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Application Of 2-D and 3-D Electrical Resistivity Tomography of Subsurface Weak Zones for Urban Infrastructure Stability Assessment: A Case Study of Anwai in Asaba, South-South Nigeria

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ABSTRACT
In the developing world, the need for comprehensive subsurface characterization prior to infrastructure development has grown. The primary cause of the instability of the foundation, differential settlement, road failure and structural collapse is still ignorance of the subsoil. This study employed integrated two-dimensional (2-D) and three-dimensional (3-D) Electrical Resistivity Tomography (ERT) to identify subsurface weak zones and evaluate their implications for urban infrastructure stability in Asaba, Delta State, Nigeria. Electrical Resistivity data was collected along nine parallel traverses of 100 m using a PASI Earth Resistivity Meter using Wenner–Schlumberger array. The data were processed and inverted to generate 2-D resistivity sections, which were integrated into quasi-3-D depth slices, fence diagrams, and volumetric resistivity models for improved subsurface visualization. The inverted models revealed highly variable lithology, moisture content, and weathering conditions, with resistivity values ranging from approximately 20 Ωm to over 5000 Ωm. Low resistivity anomalies were interpreted as zones of weathered sediments, saturated clay lenses, and possibly groundwater accumulation along Traverses 3, 5, and 6 extending through the core area of the profiles from 1.7 m down to 11 m. These weak zones' continuity was verified by the 3-D volume diagram and iso-resistivity models, which showed how they were spatially connected over several traverses. Moderate-to-high resistivity values, suggestive of relatively competent sandy formations appropriate for foundation support, were the main characteristic of Traverses 1, 7, 8, and 9. The integrated 2-D and 3-D ERT approach effectively identified areas at risk of differential settlement, foundation instability and zones of geotechnical competence The results demonstrate that electrical resistivity imaging is a reliable, cost-effective, and non-invasive tool for urban geotechnical investigations and sustainable infrastructure planning in rapidly urbanising sedimentary environments.

Keywords:
2-D ERT,
Urban Infrastructure Stability,
Weak Zones,
3-D Resistivity Imaging,
Asaba,
Geotechnical.

INTRODUCTION

The high rate of urbanization in most developing urban areas has led to the demand of solid ground conditions which are conducive to development of infrastructures. Nonetheless, lack of proper understanding of geological-subsurface conditions tends to result in structural failures, road deformation and foundation instability (Ighodalo & Airen, 2024). Geophysical engineering has thus taken a crucial role in site investigation towards the development of urban infrastructure. Electrical resistivity imaging (ERI) is one of the most successful methods in geophysics that can be used to detect lithological differences, voids, fractures, and feeble soil layers, which can undermine the stability of any engineering construction (Akingboye & Ogunyele, 2019). The working principle of electrical resistivity tomography is the electrical resistivity distribution of the ground. Lithology, porosity, moisture content and clay content are the major factors affecting variations in resistivity. Accordingly, the low values of resistivity are usually related to clay-rich or water-saturated materials, whereas the large values of resistivity deviations can denote dry sands, cavities, or voids in the underground environment (Guo et al., 2020). Three-dimensional (3-D) resistivity imaging has been receiving growing attention in both engineering geophysics since it offers a more realistic view of the conditions in the subsurface as compared to a one-dimensional or two-dimensional method. Through a combination of parallel resistivity profiles, a volumetric model of subsurface resistivity distribution can be created, thus allowing the detection of weak zones that can pose a risk to the stability of infrastructure in more detail (Iduseri et al., 2023).

In sedimentary environments like the Niger Delta area of Nigeria, the ground may be composed of interlayers of sand, clay and silt deposits in the form of fluvial and deltaic environments. These mixed structures often include soft clay lenses and high moisture retention areas that can eventually cause differential settlement and foundation failure without taking due care to investigate the area before construction (Adigun & Faleye, 2020). In the case of 2-D and 3-D geoelectrical resistivity tomography, it has been found that in complex sedimentary terrains, traditional geotechnical approaches are inadequate to fully identify the lateral heterogeneity that is a characteristic of deltaic formations (Eze et al., 2023). Ighodalo & Japhet (2024) also showed that the use of 2-D electrical resistivity tomography techniques can serve as a quality tool for obtaining high-resolution images of the subsurface layers, allowing for the identification of lateritic soils, clayey pockets, and compacted sand formations that are essential for foundation design. Similarly, Ighodalo and Ohioma (2024) employed quasi-3-D electrical resistivity imaging methods for site investigations in Mosogar, Ethiope West LGA, South-South Nigeria, and concluded that the proposed technique will greatly contribute to improving the mapping of weak zones that may jeopardize the integrity of structures especially in fast-growing urban areas. Likewise, 2-D and 3-D geo-electrical resistivity tomography with geotechnical soil evaluation were employed for engineering site investigation at Okerenkoko Primary School, Warri-Southwest, Delta State and found that, the combination of these geo-electrical methods is good for achieving reliable volumetric models of the subsurface useful for infrastructure planning. Moving from 2-D to 3-D ERT surveys offers a more detailed spatial picture of the subsurface anomalies, allowing engineers to more precisely and confidently define areas of potential instability.

The paper involves the use of the 3-D electrical resistivity imagery to map weak zones in the subsurface of Asaba, Delta State, Nigeria. The study will aim to establish the vacant spaces, find location of soft clay lenses and prepare foundation failure hazard maps that will be useful for planning and designing the urban development of the region. This study combines both 2-D and 3-D ERT techniques, reflecting current geophysical practices recommended for urban infrastructure evaluation in the Niger Delta region (Ighodalo & Japhet 2024; Eze et al., 2023), which will add value to the sustainable development and hazard mitigation efforts in the study area. Ighodalo, J.E. & Airen, O.J. (2024). Application of 2-D and 3-D Geoelectrical Imaging for Site Investigation at a Proposed Hotel Building Site in Benin. *Journal of Engineering and Technology Education*, NIPEs.

Local Geology of the Study Area

The city of Asaba, falls approximately between Latitude 6^0 10^I to 6^0 15^IN and Longitude 6^0 40^I E to 60 45^I E, it is bound on the east and north east by the River Niger and on the west by the rolling slopes of the Asaba plateau. In addition to being the administrative headquarters of Delta state, it is also the headquarters of Oshimili South Local Government Area. The climate of the region is humid tropical with two seasons namely the wet and dry seasons, the dry season occurs during November and March and wet season between April and October.

Asaba has a geology that is composed of the Benin Formation that is the upper most stratigraphic unit of the Niger Delta Basin. This form is mostly made up of unconsolidated to poorly consolidated sands that are intercalated by clay, sandy clay and silt. These are sediments deposited in fluvial and deltaic conditions and are distinguished by high levels of lateral and vertical lithological changes. The end product of this heterogeneity is in most cases weak zones under the surface like clay lenses and saturated sediments.

The sandy formations in the Benin Formation are hydrogeologically productive as aquifers and also the clay layers form the confining units. The existence of clay-containing horizons may considerably decrease the soil strength and enhance the compressibility, and therefore, it is dangerous to the engineering structures. Moreover, there is rapid urbanization in Asaba which has augmented construction operations and some geotechnical and geophysical study has to be conducted on the competence of the subsurface before the commencement of infrastructure development.

As a result, geophysical methods of characterizing the subsurface like electrical resistivity imaging are required to identify weak areas and guarantee safe and sustainable infrastructure development in the study area.

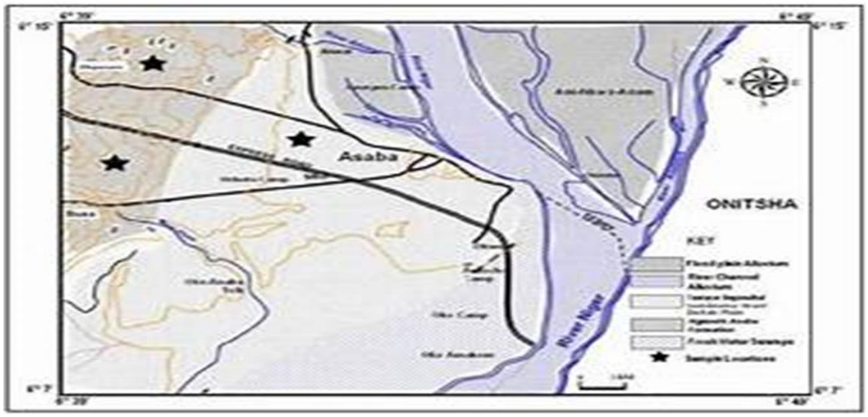

Figure 1: Geological Map of Asaba Capital Territory of Delta State

MATERIALS AND METHODS

The geophysical study was conducted as electrical resistivity imaging (ERI) test conducted on the basis of Wenner Schlumberger electrode arrangement. The data was gathered at multiple traverses of the study area, each traverse was 100 m long. The field measurements were done using a PASI Resistivity Earth Meter and stainless steel electrodes were laid along the survey lines with spacing between them through multicore cables. The Wenner Schlumberger array is a hybrid system in which the merits of the Wenner array are incorporated with the Schlumberger array, delivering good signal strength and being more sensitive to the variations in vertical and lateral resistivity (Loke *et al.*, 2018). Four electrodes (two current (A and B) and two potential (M and N)) are utilized in this array. The electric current (I) is supplied to the ground by use of electrodes A, B and the potential difference between electrodes M, N is measured.

The resistivity method is based on Ohm's Law.

$$V = I * R \quad (1)$$

Where V is the potential difference (Volts), I is the electrical current (Amperes) and R is the Resistance (Ohms).

The true resistivity of the subsurface is expressed as

$$\rho = R\frac{A}{L} \quad (2)$$

Where ρ Resistivity in (ohm.m), A is the Cross-sectional area, R is the Measured Resistance (Ohms), and L is the length of the conductor the apparent resistivity **ρa** is calculated by:

$$\rho_a = K\frac{\Delta V}{I} \quad (3)$$

Where:

ρ_a= apparent resistivity (Ωm)

ΔV = potential difference measured (V).

I = injected current (A)

K = geometric array factor of electrode array

In the case of the Wenner-Schlumberger setup the geometric factor is given as:

$$K = \pi n(n + 1)a \quad (4)$$

Where:

(a) = distance between two electrode.

(n) = level number or spacing factor to determine depth of investigation.

The 5 m minimum electrode spacing a, was gradually increased to n = 6 in order to reach deeper subsurface layers during the survey. The obtained apparent resistivity data were initially subjected into the generation of 2-D resistivity sections using RES2DINV Software, which show the change in resistivity with depth in every traverse. Thereafter, several parallel 2-D profiles were combined together in inverted using RES3DINV to form a 3-D model of resistivity that characterizes the volumetric distribution of subsurface resistivity. The Inversion quality was assessed using root-mean-square (RMS) error, with acceptance criteria of RMS < 10% for geotechnical investigations.

Conversion of the measured apparent resistivity data into true resistivity data (inversion process) allows the detection of weak areas (including the soft clay lens that has low resistivity and potential voids or cavities with high resistivity aberration) that could threaten the stability of the infrastructure (Ighodalo & Ohioma , 2024; Binley & Slater, 2020; Dahlin & Zhou, 2018).

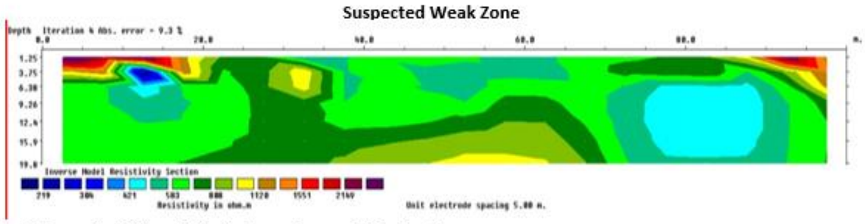

Figure 2: 2-D resistivity imaging models for the

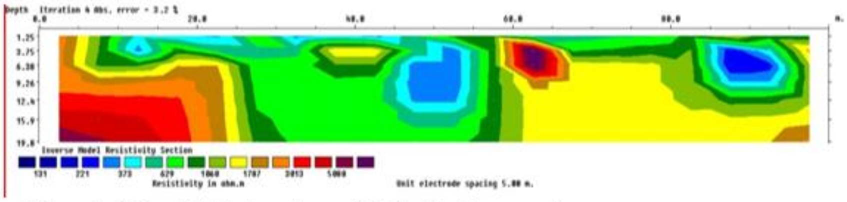

Figure 3: 2-D resistivity imaging models for the Traverses 2

RESULTS AND DISCUSSION

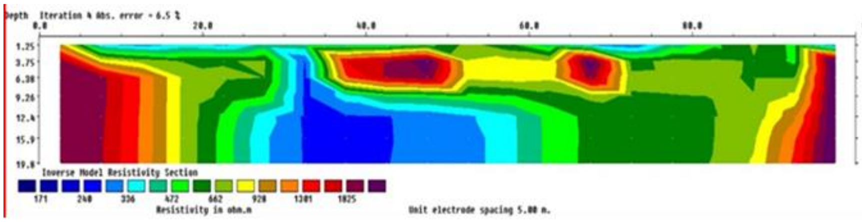

Fig 4: 2-D resistivity imaging models for the Traverses 3

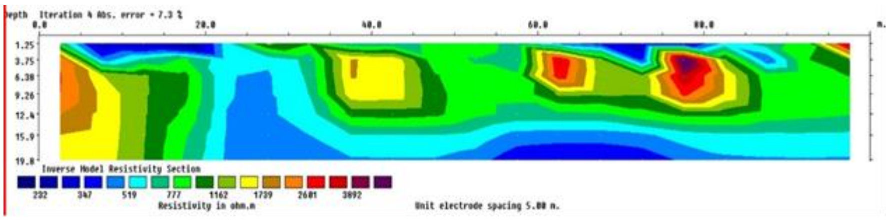

Fig 5: 2-D resistivity imaging models for the Traverses 4

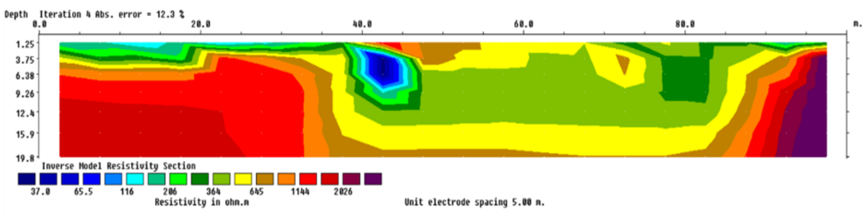

Figure 6: 2-D resistivity imaging models for the Traverses 5

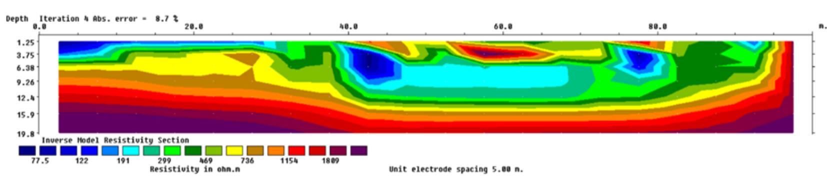

Figure 7: 2-D resistivity imaging models for the Traverses 6

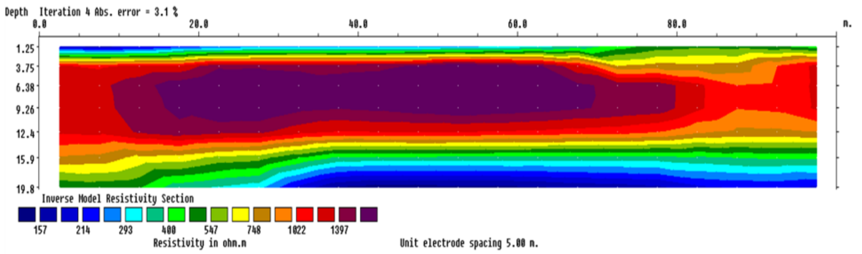

Figure 8: 2-D resistivity imaging models for the Traverses 7

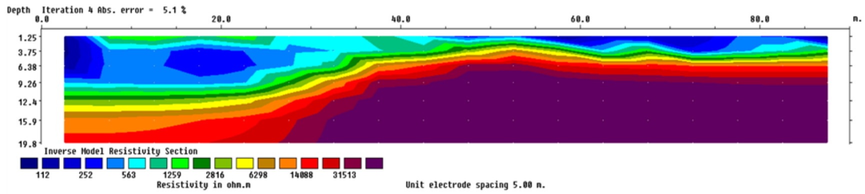

Figure 9: 2-D resistivity imaging models for the Traverses 8

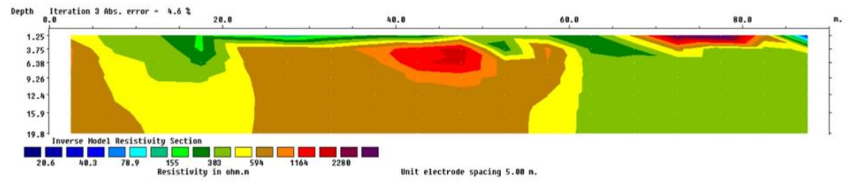

Figure 10: 2-D resistivity imaging models for the Traverses 9

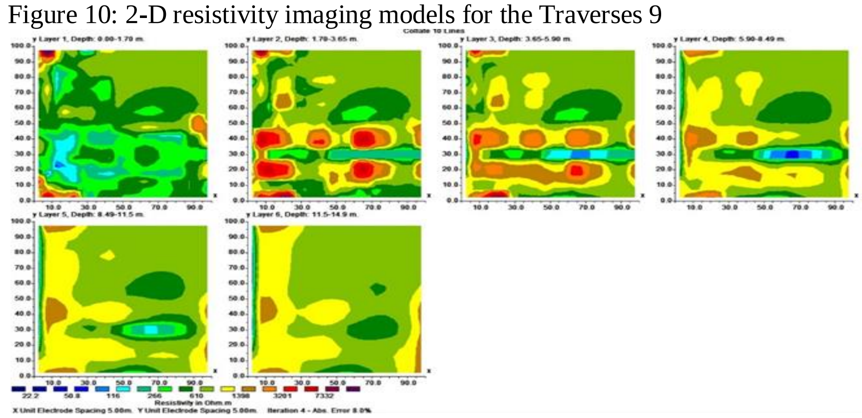

Fig 11: 3-D horizontal depth slices of the subsurface of the study area

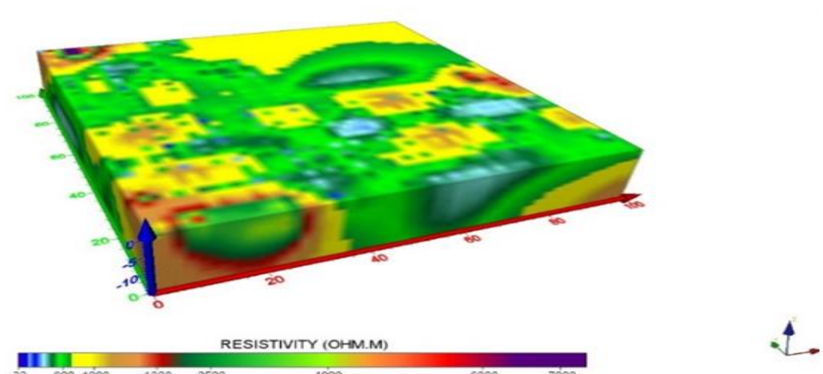

Figure 12: 3-D resistivity volumetic

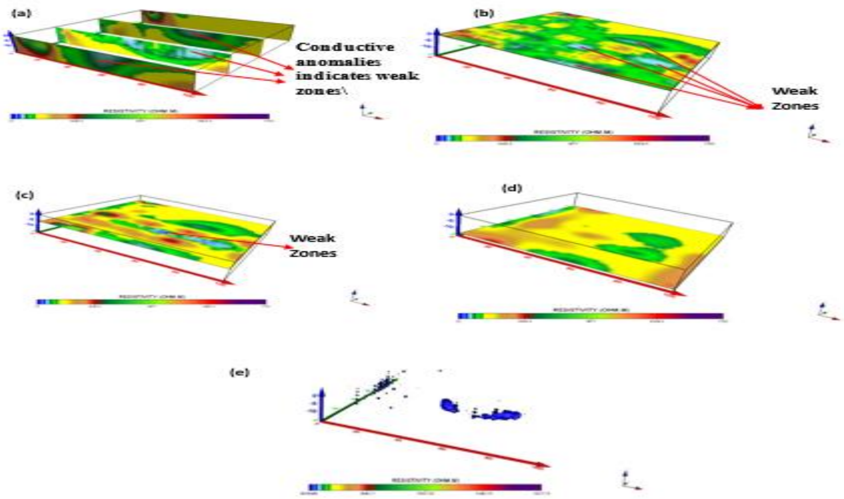

Figure 13: (A) Horizontal Slices Through The 3-D Volume Showing Pockets Of Weak Incompetent Soils (B) Top View Of The Study Showing Weak Zones (C) At 5m Depth, The Weak Zones Disappear Gradually (D) At The Bottom There Is No Visible Weak Or Incompetent Soil (E) Isovalue Of Zones Of Suspected Weak Zones Not Suitable For Foundation

Discussion

The findings from the Electrical Resistivity Tomography (ERT) survey show significant differences in the distribution of resistivity in the subsurface around the study area. These variations are due to lithology, moisture content, degree of weathering and structural conditions. Low-resistivity anomalies found in the profiles are presumed to represent areas of subsurface weak rocks composed of saturated clayey materials, weathered rocks and fractured horizons. On the other hand, high-resistivity regions are linked to good materials able to withstand engineering structures. 3-D ERT models, depth slices and 2-D ERT sections were integrated to interpret the spatial distribution of weak zones and their implications on stability of urban infrastructure.

Inverted resistivity models were interpreted using established resistivity ranges for Niger Delta lithologies, calibrated against published borehole data and previous geophysical studies in the region, (Table 1)

Table 1: Resistivity Ranges for Lithological Interpretation in the Benin Formation

Lithology	Resistivity Range (Ωm)	Characteristics	References
Lateritic topsoil	100–1000+	Iron oxide cementation, variable thickness	Aweto (2013); Ighodalo and John (2024)
Dry sand/gravel	200–2000	Loose to compacted, well-sorted	Alile et al. (2011); Ugbor et al. (2021)
Saturated sand (aquifer)	50–500	Freshwater saturated, moderate porosity	Enebeli et al. (2021); Ighodalo and Japhet (2024)
Clay/silt (aquitard)	1–50	Low permeability, conductive minerals	Ugbor et al. (2021); Ighodalo et al. (2023)
Freshwater clay	10–80	Saturated, reduced resistivity contrast	Okereke et al. (2018)
Compacted sandstone	1000–10000+	Indurated, low porosity	Ighodalo and John (2024)

Transverse 1 (Figure 2)

The resistivity readings for the inverted resistivity section on are between 219 Ωm and 2149 Ωm. In the case of traverse 1, the subsurface as seen on the inverted resistivity section is generally competent with most of the materials being sediments of the Benin Formation with moderate resistivity. The high-resistivity materials that dominate most of the profile are believed to reflect compact sandy deposits or lateritic materials considered to be a characteristic of the Benin formation. The conductive zones, from an engineering point of view, are weak foundation horizons that can be more compressible when loaded. The overall profile, however, indicates moderately good subsurface properties for infrastructure development if site-specific geotechnical verification is appropriate.

Traverse 2 (Figure 3)

The resistivity of the inverted resistivity section for traverse 2 (Figure 3) ranges from about 138Ωm to 5080Ωm. There are a few areas with low resistivity in the profile, one of which is between 10 m and 30 m and the other between 80 m and 95 m. These conductive layers are seen as weathered and water-saturated materials, of poor geotechnical competence. A significant conductive anomaly is seen in the middle portion of the traverse, and down to intermediate depths. The anomaly indicates that sediments containing clay or soils that hold moisture might be present, affecting soil strength. The high resistivity anomalies that are observed at depths of 60–70 m are interpreted to represent compacted sands or lateritic horizons. The profile is heterogeneous, which means there is a variation in the foundation conditions and it may cause differential settlement if engineering structures are built without proper ground investigation.

Traverse 3 (Figure 4)

The inverted resistivity section of traverse 3 (Figure 4) shows the resistivity to vary from 171 to 1825 ohm (Ωm). One of these low-resistivity anomalies is prominent and visible along the profile from near-surface to a depth of about 20 m. This is seen as a saturated weathered zone and is a major weak foundation horizon. The conductivity of this feature indicates that clay-rich material, highly weathered sediments, and/or groundwater-saturated formations are present. The materials have generally low bearing capacity and can settle under loading imposed by structures to an extent that is too great. The high-resistivity anomalies at depths of ~ 40–50 m and ~ 65–75 m are considered to represent small bodies of competent rock in a conductive matrix. The wide range of conductive zone suggests that potentially unstable subsurface condition that may require foundation reinforcement or ground improvement before infrastructure development.

Traverse 4 (Figure 5)

The inverted resistivity section for Traverse 4 (Figure 5) shows resistivity values between 232Ωm and 3892Ωm. Alternating conductive and resistive regions are the characteristic features of the profile. A wide conductive zone exists between 20 m and 45 m of the profile extending to great depths. This is interpreted as being a weathered and saturated subsurface layer. Several isolated high-resistivity anomalies are present between 55 and 85 m and are deemed to represent compact sandy units and/or relatively competent subsurface materials. The conductive horizon found in the western and central part of the profile is a possible weak zone that can negatively influence the stability of the foundation. These conditions can lead to differential settlement and contribute to the vulnerability of infrastructure to structural changes.

Traverse 5 (Figure 6)

The resistivity values for the inverted resistivity section of the traverse 5 (Figure 6) range from 37Ωm to 2026Ωm. Between 40 m and 50 m of the profile, a clear low-resistivity anomaly is seen. This anomaly is shallow and has a very low resistivity and extends down to approximately 10 m. The conductive zone is interpreted as a saturated horizon containing clay rich material or a highly weathered/fractured zone. These types of materials are typically correlated with low geotechnical skills and low bearing capacity. High resistivity is characteristic of the western part of the profile, which was explained as being formed under dense sandy formations or compact lateritic units. Conductive anomaly contrasts sharply with the surrounding resistive materials, which would mean that there is a high lithological heterogeneity and a high risk of localized settlement.

Traverse 6 (Figure 7)

The inverted resistivity section (Figure 7) of the traverse 6 shows resistivities of 77.5 to 1809 Ωm. The profile is mainly underlain by a wide conductive depression along the traverse from about 40 m to 80 m. This low resistivity zone extends to depths of more than 15 m and is believed to be a thick weathered and saturated sequence of materials. The continuity of the anomaly implies the existence of a structurally controlled weathered zone or the channel extending to the depth and/or the existence of a buried saturated channel. The high-resistivity materials surrounding the borehole are read as less competent rocks that can support engineering loads. Considering infrastructure stability point of view, the central conductive depression is one of the most important weak zones detected in the study area and is a significant threat to the foundation performance.

Traverse 7 (Figure 8)

The results of the inverted resistivity section for Traverse 7 (Figure 8) have values of between 157 Ωm and 1397 Ωm. The profile is defined by a thick, high resistivity layer which is laterally extensive and present throughout much of the subsurface. At deeper depths minor conductive anomalies only are observed. The high percentage of moderate to high resistivity suggests relatively good subsurface materials, typically dense sands, lateritic soil or slightly weathered materials. The lack of conductive zones indicates good foundation conditions and is also indicative of low settlement potential. As a result, this traverse is among the most appropriate sites for development of infrastructure in the study area.

Traverse 8 (Figure 9)

The resistivity values for Traverse 8 (Figure 9) vary from about 122 Ωm to 3910 Ωm. The resistivity profile indicates a pronounced increase in resistivity with depth and has a large portion of high resistivity materials at the bottom of the profile. Conductive anomalies occur close to surface primarily across the west side of the profile. The conductive zones are interpreted as shallow weathered, moist, materials and the deeper resistive zone may be compact sandy deposits or competent subsurface. The general depth stability of the foundation conditions, as possible from the profile, could imply that there is no need for site preparation such as excavation or ground treatment prior to construction, unless near surface weak materials are present.

Traverse 9 (Figure 10)

The resistivity values in the inverted resistivity section, T9 (Fig. 10) show a range of between about 20 Ωm and 2280 Ωm. Most of the profile is occupied by moderate resistivity materials and there are scattered conductive and resistive anomalies. There is a local conductive zone near the center of the traverse that could be a weathered or wet zone. The profile has some weak zones, but these are not as extensive as those encountered in Traverses 3, 5 or 6. This results in a stable overall subsurface condition, which is rated as moderate. But comprehensive geotechnical testing is suggested prior to the construction of heavy engineering structures.

The overall urban infrastructure assessment shows traverse 3 (figure 4), traverse 5 (figure 6) and traverse 6 (figure 7) as major weak zones. While traverse 2 (figure 3) and traverse 4 (figure 5) as moderate weak zones. The competent zones are traverse 1 (figure 2), traverse 7 (figure 8), traverse 8 (figure 9), and traverse 9 (figure 10)

The depth-slice (QUASI-3-D) resistivity model generated from the collation of multiple ERT lines, show the lateral distribution of resistivity at different depths and provide a better understanding of the continuity of weak zones identified in the individual 2-D ERT profiles.

Layer 1 (0.00 – 1.70 m) Shows extensive blue-cyan zones which occupy much of the central and southwestern portions these represent soft near-surface materials likely composed of Moist topsoil, Clayey overburden and Unconsolidated fill materials

Layer 2 (1.70 – 3.65 m) Shows several isolated high-resistivity pods (red-purple) occur within a conductive corridor. This suggests competent lateritic pockets embedded within weaker soils and strong heterogeneity of foundation conditions.

Layer 3 (3.65 – 5.90 m) Shows a continuous blue conductive band which extends east-west across the center. This feature likely represents Buried saturated channel, Fracture corridor, Clay-rich weathered horizon. This Strongly correate with Transverse 3 and 5. This indicates these features are not isolated but belong to a laterally continuous weak zone.

Layer 4 (5.90 – 8.49 m) the central conductive corridor remains visible but becomes narrower. This suggests persistence of weak materials with depth or a possible fracture-controlled groundwater pathway. The weak zone extends below typical shallow foundation depth which could pose risks for heavy structures

Layer 5 (8.49 – 11.15 m) Conductive anomalies become more localized, a distinct low- resistivity body remains around X = 60–80 m and Y = 25–35 m. This represents a localized deep weak zone

Layer 6 (11.15 – 14.90 m) Most conductive anomalies disappear. The subsurface becomes dominated by green-yellow resistivities. This suggests: Transition into competent weathered rock and increasing consolidation and strength.

The 3-D depth slices verify that the weak conductive features seen on individual 2-D ERT profiles are linked together together in one continuous weak conductive corridor that extends across the site. This corridor extends from about 1.7m to 11m depth and is considered as a shallow layer of saturated clayey/weathered/fractured materials that have low bearing capacity. The correlation significantly boosts confidence in the interpretation and suggests that this central zone is the main geotechnical risk for urban infrastructure development in this study area.

CONCLUSION

The 2-D ERT profiles, depth slices, 3-D fence diagrams and iso-resistivity bodies all lead to the same interpretation. A subsurface weak corridor is present at the site, and is laterally continuous between about X = 40–85 m and in the depth range 2–11 m. This corridor has low resistivity associated with it, which can be saturated clayey materials, weathered/fractured zones, or groundwater accumulation. It is the major geotechnical hazard in the study area and is a major hazard to the urban infrastructure due to decreased bearing capacity and differential settlement. The southeastern and peripheral areas, on the other hand, show high resistivity and are considered the best areas for potential development of infrastructure. The agreement between the 2-D and 3-D datasets is high, giving high confidence in delineation of both the stable and unstable foundation zones.

The central conductive corridor identified should be avoided whenever possible when siting heavy infrastructure from an engineering perspective. If development cannot be avoided within this zone modifications to the ground (such as soil stabilization, preloading, deep foundations and other appropriate geotechnical measures) should be considered so as to reduce the risks of settlement. The integrated 2-D and 3-D ERT results are a good estimate of subsurface conditions but the geophysical interpretations need to be checked with borehole drilling, geotechnical borings, in-situ testing and lab analyses prior to finalizing foundation design and construction.

In general, the findings of this study show that the use of 2-D and 3-D Electrical Resistivity Tomography can be used as a quick and low cost tool to obtain a high resolution and non-destructive method to map the subsurface competent foundation materials and weak zones. The methodology is a useful decision support system for sustainable urban development, site location and geotechnical risk analyses in rapidly urbanising sedimentary terrain.

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