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AN APPLICATION OF IMPROVISED 2D GEO-RESISTIVITY SURVEY TO ROAD FAILURE INVESTIGATION

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Summary. The Electrical Resistivity Imaging (ERI) method of geophysics has gained large-scale applications in civil engineering for pre-construction site assessment and post-construction investigative and remedial interventions. However, the cost of ERI equipment limits its applications in underdeveloped/developing countries and unfunded studies. This limitation is overcome in this study by applying an alternative and reliable technique of multiple imaging of subsurface for engineering applications using traditional 1D Earth Resistivity equipment and collocated electrodes array. This technique was used to investigate the principal cause of road pavement failure along University Teaching Hospital Road, Ilorin, Nigeria. Five profiles of 100 m were established at different parts of the road to acquire subsurface resistivity data. Resistivity models inverted from the data acquired by the improvised 2D surveys show low resistivity breakouts, weathered sections with high moisture content, weak zones, and elongated brittle structures in the top ten meters of the subsurface. The high resistivity layer corresponds to the stable portions of the pavement while the low resistivity breakouts in the shallow part of the resistivity models correspond to the failed pavements and potholes on the road. Elongated vertical structures were identified as weak zones that served as conduits for rainwater from the top and groundwater from subsurface accelerated weathering activities in the area. Water ingress due to lack of drainage, high moisture content in the top layers, and intense subsurface weathering were found as the cause of the road pavement failure. The study recommends some remedial interventions prior to reconstructing the road pavement.

Introduction

Electrical resistivity survey, ERS, is the preferred geophysical method often used for probing the subsurface in built-up areas. Because it's non-invasive and non-destructive, ERS has gained large-scale applications in construction and civil engineering works. It has been used for characterizing subsurface materials beneath the locations where engineering infrastructures are to be cited, determining foundation depth, or locating geological structures (such as fractures, and buried river channels) that may compromise the integrity of the proposed buildings or infrastructure. Recent development in field procedure, technology, instrumentation, and computer software in the field of geophysics has broadened the applications of electrical resistivity methods to other disciplines including forensic investigations, engineering, and environmental studies. In the last two decades or so, equipment for acquiring multiple resistivity data at different depth levels over large areas in real time has been developed. These data have been used to produce multi-dimensional (2D, 3D, and 4D) images of the subsurface to advise suitable locations to cite infrastructure, investigate the cause of failed buildings, roads, and dams, and determine the strength of concrete piles (Darling, 2001; Rucker, 2006; Soupios et al., 2007; Castilho, Maia, 2008; Karastathis et al., 2002; Cardarelli et al., 2018; Raji, Aluko, 2021). These images are known as subsurface resistivity models or resistivity tomograms. The process of data acquisition and processing is here known as Electrical Resistivity Imaging ERI.

Some new ERI equipment has the capacity to acquire thousands of datasets at different lateral and vertical positions in a single survey and in-built software to process data and image subsurface resistivity beneath the profile line in real time. Therefore, ERI offers on-the-spot assessments of engineering sites for timely decision making. It reduces the cost of geotechnical studies, gives higher coverage than drilling/coring and is cheaper than soil sampling and laboratory testing. However, ERI equipment is very expensive and unaffordable to many geoscience practitioners and researchers in underdeveloped and developing countries where research funding is limited and difficult to access. The limitation caused by the unaffordability and non-availability of new ERI equipment for (non-contract projects) engineering studies is overcome in this study using an augmented 2D-resistivity survey. The augmented 2D survey uses collocated electrode arrays and traditional resistivity meters that are readily available and affordable. Details of the survey are given in the material and method section.

The augmented 2D survey was applied to investigate the cause of repeated failure of road pavement along University Teaching Hospital road, Ilorin, Kwara State, Nigeria. The failed sections of the road has been repaired three times within the three years preceding this study to ease the movement of ambulances and private vehicles conveying patients to hospital for medical attention. However, the same portions keep failing. To find a lasting solution to the perennial problem, this study was conducted to characterize the subsurface materials beneath the road pavement and to advise the best way to tackle the problem. The aim of this study is to uncover the subsurface condition responsible for the repeated failure of pavement at the designated portions of the road. The objectives of the study are: (i) to show that the augmented 2D Electrical Resistivity survey is suitable for investigating road failure in the absence of expensive and unaffordable ERI equipment, and (ii) to recommend remedial strategies to prevent future failure of pavement on the road.

Application of the electrical method of geophysics to road failure investigation and other engineering applications is based on the direct relation between the electrical conductivity of soils/rocks and concrete materials and the shear strength of the materials. Sections with high moisture content which are often associated with road failure have anomalous resistivity signatures that contrast with the competent layers beneath the stable parts of the road. Clay in-fills, subsurface erosional surfaces, fractures, weathered sections, and buried river channels known to be responsible for road failure have characteristic low resistivity properties compared to competent, dry aggregate layers commonly used as base/subbase materials for roads and other engineering constructions (Adeoti et al, 2016; Feyisa and Gebissa, 2023). Feyisa and Gebissa, (2023) investigated the cause of Gedi-Ijaji Asphalt road in Ethiopia using ERI equipment and magnetic method. 2D plots of the resistivity section showed that the failed section of the road corresponds to the low resistivity structures in the subsurface. The low resistivity structure was interpreted as an area of highly weathered sections saturated with moisture infiltrated through surface fractures.

Similarly, Raji and Aluko (2021) applied electrical resistivity and seismic surveys to investigate the cause of excessive water leakage in Asa Dam in West Africa. Results of the study revealed the presence of a low resistivity high-permeability section in the dam foundation. The low resistivity section in the 2D tomogram coincided with a low-velocity oxbow structure in the seismic velocity tomogram. The joint interpretation of the electrical resistivity and seismic velocity tomograms suggested the presence of an extended high-permeable weak zone through which water leaks out of the dam. Other related studies (Osinowo et al., 2011; Arjwech et al., 2013; Adeoti et al., 2016; Raji et al., 2017; Ademila, 2021) found that subsurface causes of failed roads and buildings are often associated with weak zones or water-saturated sections which show up as low resistivity structures in 2D resistivity images. The current study is different from the previous similar studies because it used an augmented 2D resistivity survey technique. The technique removed the limitations placed by the unaffordability of ERI equipment.

Material and Method

Applications of electrical resistivity survey to investigate the cause of road pavement failure are based on the understanding that if subsurface conditions are responsible for the failure of a portion of the road, the subsurface conditions beneath the stable and failed portions of the road should have contrasting electrical resistivity signatures. The resistivity contrast can be best imaged by continuous and multi-level measurements of resistivity/ conductivity along the profile(s) that covered the stable and failed portions of the road pavement. Continuous and multi-level resistivity measurements are done by ERI equipment. However, this equipment was unavailable for this study due to cost. An augmented 2D ERI survey was performed using Campus Omega Terrameter and collocated electrode arrays. Other accessories used in the survey include a DC battery, 21 metallic electrodes, four reels of cable, crocodile clips, hammers, a portable Geographic Positioning System device (GPS), and measuring tapes.

The augmented 2D resistivity survey followed the Wenner array. 51 electrode positions were marked at 2 m intervals to cover a 100 m profile line. However, only 21 electrodes that were available were coupled to the ground at the beginning of the survey on a straight line (fewer or more electrodes could be used). At the start, only electrode numbers 1, 2, 3, and 4 were connected to the resistivity meter, and they correspond to C1, P1, P2, and C2 terminals, respectively. After measurement, the connecting wires were moved to electrodes numbers 2, 3, 4, and 5 and they were connected to C1, P1, P2, and C2 terminals, respectively, and another measurement was taken, then the wires were moved to electrode numbers 3, 4, 5 and 6 for the third measurement. The sequence of connections and measurements continued until electrodes 48, 49, 50, and 51 were connected and measurements were taken.

The electrodes used at the earlier part of the profile were moved forward after measurements to cover the later part of the profile. For example, electrodes number 1 to 17, can be moved to the position marked for electrodes 22 to 38 while taking measurements with electrodes 18, 19, 20, and 21. After completing the series of measurements using electrode spacing of 2 ($a = 2, n = 1$), electrode spacing was changed to 4 m, and measurements along the 100 m profile were repeated, ($a = 4, n = 1$). Finally, the electrode spacing was changed to 6 m to complete the third level measurements, ($a = 6, n = 1$). a is greater, penetration of the injected current is deeper. The field layout for the augmented 2D survey is shown in Fig. 1. Wenner array is selected for this study because it has better depth resolution and higher signal strength than the Dipole-dipole array, and it is less susceptible to acquisition noise (Neyamadpour et al., 2010).

This measurement was repeated at other four locations along the road with each profile covering the stable and failed portions of the road pavement. The failed portions were marked out on each profile for referencing and interpretation purposes. For quality control purposes, the profiles were set out in the following pattern. The beginning and end of Profile 1 fell into the failed road pavement, between the two ends there were stable and failed portions of the pavement. The two ends of Profile 2 fell into the stable pavement, and there were stable and failed pavement between the two ends. Profile 3 largely covered the stable pavement but has a big pothole at the beginning, Profile 4 entirely covered the failed pavement section, while Profile 5 tarted in the stable pavement and ended in the failed pavement.

Fig. 2a is the site map showing the locations of the profiles along the road. Photographs showing some failed portions of the road are shown in Fig. 2b. The bad sections of the road were marked out on each profile and recorded on the field note for reference and interpretation purposes. Data acquired on each profile line were concatenated to form 2D data. Increment in electrode separation (a= 2, 4, 6) represents greater depths penetrated by the injected current, and hence deeper probing. The data were plotted against the profile distance for different electrode separations on each profile for visual inspection. The plots were used as quality control for the 2D modelling because they represent quantitative changes in resistivity/conductivity with distance and depth. The field data were preprocessed using an in-house MATLAB program (Raji et al., 2017) to remove spurious data points that may be due to acquisition error and poor electrode contact.

The resistivity models of the subsurface beneath each profile line were obtained using least squared finite difference-based tomographic inversion (Loke, Barker, 1996). The geological model built from borehole logs and VES-based lithologic sections in the area (Abubakar et al., 2014; Aromoye et al., 2019) was fed into the inversion scheme. The starting 2D model assumed that the (i)pavement material was laid on a flat layer that comprises the subgrade/sub-grade and the topsoil and (ii) that deeper section of the subsurface is made of partially weathered crystalline rocks. The inverted resistivity models were finally processed and plotted using DiproWin Software. The resistivity models shown in Figs 3 to 5 were obtained after 5/6 iterations. The RMS error of the results ranged between 6 to 11%.

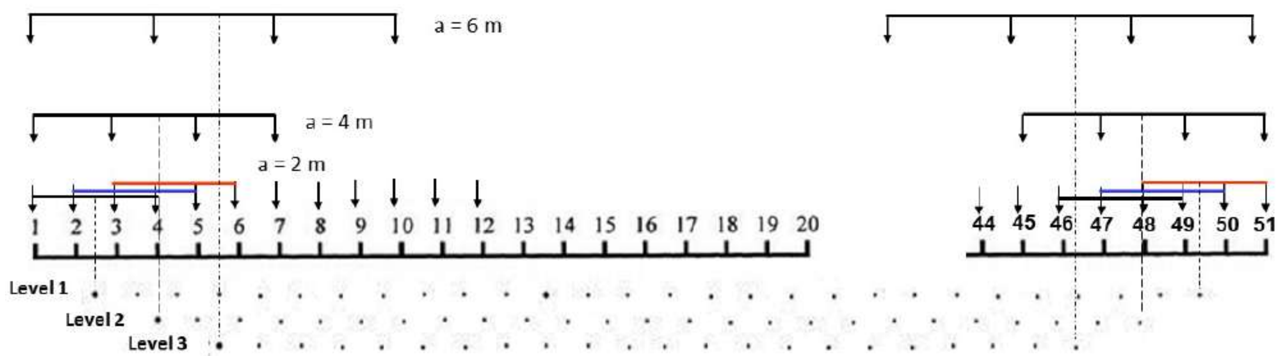

Fig. 1. Schematic image of 2D augmented survey and electrode array used for the study

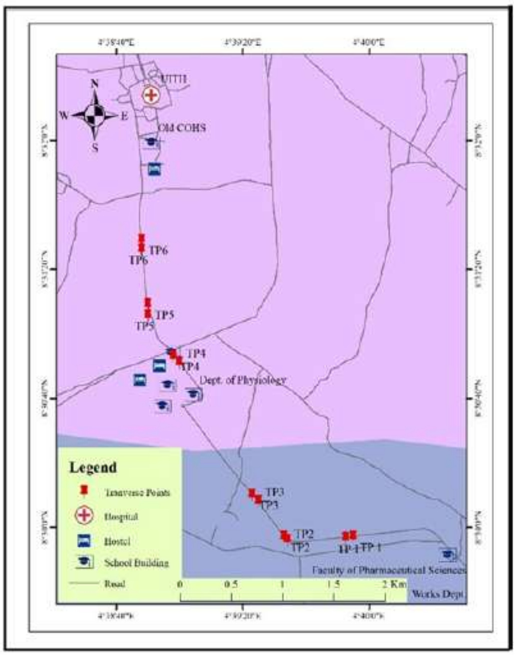

Fig. 2a. Map showing location of the 2D Survey

Fig. 2b. Photos showing parts of the road with failed pavement

Results and Discussion

Interpretations of the resistivity models for road failure in this study were based on the following background knowledge: (i) subsurface condition beneath the stable and failed portions of the road should have contrasting resistivity values and patterns; (ii) the major causes of road failure are weak zones, buried river channels, clay layers, weathered sections, and fractures that are often associated with low resistivity/high conductivity structures; and (iii) distances corresponding the failed portions of pavements marked on the profile line are compared the lateral distance on the 2D resistivity models for concurrence. The resistivity models revealed heterogeneous resistivity distribution in the subsurface, and resistivity values range from 49 - 3008 Ωm. Based on the resistivity patterns and geo-electric features, the structures in the resistivity models are classified into four broad geo-resistivity sections. The reddish–purplish laterally continuous structure at the top 2 m from the surface represents laterally a continuous geo-resistivity layer of resistivity values ranging from 760- 2684 Ωm.

This high-resistive geo-electric layer is interpreted as the combination of the base/sub-base and the topsoil (sub-grade). The base/sub-base materials are construction aggregates of high drainage characteristics. The subgrade/topsoil has high clay content with poor drainage characteristics. The high resistivity values in this geo-electric layer are interrupted by some low resistivity breakouts that indicate weak zones and conductive sections in some places (Soupios et al., 2007; Loke et al., 2020). The second geo-resistivity structure is represented by the greenish colour and has resistivity values ranging from 91 - 398 Ωm. This structure corresponds to the dry weathered layer. The third geo-resistivity section is represented by the blue colour and has resistivity values ranging from 48-86 Ωm.

This section is interpreted as a weathered rock with high moisture/water content. The moisture/water content of the rock is responsible for the low resistivity property of this geo-resistivity section. The fourth geo-resistivity section is represented by a reddish/purplish colour in deeper section of the resistivity models. This geo-resistivity section is interpreted as the stable (unweathered) crystalline rocks. They are generally resistant to weathering and have a characteristic massive structure which is common to rocks of igneous origin. The top 2 m of the resistivity models which correspond to the subgrade material and the topsoil layer characterized by high resistivity red/purple color contained some low resistivity breakouts. These low resistivity breakouts occur irregularly on the resistivity models but are consistent with the position of failed pavement on the road. The low resistivity is due to high moisture content in the failed parts of the pavement some of which have developed into potholes.

Figs. 3a and 3b showed the resistivity models beneath profiles 1 and 2, respectively. As described in the methodology section, the profiles were set out in a pattern that allows quality control during interpretation. Two ends of Profile 1 fell in the failed portion of the road pavement while the two ends of Profile 2 fell in the stable portions of the road pavement. Between two ends, there were failed and stable portions of the pavement. The resistivity model in Fig. 3a showed low resistivity sections at the beginning and end of the profile, while the resistivity model in Fig. 3b shows high resistivity at two ends with low resistivity breakout between them. These two resistivity models suggest that the failed and stable portions of road pavements are characterized by low resistivity breakouts and high resistivity sections, respectively.

These results are consistent with the findings of Osinowo et al. (2011) and Feyisa, Gebbisa (2023) who used ERI surveys for road investigation studies in Nigeria and Ethiopia, respectively. The low resistivity structure lying at 70 – 80 m on Profile 2 indicates the position of a big/deep pothole filled up with compacted laterite. Generally, the low resistivity breakouts in the top 2 -3 m appear larger on the resistivity models than their actual sizes on the road. This could be due to water/moisture in the failed pavement infiltrating the layers beneath the stable pavement. Resistivity models beneath Profile 3 and 4 are shown in Figs. 4a and 4b respectively. The big pothole at the beginning of profile 3 showed up as a low resistivity breakout measuring about 15 m while the remaining part of the profile is characterized by high resistivity section which corresponds to the stable pavement.

The continuous green colour (low resistivity) at the top of the resistivity model in Figure 4b indicated the absence of pavement on the section of the road covered by the profile. The section was filled with compacted laterite to reduce the roughness of the road. The vertical structure beneath the 40 m suggests a weak zone associated with a brittle structure that extends beyond the depth of the resistivity model. The resistivity model beneath Profile 5 is shown in Fig. 5. The image showed high resistivity top layer interrupted by low-resistivity breakouts at the 15 – 20 m mark and the end of the profile. These low resistivity breakouts correspond to the position of the failed pavement on the section of the road covered by profile 5.

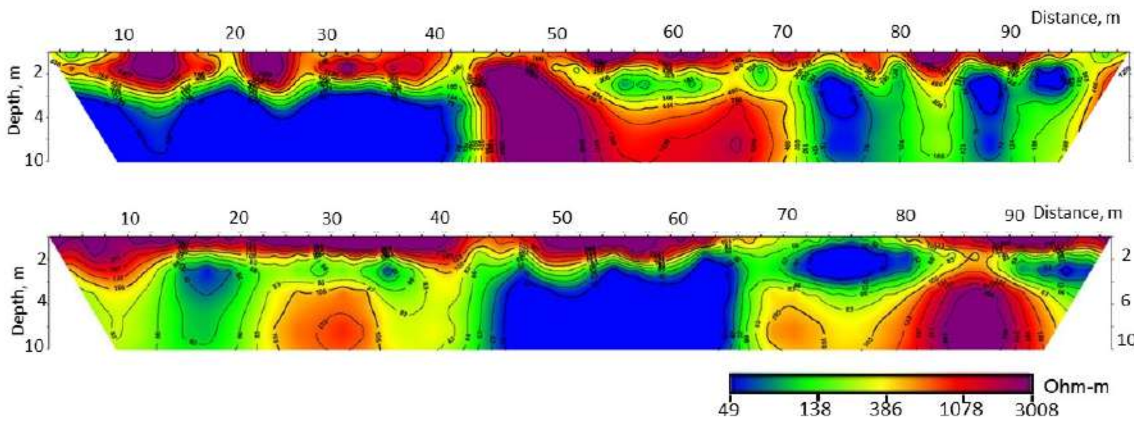

Fig. 3. 2D subsurface resistivity models beneath Profile 1(top) and Profile 2 (bottom)

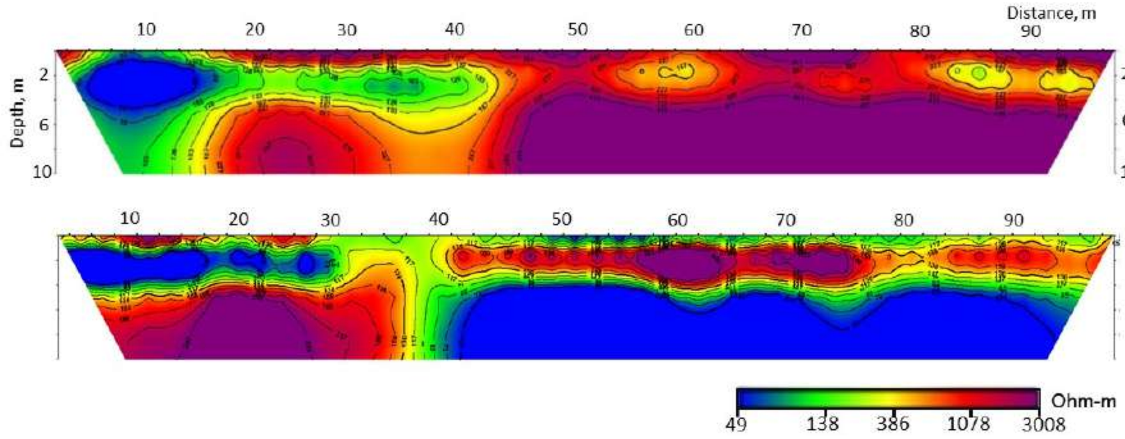

Fig. 4. 2D subsurface resistivity models beneath Profile 3 (top) and Profile 4(bottom)

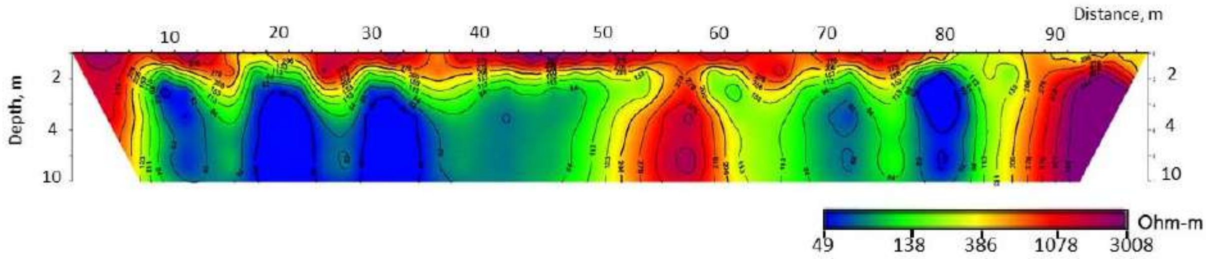

Fig. 5. 2D subsurface resistivity model beneath Profile 5

Generally, the subsurface below the topsoil is characterized by weathered rocks, water-saturated sections and vertical structures that showed shallow up as low resistivity features. These features are weak zones with high moisture content that often compromise the stability of the road. Positions 40 - 45 m on Profile 1, 65 - 68 m on Profile 2, 36 - 40 m on Profile 4, and 80 – 90 m on Profile 5 show some vertical structures that cut through the entire depth of the resistivity models. These vertical structures suggest the presence of deep-seated fractures located at depths beyond the 10 m penetrated by the survey. The structures serve as conduits for the infiltration of rainwater from the top and groundwater from the subsurface, thereby accelerating the weathering of rocks in the area. (Raji, Sulaiman, 2023).

High moisture content in the shallow part of the subsurface due to water ingress and the lack of drainage channels on the road are the main causes of pavement failure on the road. The sub-base and sub-grade contain a significant amount of clay which stores water (and swells) during the rainy season. Hydrologic data and topographic maps of the area show that the road was built on a low and flat topography and groundwater level is shallow in the area (Raji and Abdulkadir, 2020). Continuous interaction between the rocks and groundwater resulted in intense weathering of the rock in the deeper section of the subsurface. The study recommends the removal of the remaining pavement, installing thick base and sub-base materials to raise the road above the surface level, and constructing drainage channels on the two sides of the road before reconstructing new pavement.

Conclusion

The concern of road users on the cause of the repeated failure of the University of Ilorin - Teaching Hospital Road has been addressed in this study. Findings from this study have been used to propose solutions to repeat failure of the pavements along the road. The principal cause of pavement failure and pothole development on the road is the high moisture content in the near subsurface layer due to water ingress and poor drainage system. The 2D resistivity models beneath the road showed that the failed portions of the road pavement are characterized by low resistivity breakouts amidst the high resistivity layer in the top two meters. The deeper section of the road is characterized by weathered rocks of high moisture content and elongated vertical features. The vertical features suggest weak zones and brittle structures filled with low-resistivity weathered rocks that are not strong enough to support heavy loads presented by some vehicles using the road. Overall, the results showed that the augmented 2D resistivity survey is appropriate for road failure investigations. Therefore the method removed the barrier created by the unaffordability of ERI equipment. The study recommends the removal of the remaining pavement, installing thick base and sub-base materials to raise the road above the surface level, and constructing drainage channels on the two sides of the road before reconstructing new pavement.

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ПРИМЕНЕНИЕ ИНТЕГРИРОВАННОЙ 2D МОДЕЛИ ГЕОЭЛЕКТРИЧЕСКОГО СОПРОТИВЛЕНИЯ ДЛЯ ИССЛЕДОВАНИЯ ПРИЧИН РАЗРУШЕНИЯ ДОРОЖНОГО ПОКРЫТИЯ

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Резюме. Метод визуализации удельного сопротивления (ERI) в геофизике активно используется в гражданском строительстве для предварительной оценки строительных площадок, а также для послестроительных исследований и восстановительных работ. Однако высокая стоимость оборудования ERI ограничивает его применение в слаборазвитых и развивающихся странах, а также в исследованиях без финансирования. Недавние успехи в полевых методах, технологиях, инструментах и программном обеспечении в геофизике расширили применение электрорезистивных методов в таких областях, как судебные экспертизы, инженерное дело и экологические исследования. В данном исследовании эта проблема решается путем применения альтернативной и надежной техники многократной визуализации подповерхностных слоев для инженерных целей, используя традиционное оборудование 1D измерений электрического сопротивления Земли и расположенных массивов электродов. Эта техника применялась для выяснения главной причины разрушения дорожного покрытия вдоль дороги Университетской клиники в Илорине, Нигерия. Модели сопротивления, полученные на основе экспериментальных данных 2D-съемки, показывают зоны низкого сопротивления, участки выветривания с высоким содержанием влаги, зоны слабых участков и удлиненные хрупкие структуры в верхнем десятиметровом слое недр. Слои с высоким удельным сопротивлением соответствуют устойчивым участкам дорожного покрытия, в то время как зоны с низким удельным сопротивлением в верхней части моделей удельного сопротивления соответствуют поврежденным покрытиям и выбоинам на дороге. Продолговатые вертикальные структуры были определены как слабые зоны, которые служили каналами для дождевой воды сверху и грунтовых вод, что ускоряло процессы выветривания в этом районе.

Ключевые слова: *Исследование разрушений дорожного покрытия, геофизическое исследование, визуализация электрического сопротивления, 2D расширенный массив, модели подповерхностной резистивности*

YOL ÖRTÜYÜNÜN DAĞILMA SƏBƏBLƏRİNİN TƏDQİQATI ÜÇÜN İNTEQRASİYA OLUNMUŞ 2D GEOELEKTRİK MÜQAVİMƏT MODELİNİN TƏTBİQİ

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Xülasə. Geofizikada xüsusi elektrik müqavimətinin (ERI) vizuallaşdırma metodu mülki inşaat işlərində ərazilərin ilkin qiymətləndirilməsi, eləcə də tikintidən sonrakı analiz və bərpa işləri üçün geniş istifadə olunur. Lakin ERI avadanlığının yüksək dəyəri onun az inkişaf etmiş və inkişaf etməkdə olan ölkələrdə, həmçinin maliyyə dəstəyi olmayan tədqiqatlarda istifadəsini məhdudlaşdırır. Geofiziki mühitdə sahə metodları, texnologiyalar, avadanlıqlar və proqram təminatında son yeniliklər elektrik müqaviməti metodlarının hüquqi ekspertiza, mühəndislik və ekoloji tədqiqatlar kimi sahələrdə tətbiqini genişləndirib. Bu tədqiqatda mühəndislik məqsədləri üçün səthaltı təbəqələrin alternativ və etibarlı çoxölçülü təsvir texnikası təklif edilir, burada ənənəvi 1D torpaq elektrik müqaviməti ölçmə avadanlığı və elektrodlar qruplarından istifadə edilir. Bu texnika, Nigeriyanın İlori şəhərindəki Universitet Klinikasının yaxınlığındakı yolun üstünün dağılma səbəbini araşdırmaq üçün tətbiq edilmişdir. 2D çəkilişlərindən əldə edilən eksperimental məlumatlara əsaslanaraq əldə olunan rezistivlik modelləri, aşağı rezistivlik zonalarını, yüksək rütubət tərkibli aşınma sahələrini, zəif hissələri və üstdəki 10 metrlik yeraltı qatında uzanan həssas strukturları göstərir. Yüksək spesifik rezistivlik qatları yol üstünün dayanıqlı hissələrinə uyğun gəlir, aşağı spesifik rezistivlik zonaları isə zədələnmiş örtüklər və yoldaki oyuqlara uyğundur. Uzunsov şaquli strukturlar zəif zonalar kimi müəyyən edilmişdir ki, bu da üst tərəfdən yağış suyunun və yeraltı suyun kanalları kimi xidmət edərək, bu ərazidə aşınma proseslərini sürətləndirir.

Açar sözlər: *Yol örtüyünün dağılmalarının tədqiqi, elektrik müqavimətinin vizuallaşdırılması, 2D formatında genişlənmiş massiv, səthaltı rezistivliyin modeli*