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Preliminary geological investigation into the causes of foundation failure in Jalingo, Northeast Nigeria

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ABSTRACT

Post-foundation study for the preliminary causes of cracks in buildings at the Central Bank of Nigeria (old site) Jalingo branch, Northeast Nigeria, was carried out using a geophysical approach and groundwater level monitoring. The geophysical survey method employed was the electrical resistivity method. Vertical electrical sounding (VES) was carried out using a Schlumberger electrode array with a maximum half current electrode separation of 20 m. The VES results revealed the presence of three geo-electric subsurface layers in the area, namely clayey sand, fractured/weathered basement, and crystalline basement. The resistivity of the clayey sand varies from 45 to 210 Ωm, while that of fractured/weathered basement varies from 305 to 5,858 Ωm and that of the crystalline basement varies from 1,000 to 10,075 Ωm, with corresponding thicknesses ranging from 0.5 to 2.3 m, 0.2 to 6 m, and 2.6 to 4 m to an infinite depth, respectively. The study area's field curves were analyzed; H- and Q-curve types were 35.7% and 64.3%, respectively. Iso-resistivity delineation at 0.5, 1.5, and 3 m showed that the region with high resistivity corresponding to the crystalline basement is found in the northeastern part of the study area and is most suitable for the foundation. The results show that the investigated building was sited within the incompetent clayey sand layer with resistivity generally less than 200 Ωm.

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1. Introduction

The continuing collapse of foundations has been linked to subsurface (geologic) concerns that engineers did not anticipate prior to designing and constructing the foundations. Numerous lives and property have been lost as a result of building collapses caused by foundation failure, bad construction practices, lack of information about underlying geology, and the use of substandard building materials. Frequently, foundation failures have developed due to the resulting differential settling in the subsoil. The depth of the foundation, the strength of the materials employed, and the stability of the ground can all aid in differentiating between possible causes of foundation-related failures (Tim, 2002).

Geotechnical engineers and engineering geologists are key members of the design team for practically all modern engineering projects involving site characterization and geotechnical design. Typically, evaluating various project sites or selecting a specific site entails data gathering, analysis, and communication of physical site conditions to other project design team members. The necessity of developing a shared

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understanding of geologic conditions and their consequences for design criteria is critical to understand the relationship between geologic origin and geotechnical qualities. It is crucial for geologists and engineers to work closely to provide the highest possible product quality.

Any structure's foundation is designed to transfer to the ground the structure's load without eliciting a response from it unequally or excessively. Pile-supported construction is the norm for most buildings (Blyth and De Freitas, 1988). The probable cause of widespread foundation failure owing to subsurface movement resulting in fissures or differential settlements of structures has long been a source of worry for geoscientists. Temporal volumetric variations in precise types of soil are key contributors to the failure of foundations in most of the world. Certain types of clayey sand can expand when saturated with water during the wet season and yet contract dramatically during the dry season. The alternating expansion and contraction of clayey sand can cause fissures in buildings either during pre- or post-construction processes (Egwuonwu and Sule, 2012). Furthermore, water static levels close to the beds of the foundation may contribute to the instability of the foundations (Adeyemo and Omosuyi, 2012).

As Kelman and Spence (2004) noted, capillary soil rise can occur. Capillary water saturation occurs up to 0.5 m above the water table in fine soils, like clay, and partial saturation occurs up to 10 m above the water table. Active clay soils (alternatively referred to as "expansive clays") are highly responsive to changes in soil moisture. During the wet season, the soil swells as the moisture content of the clay increases, resulting in surface heave. The clay shrinks during the dry season, causing the ground surface to settle downward. This cyclical shrinkage/swelling cycle can cause significant damage to structures constructed of such clays. According to Crilly (2001) and Sanders and Phillipson (2003), the single most common cause of low-rise structure foundation failures is the clay soils' swelling and shrinking.

In light of the aforementioned factors, it is critical to conduct pre- and post-construction geophysical investigations and rise in water level studies on sites (Akintorinwa and Abiola, 2011; Akintorinwa and Adeusi, 2009; Bayode et al., 2012; Egwuonwu and Sule, 2012; Ofomola et al., 2009) to define the underlying geological, geophysical, and other conditions; thus, civil engineers, builders, and town planners need to know about the subsurface to build foundations for civil engineering structures. This is why subsurface geophysical and water level studies are becoming more critical.

Engineering site studies use geophysical techniques like electrical resistivity, electromagnetic, ground penetrating radar, and seismic reflection and refraction. These techniques can be used on their own or together. These geophysical investigations are used to determine the depth to bedrock, map structural features, and evaluate subsurface rocks' competency (Umar and Igwe, 2019). Vertical electrical sounding (VES) and increase and fall in water level were used to discover the fundamental causes of cracks at the Central Bank of Nigeria (old site) in Jalingo, Taraba State, Northeast Nigeria.

Location, extent, and accessibility

Jalingo, the capital city of Taraba state in northeast Nigeria, lies between latitudes 8° 53' 13.2"N and 8° 53' 15.4"N and longitudes 11° 22' 17.7"E and 11° 22' 15.4"E (Fig. 1) and is accessible through the Zola–Jalingo and Jalingo–Wukari Trunk A roads and through many secondary roads that link the town.

Climate and vegetation

The study area is Sudan Savannah. The area experiences wet and dry distinct seasons. The wet season lasts from May to October and the dry season lasts from October to April. Between January and March, rainfall is uncommon, with an average yearly rainfall of 918.9 mm and an average minimum temperature of 15°C and a maximum temperature of 40°C. Agriculture is the primary activity of the inhabitants, and the main crops farmed are maize, guinea corn, and groundnut. The area is largely devoid of dense forest, consisting instead of grasses, bushes, and scattered trees. However, shrubs are the dominating vegetation type (Iloeje, 1981). Due to human activities such as farming, bush burning, and grazing, the natural vegetation has been altered, resulting in the establishment of a secondary forest.

Relief and drainage pattern of the area

Jalingo's landscape is moderately undulating. The elevation of the topography ranges from 146 to 479 m above sea level. The drainage pattern of the area of study is predominantly dendritic (tree-like branching), with south and southeast flow directions (Fig. 1). They are primarily drained by River Donga and a few lesser tributaries. The residents receive water via piped water, hand-dug wells, and boreholes.

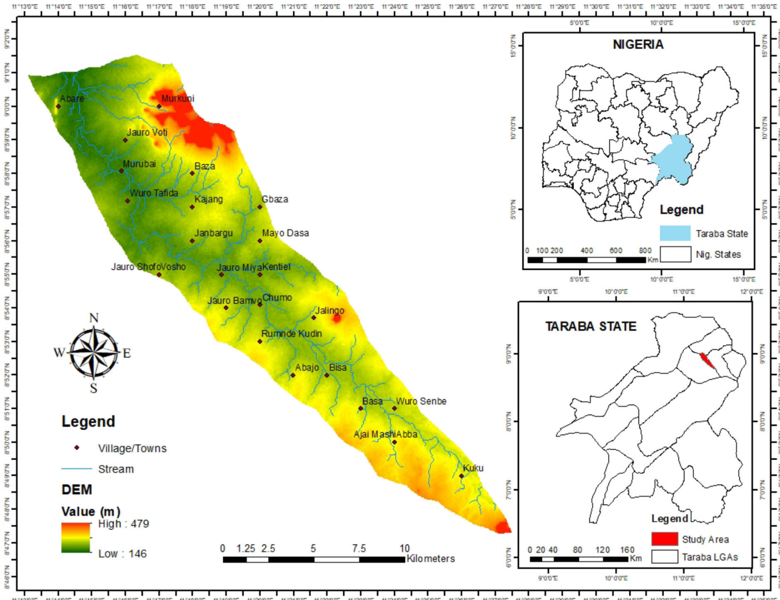

Figure 1. Digital elevation model map of the study area.

1.4. Geology and hydrogeology of the area

Undifferentiated Basement Complex rocks comprising migmatite and older granites underlie the research area. These rocks, notably the migmatites, range in texture from mixed coarsely gneisses to dispersed grained rocks with varying grain sizes and are usually porphyroblasts in nature. The rock units near the Central Bank of Nigeria (old site), Jalingo, constitute the migmatite-gneiss and the older granites (Ishaku et al., 2009; Kanu et al., 2013; Nur and Goji, 2005). Weathering of the gneiss-migmatite rocks results in developing gravel, laterite, sand, clay, and silt elements. The granitoids are composed primarily of feldspars, biotite, and, on rare occasions, microcline (Fig. 2). Granitoids, alternatively referred to as older granites, are a product of the Pan-African orogeny.

The hydrogeology of Jalingo and environs was pioneered by the work of Conred Nigeria Limited based on hydrogeological field reconnaissance carried out from May 1977 to February 1978, who arrived at a stratigraphic sequence of the study area. Groundwater is a significant source of drinking water used extensively for manufacturing, agriculture, and domestic use (Achyara, 2004; Foster et al., 2008; MacDonald , 2005; Srinivasa et al., 2000).

Groundwater development is often problematic in the basement terrain as a result of the bedrock's lack of primary porosity. The movement of groundwater is influenced by secondary porosities like joints and faults (Chilton and Foster, 1995; Foster et al., 2008; Wright and Burgess,1992). Consequently, the various aquifer systems in and around Jalingo are defined by the high porosity and weathered zones. Borehole lithologic logs revealed that the area is divided into two zones that contain water: fractured and weathered rocks. The Basement Complex rocks in the study region have been worn to varying degrees, resulting in thick weathered materials in some locations. The weathered elements are sandstone, clays, and silts and range from 3 to 37.73 m in thickness, with 17.8 m as an average. The weathered zone covers the fractured rock zone and conduits for groundwater migration. The weathered region's upper portion receives infiltration, which recharges the zone (Ishaku et al., 2009). The study area's water supply is primarily provided by boreholes and hand-dug wells, all of which are insufficient in number. Groundwater resources require geophysical data on aquifer properties like hydraulic conductivity, transmissivity, and storativity coefficient (Uma et al., 1989). Because the aquifer units in the study area are mostly weathered and fractured basements with poor infiltration of surface water during the rainy season, shallow water tables are expected.

2. Materials and Methods

2.1. Field mapping

Field research began with a 1:100,000 scale topographic map (from Jalingo Sheet 150). The research area was divided into six quadrants to facilitate outcrops and rock exposures' mapping along streams,

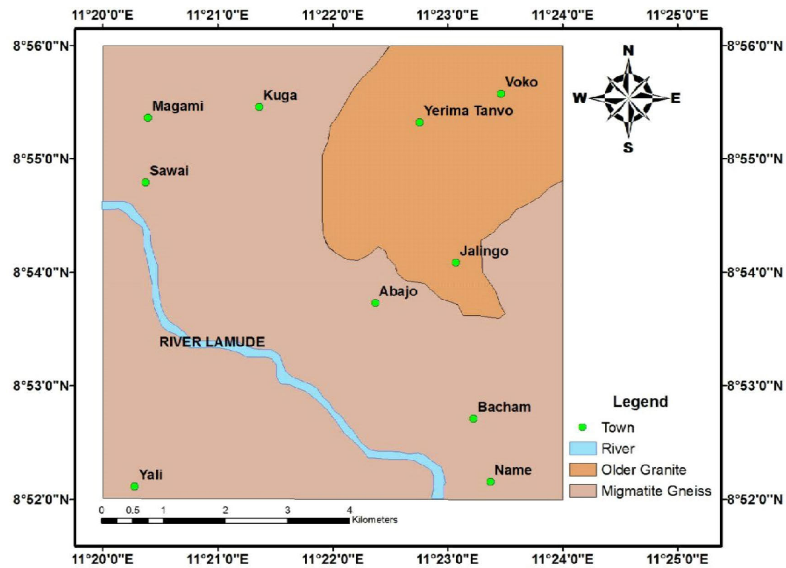

Figure 2. Geological map of Jalingo and Environs (Simon, 2017).

rivers, and road cuts with the aid of a compass, clinometer, and geographic positioning system (Garmin e-Trex 20).

2.2. Vertical electrical sounding(VES)

A Geotron resistivity meter was used for subsurface exploration. The VES technique was employed via the Schlumberger electrode array to generate data. In this procedure, a known low-frequency direct current was introduced into the subsurface using a pair of current electrodes (AB) and the resulting voltage drop is monitored using a second pair of potential electrodes (MN). In a homogeneous subsurface, the penetration depth is proportional to the separation between the electrodes and altering the electrode spacing gives information on the ground's stratification (Umar and Igwe, 2019). The spacing between current electrodes (AB/2) was varied between 1 and 20 m, whereas the gap between potential electrodes was altered between 0.2 and 2.5 m. The apparent resistivity was determined using the following formula (Ibuot et al., 2013):

$$\rho a = \pi . \frac{(\qquad) - (\qquad)}{\qquad} Ra \qquad (1)$$

where,
ρa is the apparent resistivity;
AB is the distance between the two current electrodes;
MN is the distance between the potential electrodes; and
R_a is the apparent electrical resistance measured.

Each apparent resistivity value computed from Equation (1) was plotted on a log-log graph to the appropriate spacing of the current electrode. The resistivity and curve types, depth, and thicknesses of the layers were determined. The standard quantitative interpretation was accomplished by field curves matching the auxiliary curves. IX1D was used to invert and iterate those VES points from which the resistivities and thicknesses of the layers could be found.

2.3. Static water level measurements

The dipper-T model was used to figure out the static water levels (SWLs) and well depths of 14 boreholes and hand-dug wells. Global Positioning System (GPS) was used to figure out each location's topography and coordinates (latitude and longitude) (e-Trex 20 Garmin model). Sampling was conducted early in the morning before residents began water abstraction. The study area was griddled into 10 quadrants to distribute samples evenly.

Each well's hydraulic head was approximated using the SWL and topographic elevation above mean sea level measurements. These readings were to be utilized to create a hydraulic head map using Surfer 13 software. Piezometric lines were created at an angle to indicate the direction of groundwater movement in the area.

3. Results and Discussion

3.1. Electrical resistivity

VES results are presented in Table 1. The sections revealed three geo-electric layers: the clayey sand, fracture/weathered basement, and the crystalline basement. The resistivity of the clayey sand varies

Table 1. Summary of layers' resistivity and thickness.

VES	Coordinates		Layers thickness (m)			Layers rresistivity (Ωm)		
	Latitude (N)	Longitude (E)	H1	H2	H3	ρ_1	ρ_2	ρ_3
1	8° 53′ 15.4″	11° 22′ 17.2″	0.20	4.20	∞	132	288	1,400
2	8° 53′ 15.0″	11° 22′ 17.5″	0.40	4.45	∞	160	292	1,200
3	8° 53′ 14.3″	11° 22′ 17.7″	0.60	4.42	∞	200.26	138.16	1,000.33
4	8° 53′ 15.1″	11° 22′ 16.5″	0.50	5.05	∞	2.2	1.2	2,000
5	8° 53′ 14.8″	11° 22′ 16.1″	0.70	4.67	∞	100	20	2,000
6	8° 53′ 14.6″	11° 22′ 15.8″	0.81	4.31	∞	182	20	1,230
7	8° 53′ 14.2″	11° 22′ 15.4″	0.44	4.12	∞	30	50	1,000
8	8° 53′ 13.9″	11° 22′ 15.4″	0.16	4.53	∞	200	40	1,200
9	8° 53′ 13.7″	11° 22′ 15.5″	0.23	4.26	∞	311.58	425	381
10	8° 53′ 13.2″	11° 22′ 15.7″	0.36	4.60	∞	125	311	375
11	8° 53′ 14.9″	11° 22′ 16.8″	0.38	4.55	∞	250	300	1,000
12	8° 53′ 14.2″	11° 22′ 17.3″	0.99	4.31	∞	263.40	139.35	590
13	8°53′ 14.7″	11° 22′ 16.3″	0.43	4.65	∞	300	220	400
14	8° 53′ 13.8″	11° 22′ 16.4″	0.55	4.35	∞	328.72	83.87	600

from 45 to 210 Ωm, while that of fractured/weathered basement varies from 305 to 5,858 Ωm and that of the crystalline basement varies from 1,000 to 10,075 Ωm, with corresponding thicknesses ranging from 0.5 to 2.3 m, 0.2 to 6 m, and 2.6 to 4 m to an infinite depth, respectively.

3.2. Curve types

The resultant field curves from the study in the area were the H- and Q-curve types (Figs. 3–6). The H-curve type and the Q-curve type represent 35.7% and 64.3%, respectively. The Q-curve type has a resistivity relationship of $\rho_1 > \rho_2 > \rho_3$ and the H-curve type has the relationship of $\rho_1 > \rho_2 < \rho_3$. The study's findings are summarized in Table 1.

3.3. ISO-resistivity maps

These are contoured maps of places with equal resistivity values. This is a qualitative interpretation that depicts the variation in resistivity at a particular location within the research region but just illustrates the general lateral shift in the subsurface's electrical characteristics.

3.3.1. Iso-resistivity for AB/2 = 1 m

This shows resistivity values ranging from 10 to 220 Ωm (Fig. 7). The map reveals the heterogeneity in the composition of the subsurface. The high resistivity values were observed along the northeastern parts of the study area corresponding to the crystalline Basement Complex terrain. On the contrary, the southeastern, southwestern, and central regions recorded low resistivity values along the study area, corresponding to the clayey sandy areas.

At 0.5 m, the region of high resistivity corresponding to the crystalline basement is found in the northeastern part of the study area. Structures with a foundation depth less than 3 m should be sited around this zone.

3.3.2. Iso-resistivity for AB/2 = 3 m

This shows resistivity values ranging from 10 to 170 Ωm (Fig. 8). The map revealed heterogeneity of the ground, whose composition varies. The northeastern part of the study area has high resistivity values corresponding to the crystalline basement. On the contrary, the study area's north, northwestern, and southwestern parts have low resistivity values corresponding to the fractured/weathered basement and clayey sandy areas, respectively.

At 1.5 m, the region of high resistivity corresponding to the crystalline basement is found in the northeastern part of the study area. Structures with a foundation depth less than 3 m should be sited around this zone.

3.3.3. Iso-resistivity for AB/2 = 6 m

This shows resistivity values ranging from 10 to 85 Ωm (Fig. 9). The map revealed heterogeneity of the ground, whose composition varies. The southeastern and northeastern parts of the study area have high resistivity values, corresponding to the crystalline

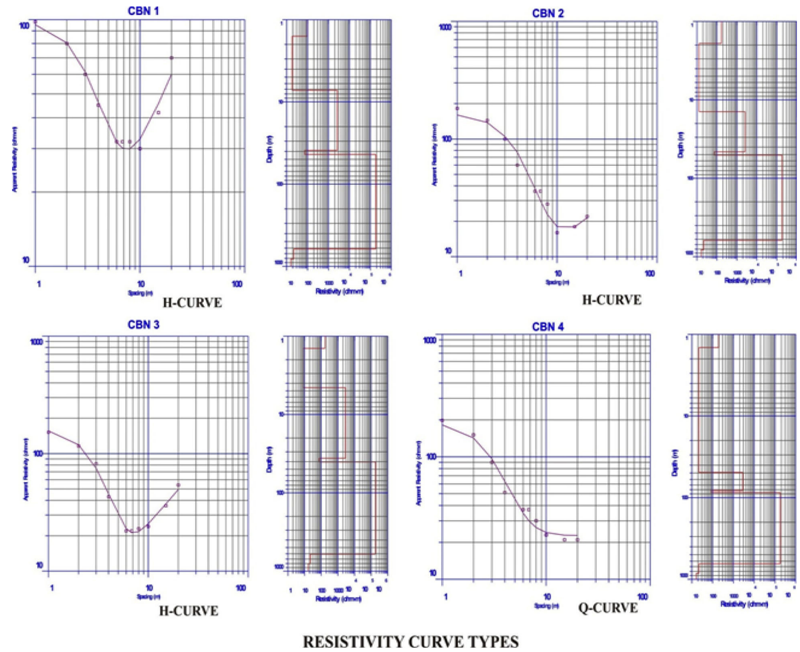

Figure 3. Graph showing VES 1, 2, 3, and 4.

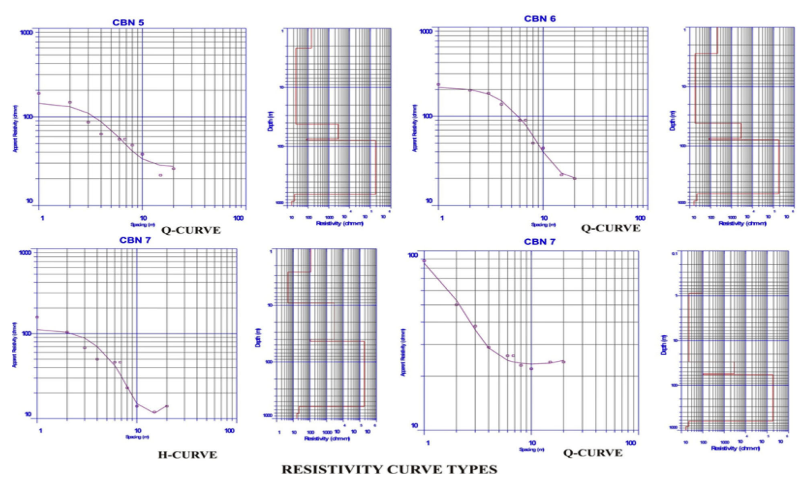

Figure 4. Graph showing VES 5, 6, 7, and 8.

basement. On the contrary, the north, northwestern, and southwestern parts of the study area have low resistivity values, corresponding to the clayey sandy lithology.

At 3 m, the region of high resistivity which corresponds to the crystalline basement is found in the northeastern part of the study area. Structures with a foundation depth less than 3 m should be sited around this zone.

3.4. Geo-electric sections

Geo-electric sections are cross-sections of stratified layers determined through electrical (resistivity) depth probing, with layers identified by their apparent resistivities. These sections are advantageous for detecting competent and incompetent layers, determining the water table level, and determining the presence of saline and fresh water zones.

3.4.1. Geo-electric section along A-A^1

This section reveals three geo-electric layers which include clayey sand, fractured basement, and crystalline basement (Fig. 10). The clayey sand has resistivity ranging from 113.35 to 264.21 Ωm and thickness ranging from 0.56 to 3.77 m, while the fractured/weathered basement has resistivity value ranging from 76.20 to 999.99 Ωm and thicknesses ranging from 0.93 to 6.47 m. The crystalline basement has a resistivity

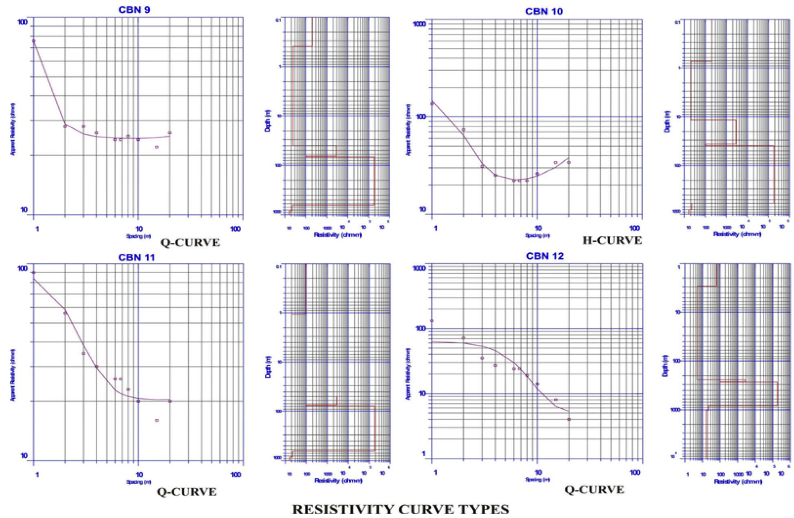

Figure 5. Graph showing VES 9, 10, 11, and 12.

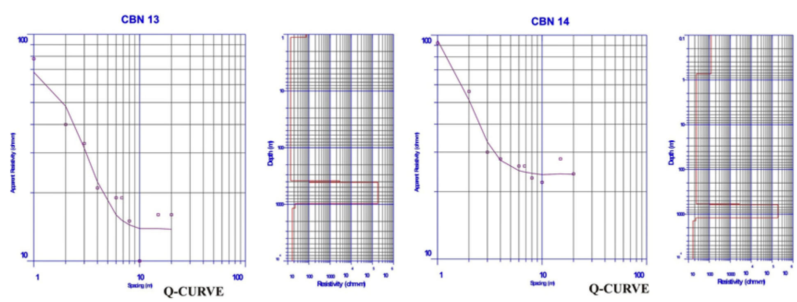

Figure 6. Graph showing VES 13 and 14.

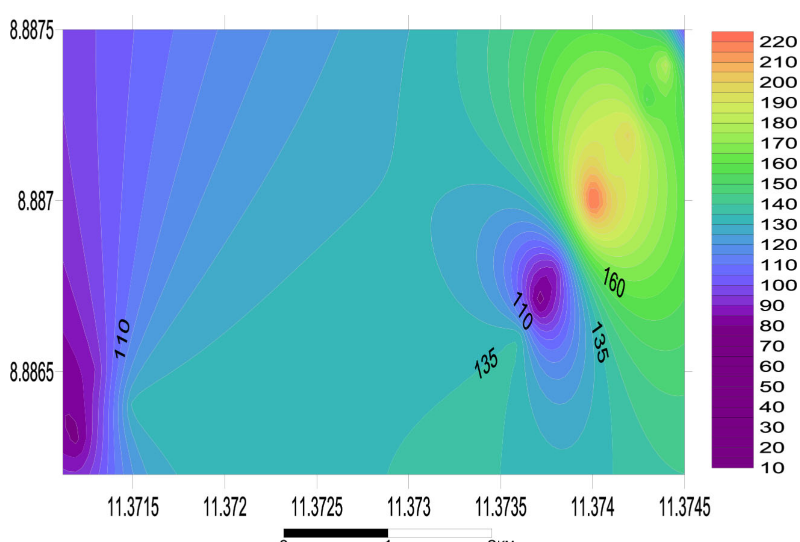

Figure 7. Iso-resistivity map for AB/2 = 1 m of the study area (contour interval = 5 Ωm).

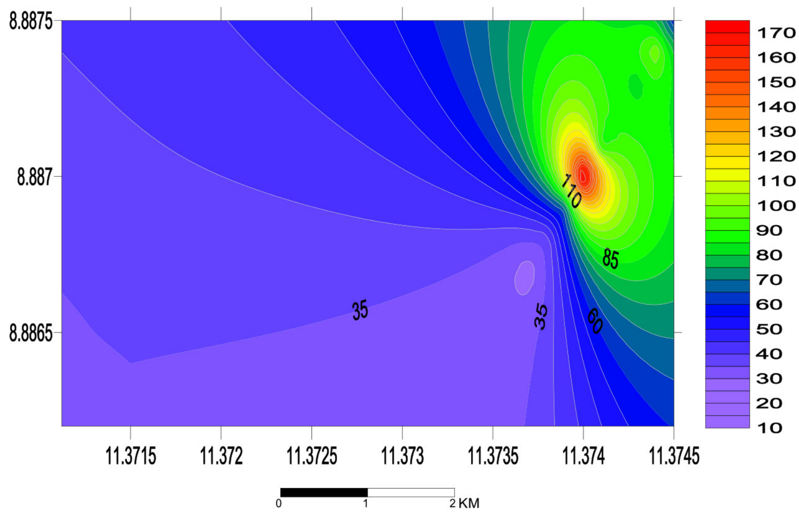

Figure 8. Iso-resistivity map for AB/2 = 3 m of the study area (contour interval = 5 Ωm).

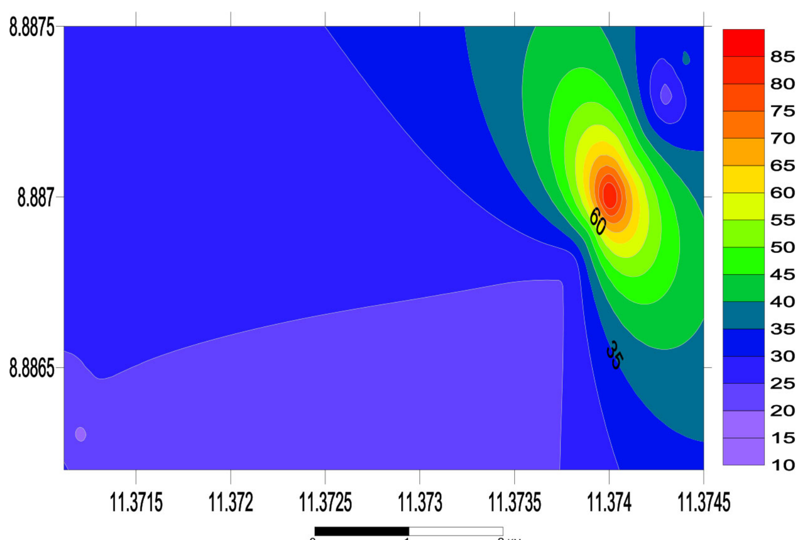

Figure 9. Iso-resistivity map for AB/2 = 6 m of the study area (contour interval = 5 Ωm).

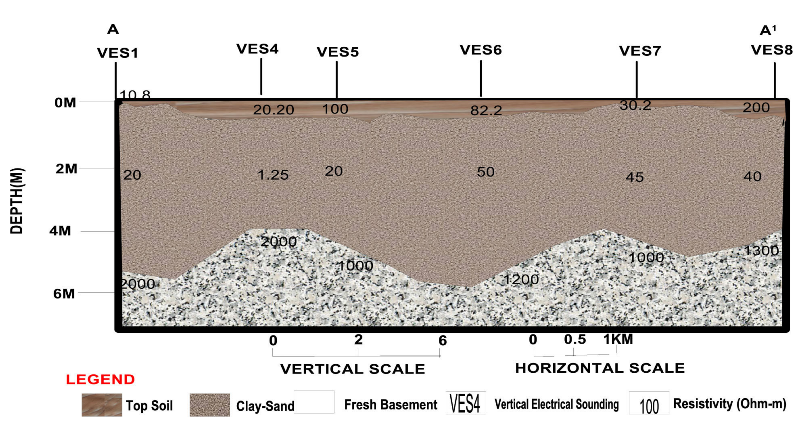

Figure 10. Geo-electrostratigraphic section along A-A[1].

Table 2. Hydraulic head distribution in the study area during dry and rainy seasons.

S/N	Longitude (E)	Lattitude (N)	Elevation (m)	SWL (DS) (m)	HH (DS) (m)	SWL (RS) (m)	HH (RS) (m)
1	11° 22′ 17.2	8° 53′ 15.4	470	14	450	6	464
2	11° 22′ 17.5	8° 53′ 15.0	468	14	454	6	452
3	11° 22′ 17.7	8° 53′ 14.3	452	11	441	2	450
4	11° 22′ 16.5	8° 53′ 15.1	470	18	452	10	460
5	11° 22′ 16.1	8° 53′ 14.8	302	15	287	7	295
6	11° 22′ 15.8	8^{0} 53′ 14.6	298	13	285	6	292
7	11° 22′ 15.4	8° 53′ 14.2	308	12	296	4	304
8	11° 22′ 15.4	8° 53′ 13.9	240	9	231	1	239
9	11° 22′ 15.5	8° 53′ 13.7	150	7	143	1	149
10	11° 22′ 15.7	8° 53′ 13.2	148	6	142	6	144
11	11°22′ 16.8	8° 53′ 14.9	420	16	404	8	412
12	11° 22′ 17.3	8° 53′ 14.2	424	10	408	2	319
13	11° 22′ 16.3	8° 53′ 14.7	424	16	408	2	319
14	11° 22' 16.4	8° 53' 13.8	406	13	393	5	422

SWL = Static water level; HH = hydraulic head; DS = dry season; RS = rainy season.

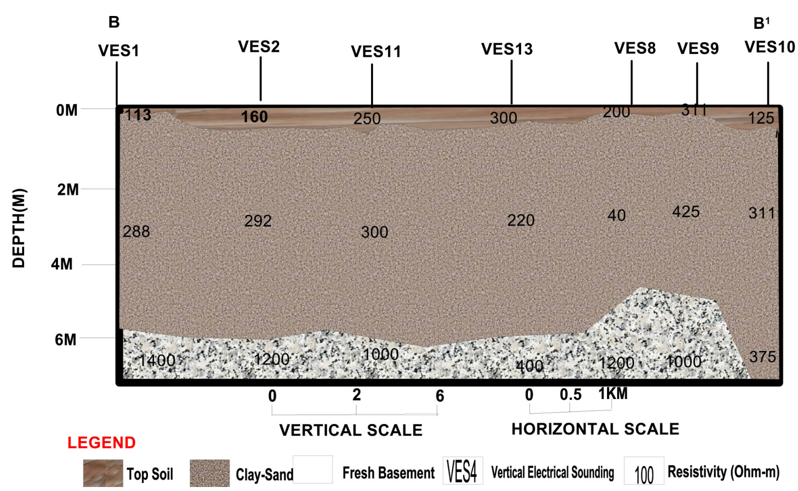

Figure 11. Geo-electrostratigraphic section along B-B[1] of the study area.

value ranging from 1,000.33 to 1,400 Ωm and a thickness ranging from 6.35 m to infinite depth.

3.4.2. Geo-electric section along B-B[1]

Geo-electric sections are cross-sections of stratified strata determined from electrical (resistivity) depth probing, with layers distinguished by their apparent resistivities. These portions are beneficial for detecting competent and incompetent layers, as well as calculating the water table level and determining the salty and freshwater zones.

3.5. Hydraulic head and groundwater flow direction

For the dry and wet seasons, Table 2 summarizes the results of the SWL measurements in hand-dug wells and boreholes, topographic elevations above mean sea level with GPS coordinates, and computed hydraulic head.

SWL shows that the water table is generally shallow and ranges from 6 to 18 m and 1 to 10 m, while the hydraulic head ranges from 142 to 454 m and 144 to 452 m for dry and rainy seasons, respectively. The hydraulic head maps (Figs. 12 and 13) enabled the zoning of the area into regional groundwater converging and diverging zones representing high groundwater potential and low groundwater potential, respectively. Groundwater flows radially from the northwestern, central, and southern areas (diverging zone) into the southeastern area (the converging zones). The contour pattern is characterized by isolated closures and

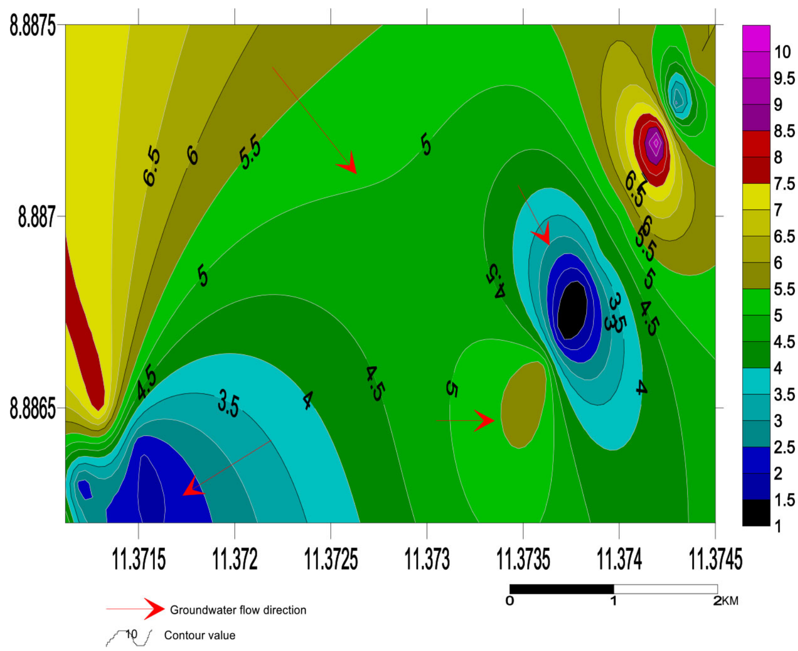

Figure 12. Map showing the hydraulic head distribution of the study area during the rainy season.

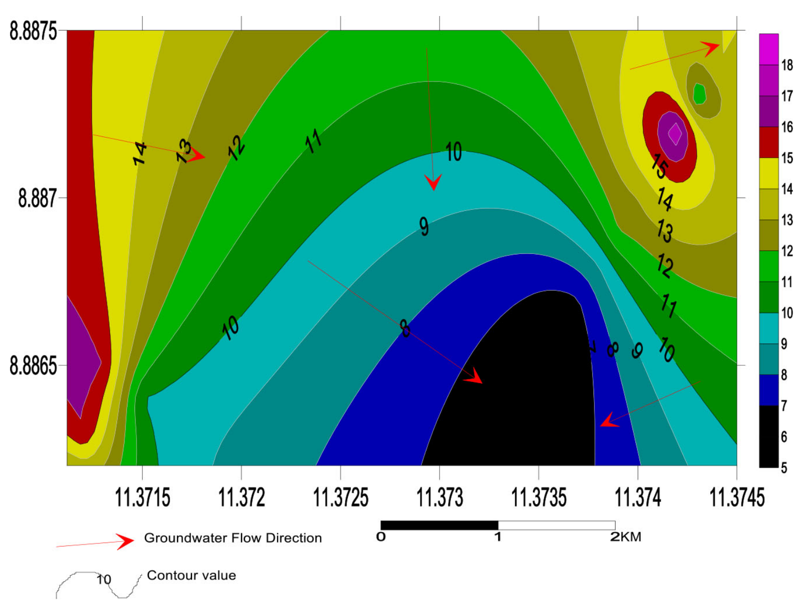

Figure 13. Map showing hydraulic head distribution of the study area during the dry season.

is typical of the noncontinuous aquifer system found in the area.

An upsurge in the water levels can change the pressure on the framework. When the groundwater level rises, the borewater pressures go up. Effective stress goes down. People think the ground will move down when there is not enough water, and it will move up when there is. Differential settlements can happen in the study area because of higher total strains above the compressible layer during this transient phase because the layer above the compressible layer is wet (clayey sand).

A decrease in effective stress can also result in a decrease in the soil's strength (Powrie, 2008). It is seen in the research region that an increase in borewater pressure caused by transient groundwater flow might result in the failure of an initially stable trench, slope, or retaining wall over the medium to long term. As a result, ground movements caused by slope or retaining wall collapse might cause damage to the surrounding structures.

4. Conclusion

The importance of geological information in the selection, design, construction, good performance, and maintenance cannot be over-emphasized. In situations where such information is not available or neglected, failure of the highway building can lead to loss of time, money, and sometimes lives and property.

Changes in the groundwater level or seasonal wetting/drying cycles can cause foundation damage in the research area. As a result of groundwater depletion and recharge, the ground surface is expected to shift differently, resulting in differential settlement.

Reduced groundwater levels can lead the soil to consolidate, resulting in settlement. Settlements can become significant in softer, more compressible soils, leading in foundation failure.

5. Recommendation

A foundation's long-term stability and durability should be assessed in light of the material's current weathering state, the surrounding environment, the construction method, and any other future changes that may be caused by disintegration or decomposition.

Visual inspection, supported by petrological studies, will reveal more information, and an X-ray is very useful, especially when harmful minerals, particularly clay, is suspected.

Highly heterogeneous geologic materials underlie the foundation that respond to imposed stress differently Hence, civil engineers should ensure a proper design that suits each geologic material is made and adhered to during construction.

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