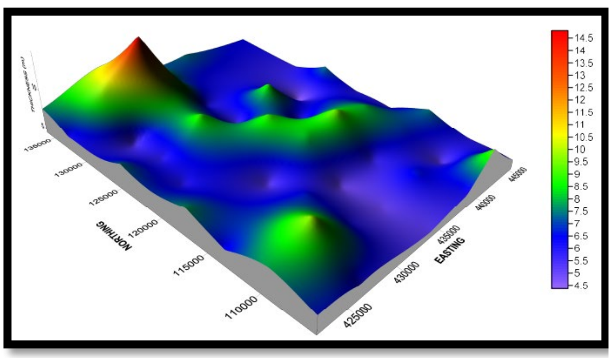

Figure 3. Weathered layer thickness 3D plot.

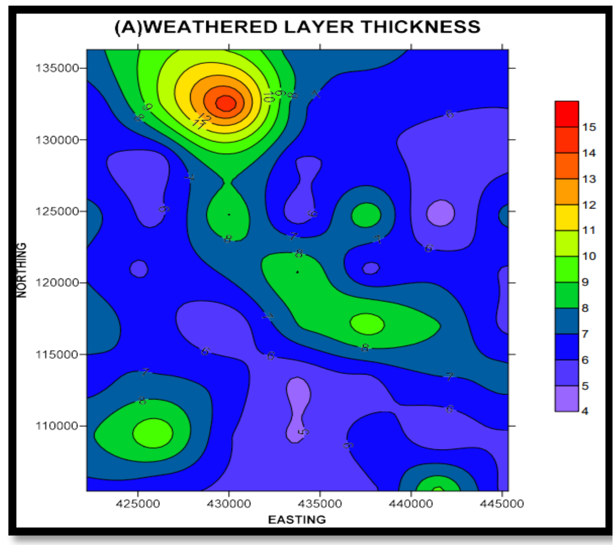

Figure 4. Weathered layer thickness 2D contour.

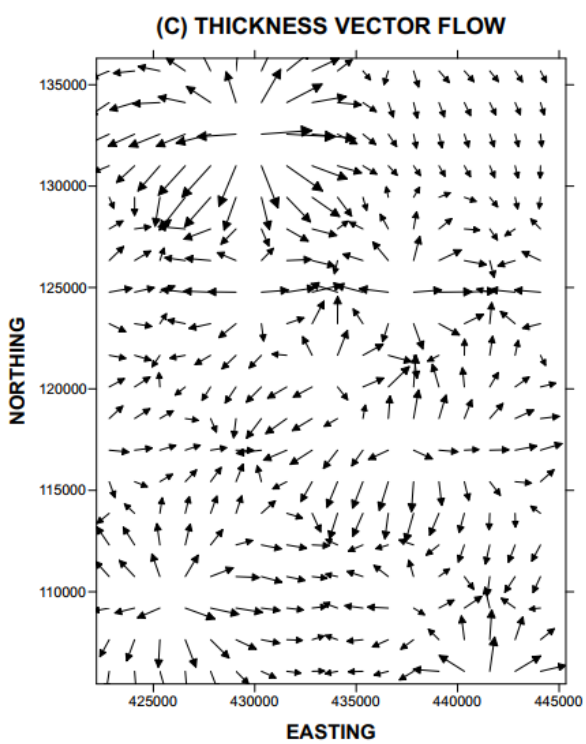

Figure 5. Weathered layer thickness vector diagram

4.2. Weathered layer velocity analysis

The weathered velocity of propagation is the velocity of seismic pulses within the unconsolidated or worn layer, which always occurs near the surface. The magnitude of this velocity is consistently smaller than that of the consolidated layer. This is due to insufficient layer consolidation and the composition of the elements that comprise the layer. Therefore, the velocity within this medium is decreased as a result of the existence of empty spaces or gaps between particles in the layers, leading to the creation of voids or vacuums between the particles of the layers. It is widely recognised that energy travels faster in solid or tightly packed particles than in loosely packed particles. This occurs because to the close proximity of the particles within the layer, resulting in the absence of any air gaps and consequently producing a drop in energy. The research findings suggest that the minimum velocity within the unconsolidated layer is 299 m/s, whilst the maximum velocity is 997 m/s. The average velocity of the loose layer is 697.14 m/s. Therefore, the velocity at which seismic energy travels through the weathered layer of the GBARAN field ranges from 299 m/s to 997 m/s, with an average speed of 697.14 m/s. Figures 6 and 7 illustrate the velocities of the weathered layer in two-dimensional and three-dimensional representations, respectively. The highest rates of weathering were observed inside the research area, specifically between the coordinates of 430,000 easting and 125,000 to 135,000 northing, as depicted in Figures 6 and 7. The greatest values for the parameters for coordinates with an easting of 430,000 and a northing between 125,000 and 135,000 are elevation, weathered layer thickness, and weathered layer velocity. It is clear from my research and observations that there is a direct relationship between weathered layer velocity and thickness. An increase in one has a direct impact on the others, and vice versa (as illustrated in figures 3 - 7).

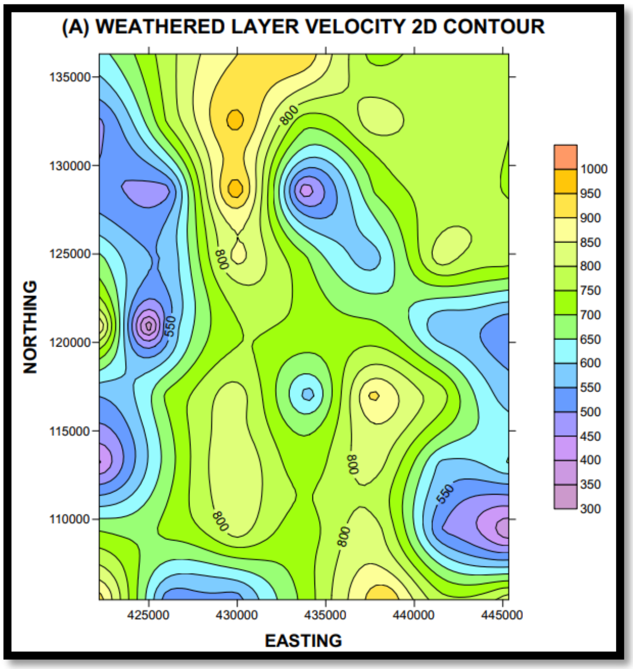

Figure 6. 2D contour of weathered layer velocity.

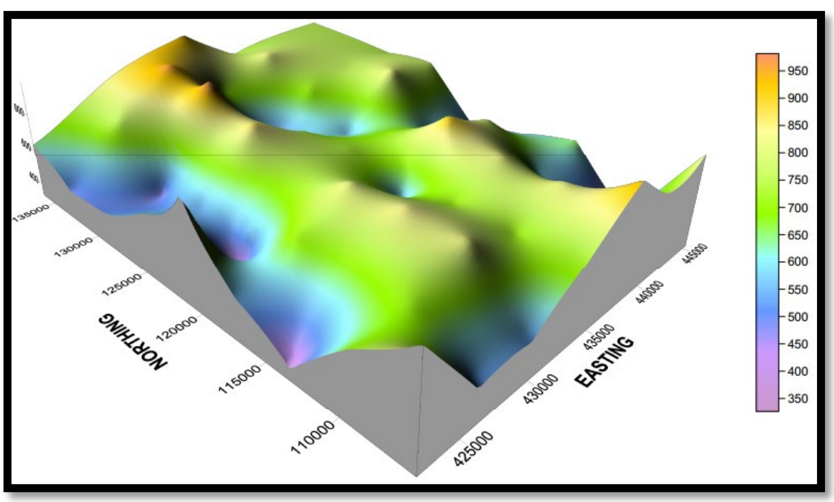

Figure 7. 3D expression of weathered layer velocity.

4.3. Consolidated layer velocity analysis

Consolidated layer velocity, like weathered layer velocity, defines the rate at which seismic energy passes through a solidified layer. Consolidated particles are those that are closely packed together and have very little space between them inside a layer. Because there is no energy dissipation due to empty spaces or substantial air gaps, the intrinsic features of this layer allow for a more efficient and rapid transfer of energy. During drilling, the consolidated layer is consistently selected as the primary layer for acquiring reflection data. The quantity of energy dissipated internally is negligible. There is minimal or insignificant ground movement noticed in the reflection data produced by the consolidated layer. Noise interference has been decreased in the data. When sampling the subsurface using the seismic method, the importance of this layer cannot be overstated. The consolidated stratum velocities in this study range from 1551 m/s to 1925 m/s, with an average velocity of 1742.58 m/s. Figures 8 and 9 show that the greatest total velocity is found between the geographic coordinates of easting 425,000 and northing 120,000 to 125,000. This means that seismic energy moves faster along that specific axis within the medium or layer than in other regions.

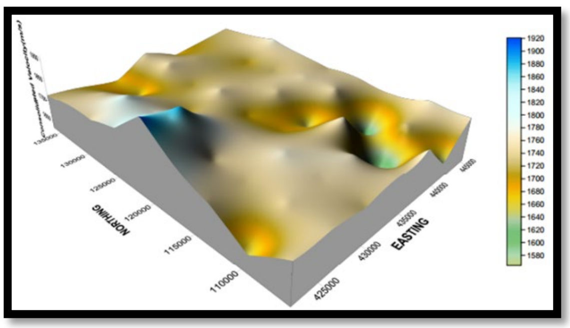

Figure 8. 3D expression of consolidated layer velocity.

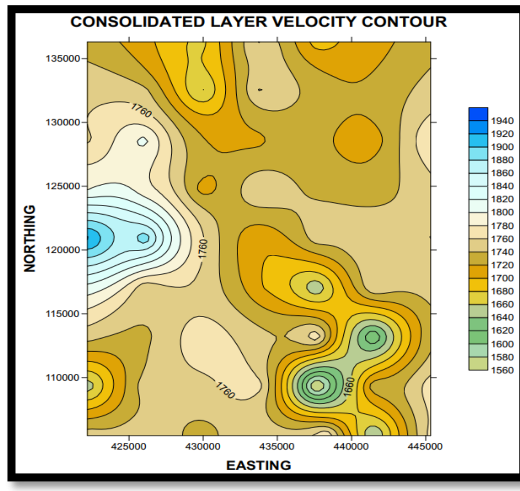

Figure 9. 2D contour of consolidated layer velocity.

4.4. Relationship between weathered layer thickness, weathered layer and consolidated layer velocities

In addition, Figures 10 and 11 show that the weathered velocity peaks at the maximum weathered thickness. Furthermore, the weathered layer velocity peaked in the GBARAN field when the consolidated velocity was between 1600 and 1700 m/s. The same location also has the highest altitude and the thickest weathered layer.

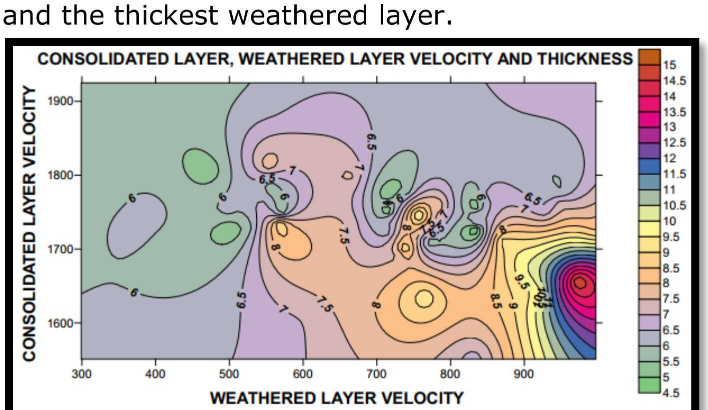

Figure 10. 2D contour of weathered layer thickness, weathered and consolidated layer velocities.

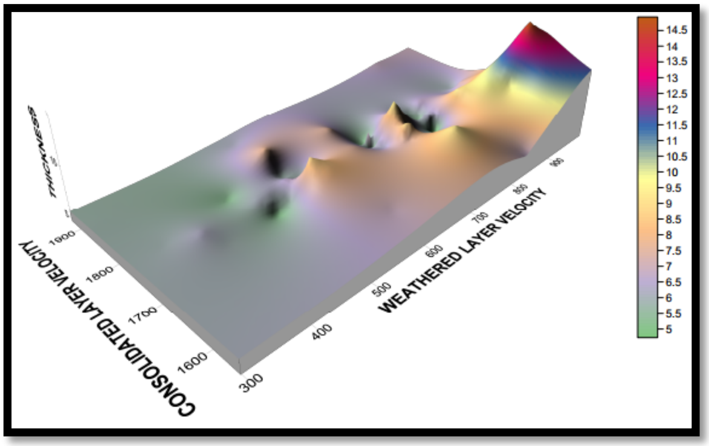

Figure 11. 3D plot of weathered layer thickness, weathered and consolidated layer velocities.

5. Conclusion and recommendation

Using the uphole refraction technique, the weathered layer thickness of the Gbaran (OML 28) field was rigorously examined. A total of 57 holes were drilled and correctly logged in this investigation to determine the various layer components and their accompanying behaviours. Contrary to popular belief, the field's weathered layer thickness spans from 15.1m to 4.3m, with an average unconsolidated layer thickness of 6.9105m. It was also discovered that this layer is composed of loose particles, which allow for the peculation of water in between particles most of the time. In comparison to the consolidated medium, the velocity at which seismic waves transmit through it is low. According to the research findings, the lowest velocity within the unconsolidated layer is 299 m/s, while the highest velocity is 997 m/s. The unconsolidated layer has a mean velocity of 697.14 m/s. Similarly, the consolidated stratum velocities in this study range from 1551 m/s to 1925 m/s, with an average velocity of 1742.58 m/s. This shows that seismic refraction surveys are effective in characterizing the velocity variations in different subsurface materials.

Regarding the field of research, the following recommendations were made:

- **Foundation design:** Because of the unconsolidated character of the weathered layer with loose particles and the inadequate interconnectivity of pore spaces, foundation design should be given special consideration. To account for the potential settlement and instability associated with unconsolidated materials, structures and foundations in this area requires additional support or specialised design.
- **Techniques for site development and construction**: Construction activities in the area should be planned with the varied thickness of the weathered layer in mind. Excavation to a minimum depth of at least 20m and construction procedures should be carefully chosen to reduce the influence on the unconsolidated layer and to avoid problems like soil erosion and water percolation between particles.
- Water management techniques should be implemented in light of the discovery that the weathered layer facilitates water percolation between particles. This could include proper drainage systems and erosion control methods to prevent water-related difficulties and keep the region stable.
- **Geotechnical studies:** Additional geotechnical studies are required to fully understand the composition and features of the unconsolidated layer. Additional boreholes, geophysical surveys, and laboratory testing is also required to offer more precise information for engineering design and risk assessment.
- **Considerations for seismic design:** Structures in the area should be constructed with the seismic properties of the unconsolidated and consolidated strata in mind. The varied velocity of seismic waves through various layers should be considered when designing seismic structures and ensuring the structural integrity of buildings and infrastructure.

- **Monitoring and upkeep:** Continuous monitoring of ground conditions is advised, particularly in locations with unconsolidated layers. To address any changes in the behaviour of the weathered layer and ensure the long-term stability of buildings, regular inspections and maintenance operations should be carried out.
- **Collaboration with geotechnical consultants:** The engagement of a geotechnical engineer to evaluate and validate the study's findings is of uttermost importance. Their knowledge can help to build effective technical solutions by providing significant insights into the specific issues associated with the unconsolidated layer.
- If feasible, repeat surveys should be conducted over time to monitor changes in the subsurface, especially in the unconsolidated layer where water percolation may cause variations.

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