



Research article

Evaluation of geotechnical parameters of reclaimed land from near-surface seismic refraction method

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ABSTRACT

Correct execution of civil engineering structures depends largely on the adequate and detailed mapping of the subsurface. This can be achieved by the application of appropriate geophysical or geotechnical methods in association with a detailed information on the geological sequence of the subsurface structure. In this study, a combination of near surface seismic refraction method, cone penetration test and borehole logs were used to obtain 2-dimensional (2D) information of the subsurface geological features. These methods were used to characterize the subsurface condition of a reclaimed land in Ajah area of Lagos for the purpose of construction. The seismic refraction method revealed three geologic layers with seismic velocities ranging between 258 and 3544 m/s. Additionally, the cone penetration test revealed that the geologic formation from the topsoil to a depth of 6 m was an alluvium of soft and highly compressible property. Furthermore, the percussion drilling test also confirmed the geologic formation from the topsoil to a depth of about 6 m to be highly compressible. However, a geologic formation with good geotechnical characteristics, such as a low compressibility potential, was encountered at a depth between 7 and 16 m, which coincides with the third layer of the seismic refraction method. The results of the three methods confirmed that the depth to most competent layer must be located before the foundations of engineering constructions are sited.

1. Introduction

The cost of damages to human lives and infra-structures, as a result of building collapse, may be difficult to estimate. Most often, this collapse could be as a result of improper investigation to determine the competence limit of the subsurface before a building is constructed (Shimobe and Spagnoli, 2020). Studies have shown that most of the major cities and highly populated areas of the world such as Dubai in the United Arab Emirates and Lagos State in Nigeria are located on soft sediments and recent geological deposits (Ayolabi et al., 2012; Alkroosh et al., 2015). However, soil structure possessing this characteristic, subjects the building on it to collapse (Deidda and Ranieri, 2005; Martinez and Mendoza, 2011; Azwin et al., 2013a; Fang et al., 2019). Studies have revealed that constructions dependent solely on engineering judgment fails 70% of the time (Das and Basudhar, 2009). Therefore, adequate understanding of the near surface geology in relation to the nature of the engineering project at hand is an important factor in deciding the best land use in many areas.

In order to understand the near surface geology of an area, it is important to conduct some investigations on the soil. The most common approach for soil characterizations is based on drillings, excavations and laboratory analyses. The results obtained from these methods are site-specific (Das and Basudhar, 2009; Robertson, 2009) and are limited to the tested point, which may be difficult to generalize the same result in the development of a very wider space of the area studied (Godio et al., 2006; Bizjak and Zupancic, 2009; Prasad et al., 2010; Mohamed et al., 2013a). Due to the heterogeneous nature of the subsurface, the results obtained for a point test on a site may not be the same for some other parts of the same site (Robertson, 1990; Miller et al., 2018). However, traditional geological interpretation from geotechnical methods (such as drilling) alone would provide inadequate subsurface information (Engesfeld et al., 2011; Cardarelli et al., 2014; Feng et al., 2016). As a result of this, the results from such methods must be correlated with results from other relevant geophysical methods in order to obtain a more reliable and adequate information of the subsurface (Lim et al., 2020; Shimobe and Spagnoli, 2020).

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Based on the above, it is recommended that the condition of the subsurface must be properly evaluated by other methods, especially, geophysical methods other than the geotechnical methods alone. In some cases, application of geophysical techniques to subsurface investigation has been discovered to provide very reliable, fast and cost effective means of understanding the geological settings of area of interest before commencing the construction of large infrastructures (Grelle and Guadagno, 2009; Fabien-Ouellet and Fortier, 2014; Pegah and Liu, 2016). Some of the geophysical methods engaged for site investigations include electrical resistivity methods, multi-channel analysis of surface waves, ground penetrating radar, seismic refraction method to mention a few (Mohamed et al., 2013b).

Seismic refraction method is one of the first major geophysical methods, that does not alter the original geological formation of the soil during investigation (Osazuwa and Chinedu, 2008; Eker et al., 2012). This method has been found to be very useful in mapping the near

surface, particularly in site investigations for civil and geotechnical engineering (Das, 2007; Pueyo-Anchuela et al., 2011; Azwin et al., 2013b; Lorenzo et al., 2014; Boi et al., 2019). Seismic refraction method has also proven to be a very powerful investigative tool, for shallow survey; this is because it operates by propagation of elastic energy into the subsurface. The transmitted energy is recorded by several receivers to provide information on the subsurface. One of the advantages of this method is that it helps to visualize the subsurface as a medium with different layers. Where each layer has its unique characteristics such as the seismic velocity, thickness and geotechnical parameters (Cai et al., 2014; Sopaci and Akgun, 2015; Raptakis and Makra, 2015). Azwin et al. (2013b) confirmed the possibility of applying seismic refraction method in the production of 2D profiles of the subsurface for site characterization. In a related development, Mohamed et al. (2013a) buttressed that seismic method would be of great advantage for studying near surface site response in order to mitigate disasters.



Figure 1. Topographic map of the study area.

Although, the results of geotechnical methods may not be independently used for decision on construction of buildings, they can help to provide control and ground-truth information of the subsurface (Hunt, 2005; Lorenzo et al., 2014; Cai et al., 2014; Rumpf and Tronicke, 2014; Olatinsu et al., 2018). Prominent among the geotechnical methods are the cone penetration test (CPT) and percussion drilling test (PDT). Cone penetration tests are conducted to obtain information on the bearing capacity of the subsurface (Eker et al., 2015; Shahri et al., 2015). Das and Basudhar (2009) engaged piezocone data from available cone penetration test results to create different layers of soil. Similarly, Robertson (2009) and Miller et al. (2018) presented updates on the interpretation of key behavior of a wide range of soils from cone penetration test results. Furthermore, the percussion drilling test is often conducted in order to obtain information on the local geology of the study area. It gives information on the nature, texture and colour of the composition of the geological formation. Therefore, combination of seismic refraction method, cone penetration and percussion drilling tests were engaged in this investigation to study the subsurface condition/soil behaviour of a site reclaimed from water body in order to determine the depth to competent layer for the purpose of engineering construction.

2. Field description

2.1. Geologic setting

The study area is located at Eti-Osa local government in the south-eastern part of Lagos state as described in Adewoyin et al. (2017b), Obaje (2009), Adepelumi and Olorunfemi (2000). The choice of the study area is because the area is reclaimed from water bodies and it is always logged with water (see Figures 1 and 2).

3. Materials and methods

3.1. Seismic refraction method

For the purpose of this study, 2D seismic refraction survey was conducted at a site reclaimed from water bodies using a 24-Channel ABEM MK6 Terraloc seismogram. Nine (9) seismic profiles were surveyed with each profile ranging between 48 and 200 m in length (Figure 3). A 15 kg

weight sledge hammer and a metallic base plate was used to generate the seismic energy that propagated through the subsurface to the receivers (geophones). The geophone spacing of 2 m was used in order to adequately cover the refraction zone and obtain subsurface images of good resolution. Multiple shots were taken at different shot points and the resulting data were stacked about 6–8 times before they were recorded. Shots were taken at points, 2 m before the first geophone, between the 6th and 7th geophones, between the 12th and 13th geophones, between the 18th and 19th geophones and at a point 2 m after the last geophone. The raw data of the seismic refraction tomography survey was downloaded from the seismograph and processed using seisImager/2D™ software package. The software package allowed the first arrivals to be picked from wiggle mode of seismic signal for each shot along the profiles. The arrival times were assigned to layers and models were generated.

The inversion tomograms for the seismic survey were displayed after the data were processed. Although, laboratory testing approaches have been used to determine various geotechnical parameters, however, empirical formulations have been developed for rapid determination of these parameters. These empirical equations are formulated based on variety of case histories of site investigations, extensive borehole data, laboratory testing and geophysical prospecting (Sayeed et al., 2007; Tezcan et al., 2009; Altindag, 2012; Mohd et al., 2012; Azwin et al., 2013a & b and Atat et al., 2013). Therefore, from the seismic velocities of each layer presented on the 2D images, other geotechnical parameters such as the Young's modulus, bulk modulus, Poisson's ratio and shear modulus for each layer of the subsurface were determined as presented in Adewoyin et al. (2017a). This information further assisted in characterizing the subsurface of the study area.

3.2. Drilling/boring tests

One percussion drilling test was also conducted using a Shell and Auger percussion boring techniques with a Pilcon wayfarer rig. The equipment was used to bore through the subsurface in agreement with the code of practice for soil investigations (Hunt, 2005; Das 2007). Sampling and insitu tests were carried out progressively with the advancement of the boreholes through the overburden sediments below the water bed. Moreover, six (6) cone penetration tests were

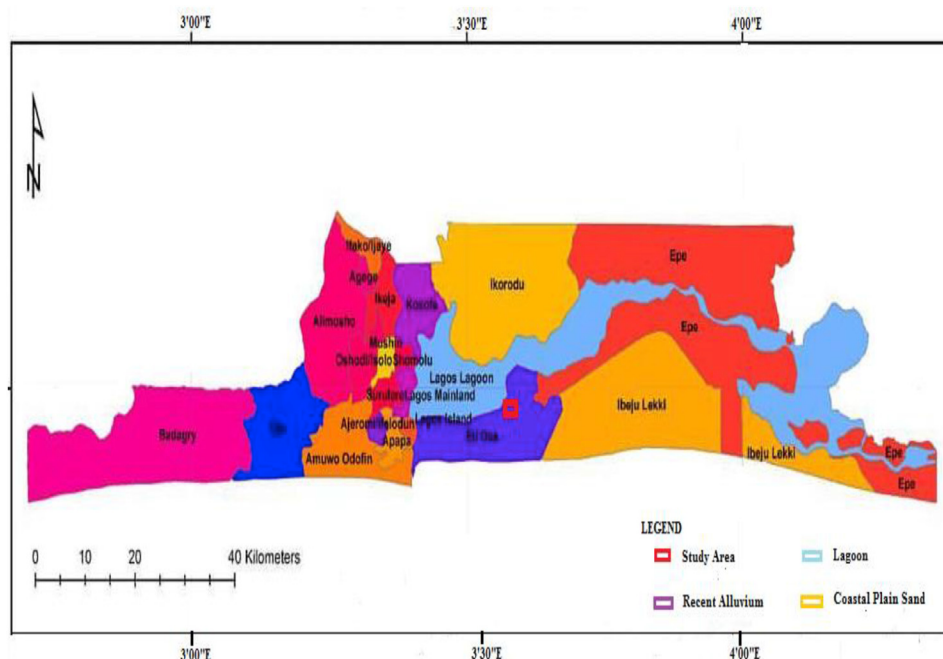


Figure 2. Simplified geological map of the study area.

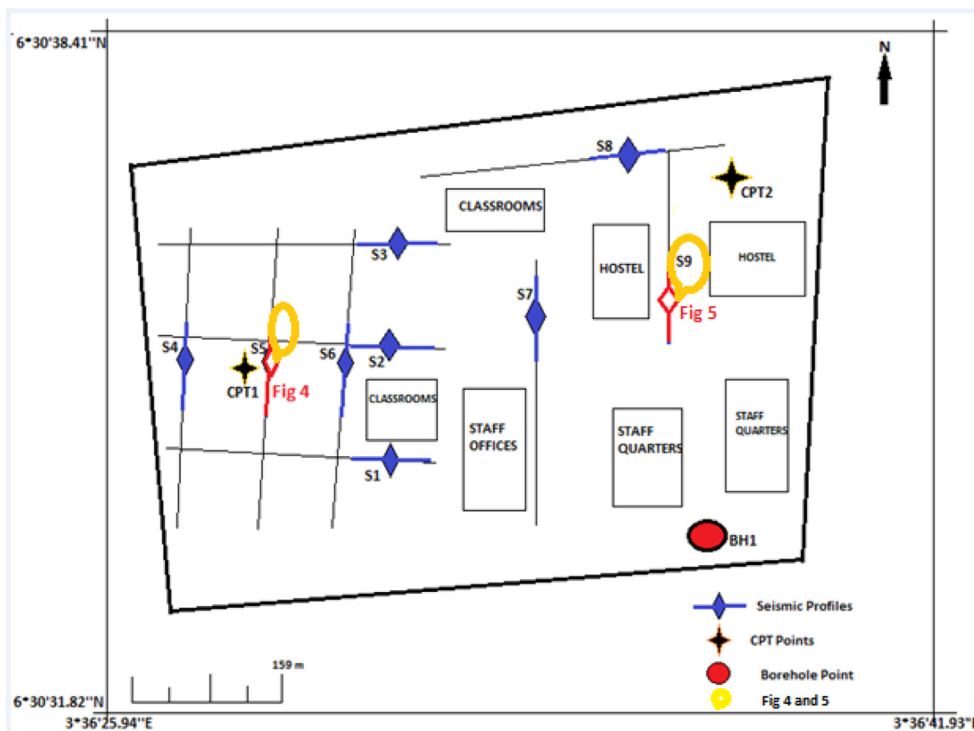


Figure 3. Base map of the study area with the seismic lines of Figures 4 and 5 denoted by yellow rings.

carried out in the study area using a manually operated 2.5 ton Shell and Auger penetration machine (Adewoyin et al., 2017a). The machine was used to drive probes (a number of 1 m length iron rods, attached to one another, one at a time) into the subsurface, which measured the resistance of the subsurface to the force applied to the probes. The result of the resistance of the subsurface to the probe was used to determine the bearing capacity or level of competence of the area of study.

4. Results and discussion

2D seismic refraction tomography showed the lateral and vertical distribution of the geologic layers (Figures 4 and 5). The results revealed three distinct layers which were interpreted in relation to the information obtained from the borehole, hand dug well and the available local geology of the study site. The three layers varied in thickness from the

topsoil to a depth of about 16 m in the subsurface. The various colour configurations of the 2D seismic refraction tomography, revealed the variation in the thickness of each layer, which may be as a result of the age of deposition, the geologic composition and other geological processes (Tezcan et al., 2009). The thickness of the first layer varied between the topsoil to a depth of about 5 m. This layer is considered to be the unconsolidated layer, which is characterized by loose dry sand as delineated by the borehole log and also low velocity zone as revealed by the propagation velocity of the seismic wave. The second layer varied in extent across the entire length of the survey with the most deposit between 2 and 28 m portion of the profile length. The deposit in this region also intruded into the first and the third layer. This layer is a semi-consolidated layer as shown by the geotechnical parameters. This layer was observed to gradually reduce in thickness towards the other end of the profile. The third layer was observed to have the highest seismic velocity which is characteristic of a consolidated layer having

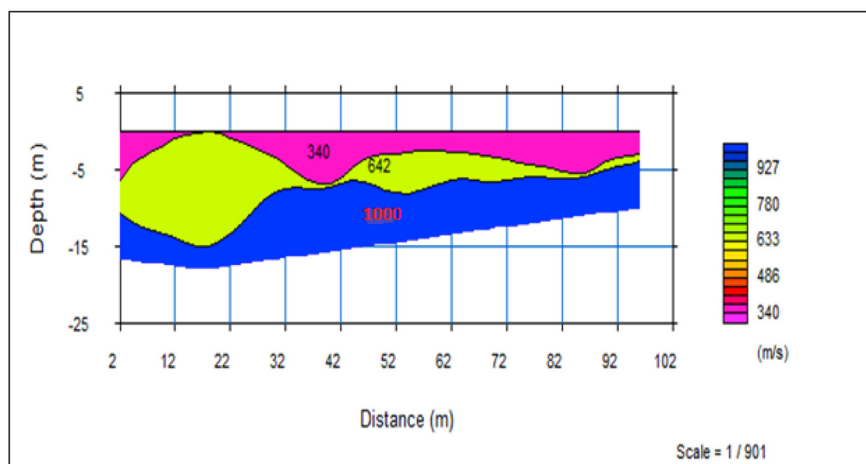


Figure 4. 2D seismic refraction profile conducted in the study area showing the length and the depth of investigation in meters (m).

non-uniform thickness across the profile. The thickness extended over a larger area than the first two layers earlier discussed; it also intruded along the length, into the second layer between 22 to 50 m portion of the profile. This layer was observed to be more competent than the two previously outlined layers, which could be as a result of the composition or age of deposition of the sediments that form this layer. The result obtained in this investigation is in line with Osazuwa and Chinedu (2008) and Mohd et al. (2012), where the first layer with the lowest seismic velocity was noted to be unconsolidated lateritic clay or alluvium. The second layer of intermediated seismic velocity was noted to be saturated sandy clay while the third layer with the highest velocity was presented to be saturated sand stone or weathered granite. The only difference in the results was the depth of occurrence of the second and third layers in the two study, which may be the result of depth of interest during the investigation or the age of deposition as earlier pointed out.

Moreover, it was noted from Figures 4 and 5 (as shown on the base map) that the subsurface is not homogeneous and the different geologic composition varied in thickness across each profile. In Figure 4 (denoted by a red line on the base map), a reduction in thickness, was noted in the first layer along the 12 and 20 m length on the seismic profile. Thus, resulting in an intrusion of the second layer into the topsoil. A similar trend was observed in Figure 5, in which from a region between 4 and 8 m along the profile, the second layer was noticed to be protruding into the topsoil. In Figure 4, the second layer also varied in thickness along the profile. The second layer was also noticed to be gradually reducing in thickness along the profile length between 32 and 42 and 82 and 92 m. This could be as a result of the level of saturation of this region of the reclaimed land.

A similar variation occurred in Figure 5 (represented by a red line on Figure 3), with a gradual reduction in the second layer between 12 and 32 m length along the profile. This variation could be as a result of the age of deposition and the level of consolidation of the formation. The third layers in both figures are the basement and they were noticed to have the highest thickness both vertically and horizontally. This could be the geologic formation at the basement is shielded by the first two layers from being saturated, which allowed it to be naturally settled.

It could also be observed from the values of the velocities of the different layers in Figures 4 and 5 that in Figure 4, the velocity of the topsoil is higher than the value observed in the same layer of Figure 5. This could be the result of the thickness of the foreign materials deposited to reclaim the region from over saturation. In Figure 5, the velocity of the topsoil is lower than the one reported in Figure 4 because, there are still some water present in the layer influencing the speed of the elastic energy through it. The second layers in the two figures are overlaid by some layers of clay as revealed by the borehole log which influenced the

interaction of the layer with water, thus reducing its level of saturation. This allows the formation to be well cemented resulting in the high velocity values observed. From the results expressed by Figures 4 and 5, the second and third layers of Figure 5 are dryer than those in Figure 4.

The geologic formation in this layer was observed from the result of the cone penetration test to have low bearing capacity with cone resistance within the range of 2–11 kg/cm² (Figure 6). The result obtained from the cone penetration test correlated with the result of Adepelumi and Olorunfemi (2000). The results of Adepelumi and Olorunfemi (2000) showed the same cone resistance signature as the present study to a depth of about 6 m, which was a low cone resistance result. But, in the present study, a change in the trend of cone resistance signature was observed at a depth below 6 m in the subsurface, as the resistance values began to increase. This result revealed that beyond the depth of 6 m in the subsurface, another geologic formation was encountered different from the geologic formation in Adepelumi and Olorunfemi (2000). The results of the cone penetration tests were subjected to the standards developed by Wetland and Head (1990). The cone resistance of 66–168 kg/cm² observed in the third layer of the 2D seismic refraction profile in this study was found to be in the range of geological formation classified as medium to dense consistency.

The borehole log obtained from the percussion drilling test (Figure 7) was correlated with the 2D seismic refraction section conducted in the area of study. The borehole log delineated both the coastal plain sand and the alluvium which characterized the geology of the study area with the alluvium being the recent deposit. The log revealed a geologic formation of soft sand between the depth of 0 and 0.75 m which is a stratum thickness of about 0.75 m within the alluvium deposit (Figure 7). This stratum could largely be the foreign sand materials deposited in the area to cover up the water that always logged the surface of the original alluvium layer. The very low seismic velocity recorded in this layer confirmed the formation in this region to be very soft and incompetent for siting the foundation of a building. The borehole log result also showed that from 0.75–5.25 m represents another layer of soft geologic formation with thickness of about 4 m. The intrusion of the upper part of this stratum into the first layer while the lower portion laid within the second geologic layer has revealed by the seismic refraction section (Figure 4). This geologic formation was confirmed by the seismic refraction method to be an unconsolidated formation by its relatively low seismic velocity measured within this layer (Figures 4 and 5).

The geologic formation at this depth was identified to be soft sandy clay which is a characteristic of the intercalation of sand and clay. The result of the cone penetration test conducted within the formation went further to confirm that the layer is made up of geologic formation of

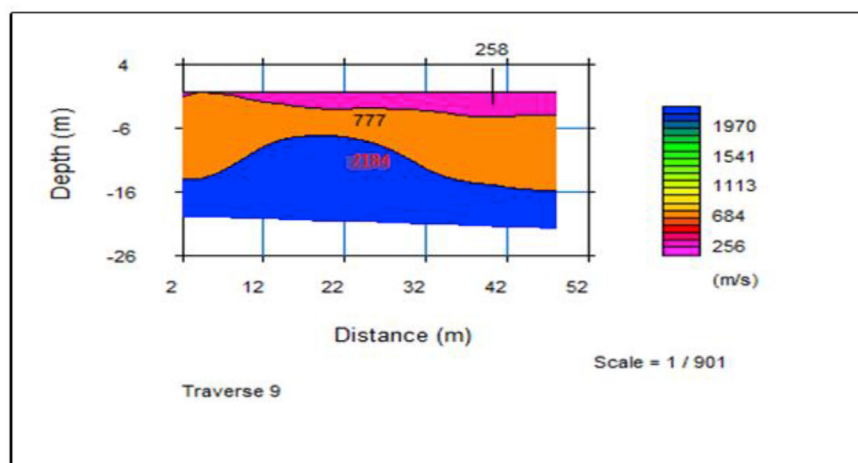


Figure 5. 2D seismic refraction profile conducted in the study area showing the length and depth of investigation in meters (m).

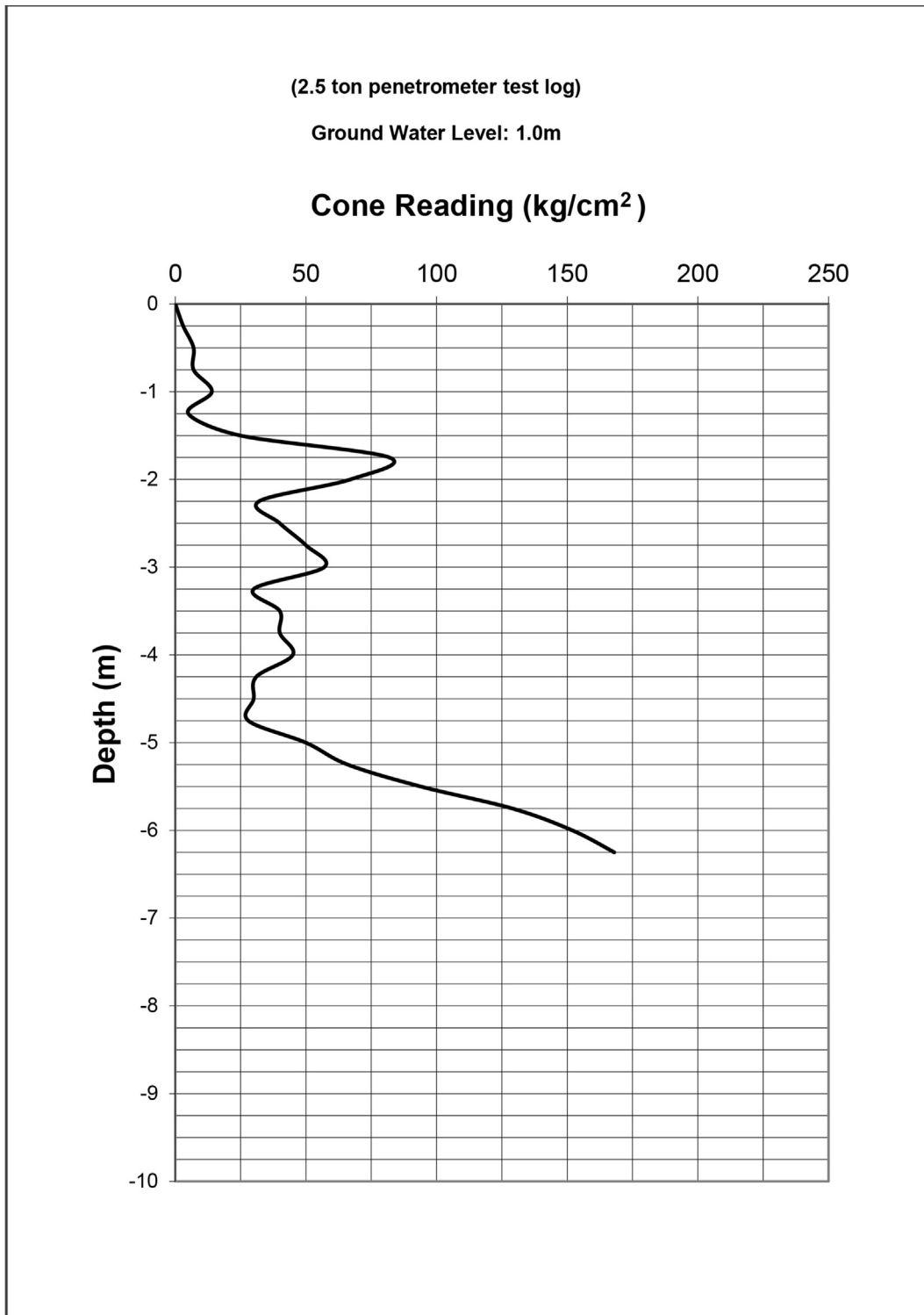


Figure 6. Results of cone penetration test conducted in the study area. Geotechnical data (soil classification) profile from literature (Adewoyin et al., 2017a).

highly compressible and low shear strength which also confirmed the soft nature of the alluvium deposit in the area of study (Figure 6). Furthermore, it was revealed by the result of the borehole log that from 5.25-7.5 m depth in the subsurface was composed of soft geologic formation which was identified as soft clay. This layer lay within the upper portion of the second layer of the seismic refraction section which was characterized by very low velocity. Although, the result of the cone penetration test (Figure 6) revealed a geomaterial of increasing strength at this depth, which could be the report of the single point that was investigated.

Generally, the formation at this depth is characterized by alluvium of recent deposit that would not support the foundation of a building.

A change was observed in the borehole log from 7.5-10.5 m as the alluvium geologic formation began to show some degree of strength. This portion of the log correlated with the lower part of the second geologic layer delineated by the seismic refraction method. The formation was identified as medium dense sand, in which the sediment could have been deposited earlier as a result of its depth of occurrence. The formation was already undergoing some degree of solidification which may be as a

Depth: 30.00 m		BOREHOLE LOG 1			GROUNDWATER LEVEL: 0.50 m						
Type of Boring: Shell and Auger Percussion boring test											
Location: Badore Model College, Badore, Ajah					BH No. 1						
Depth (m)	Samples	Soil Description	Symbol	Nspt							
				0	10	20	30	40	50		
0	<input type="checkbox"/>	Dark brownish silty fine SAND									
0.75	<input type="checkbox"/>										
1.5	<input type="checkbox"/>	Soft light yellowish sandy CLAY									
1.75	<input type="checkbox"/>										
3	<input checked="" type="checkbox"/>										
3.75	<input type="checkbox"/>										
4.5	<input type="checkbox"/>										
5.25	<input type="checkbox"/>										
6	<input type="checkbox"/>	Soft dark greyish organic silty CLAY									
7.5	<input type="checkbox"/>										
9	<input type="checkbox"/>	Loose becoming medium dense light greyish silty SAND			13						
10.5	<input type="checkbox"/>										
12	<input checked="" type="checkbox"/>	Firm dark greyish organic CLAY									
13.5	<input type="checkbox"/>										
14.25											
15	<input type="checkbox"/>	Light greyish coarse SAND									
16.5	<input type="checkbox"/>	Soft to firm dark greyish organic sandy CLAY									
18	<input type="checkbox"/>										
21.5	<input type="checkbox"/>										
22	<input type="checkbox"/>	Firm to stiff dark greyish organic CLAY									
24.5	<input type="checkbox"/>										
26.25	<input type="checkbox"/>	Light greyish coarse SAND									
28	<input type="checkbox"/>										
30	<input type="checkbox"/>	Very stiff dark greyish organic CLAY									
End of Borehole											
KEYS:											
<input type="checkbox"/>					DISTURBED SAMPLE						
<input checked="" type="checkbox"/>					UNDISTURBED SAMPLE						

Figure 7. Result of the borehole log conducted in the study area. Figure 7 was reprinted from Adewoyin et al. (2019), Predicting dynamic geotechnical parameters in near-surface coastal environment, 6 (1).

result of heat and pressure from the immediate environment. The sudden rise in the result of the seismic velocity measured at the lower portion of this layer confirmed the increase in strength revealed by the borehole log within the same geology. A more strengthened geologic formation was discovered from 10.5–14.25 m which further confirmed that the lower part of the second layer to the upper part of the third layer were composed of firm intercalation of sand and clay. The high velocity recorded by the seismic refraction method in this region revealed this portion as a zone of competence in the study area. It was also observed that from 14.25–18 m a very stiff geologic formation was encountered, this could be as a result of settlement of coarse grained sediments cemented with fine grained soil materials, which prevented the influx of fluid that could affect the strength of the geologic formation (Shahri et al., 2015). Other factors that could contribute to the nature of the formation in this region could be the age of settlement, depth of the deposit and the degree of compression by the more recent deposits. This showed that the most competent layer for foundation siting lay between the second to the third geologic layer as revealed by the geologic section.

By comparing the interpreted lithology of the seismic profiles with the borehole log (Figure 7), it was observed that the seismic models obtained, agreed with the borehole where, the topsoil to a depth of about 7.5 m is composed of soft geologic formation. A more competent layer was encountered from the depth beyond 7.5 m into the subsurface which is the region of the third layer as depicted by the seismic result. This layer is composed of sandy clay of low compressibility potential and high shear strength. However, the result of the cone penetration test (Figure 6) revealed that from the topsoil to a depth of about 5.5 m is composed of soft geologic formation with low cone resistance values. It also showed that from the depth of 6 m and below a geomaterial of high cone resistance values was encountered, which agreed with the third layer delineated by the seismic method. It is important to state at this point that the result of the seismic refraction method obtained in this method are comparable to the ones obtained by (Leucci et al. (2007)) and Pegah and Liu (2016). In Leucci et al. (2007) two layers were delineated by the seismic refraction survey conducted in Italy, unlike in the present study where three layers were delineated. This could be as a result of the difference in the field design and variation in the geological formation of the area. Pegah and Liu (2016) conducted a seismic refraction survey in northern Iran which had similar geological composition as the present study area. The slight difference observed in the results could be as a result of the geophone spacing used, which was different from the present study by 2 m.

5. Conclusion

In this study, a combination of 2D seismic refraction method, cone penetration and percussion drilling were used to characterize a site reclaimed from the bodies of water in an alluvium geologic setting. Three (3) distinct layers were delineated by the seismic refraction method. Moreover, the percussion drilling test revealed the first geologic layer to be loose sand of recent alluvium deposit. The second layer was found to be soft sandy clay while the third layer is composed of sandy clay of medium to dense consistency. Furthermore, the results of the cone penetration test showed that the topsoil to a depth of about 6 m is composed of soft geologic formation. The results of the three methods were correlated, which confirmed that the topsoil to the upper region of the second layer is composed of geologic formation of low shear strength and low compressibility potential. However, it was noted that at depth between 6 m and 18 m in the subsurface is composed of a more consolidated formation of high shear strength and high compressibility potential. Therefore, it can be concluded that from the lower region of the second layer to the third layer are the most mechanically stable region for siting any engineering construction in the study area. Significantly, this study revealed that the combination of seismic refraction method, percussion drilling and cone penetration tests would give extensive characterization and

detailed geo-mechanical properties of a complex geological setting like the present study.

Declarations

Author contribution statement

Adewoyin, O. O.: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Joshua, E. O., Akinyemi, M. L.: Performed the experiments.

Omeje, M.: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Adagunodo, T.: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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