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Contribution of Electrical Resistivity Tomography to the Anticipation of Potential Disasters: Case of Pipe Ramming Works Under Road Embankments

Hamma Fabien Yonli[1,2] · **Mahamadou Koïta**[3] · **Issouf Kanla**[2] · **Aristide Compaoré**[4] · **Gilbert Mano**[2]

[1]Department of physics, Université Joseph KI-ZERBO, BP 7021 Ouagadougou 03, Burkina Faso.
[2]Department of Civil Engineering, Université de Fada N'Gourma, BP 46 FadaN'Gourma, Burkina Faso.
[3]Departement of Civil Engineering and Hydraulics, Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso.
[4]Department of soils and foundations, Laboratoire National du Bâtiment et des Travaux Publics, BP 133 Ouagadougou 01, Burkina Faso.

ABSTRACT

Throughout Burkina Faso's road network, some roadways have experienced subsidence or collapse following pipe ramming works conducted for the laying of pipes such as drinking water supply networks. When such works are conducted, it is difficult to make a diagnosis of the properties of the formations underlying the road embankment because a destructive sounding would lead to expensive and tedious repairs. In this present study, a geophysical method, namely electrical resistivity tomography has been used to image the structure and the geometry of these formations so as to anticipate potential disasters. Four electrical resistivity profiles were conducted near the insertion and receiving pits, parallel to the national road N°4, at the exit of the capital Ouagadougou. The strategy of prospection has allowed to image down to an investigation depth of approximately 10 m. The study showed that at an average depth of 2 m, an environment of very low electrical resistivity (about 50 ohm.m) is observed in a very resistant environment. This conductive environment corresponds to the presence of a porous and very wet material which extends laterally and in depth under the roadway, and which can lead to a subsidence or a collapse of this roadway on the surface.

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Introduction

Pipe ramming is a trenchless method for installation of steel pipes or casings, in which a pneumatic tool is used to hammer the pipe or the casing into the ground while the excess soil from creating borehole is removed to the surface. The methodisfrequentlyusedunder railway and road embankments [1] and has the advantage to be conducted without affecting traffic. Pipe ramming has the benefice of cost-effectiveness operation [2] and is suitable for all ground conditions except solid rock. However, despite an increasing usage, little technical guidance is available to owners and engineers who plan installations with pipe ramming [3]. Indeed, pipe ramming works present some constraints because they require on the one hand a thorough knowledge, of the nature of the subsoil, and also of its size, in particular in regards to the other buried networks [4]. The damage resulting for pipe ramming when it occurs can have serious economic and security consequences. concerning roads, pipe ramming may lead to localized subsidence or collapse, because of the modification of the structure of the ground underlying the road. Monitoring the occurrence of such phenomena can be difficult without the use of non-destructive methods. For this purpose, geophysical methods can be of great interest. Among these methods, electrical resistivity tomography (ERT) is a geophysical technique widely used for imaging in two dimensions subsurface structures. The technique is used to locate geological discontinuities as well as areas of great geological interest [5-7]. Studies such as Alle et al. [8] have shown the efficiency of the method in identifying hydrogeological targets for proper borehole siting compared to other commonly used geophysical methods. Soro et al. [9] showed that the application of ERT allows to design a geological conceptual model of an aquifer. Such applications are certainly useful to characterize aquifers and so for the mobilization of groundwater [10-12]. Moreover, in the field of civil engineering, there are also examples of the application of ERT of practical utility. Indeed, Kim et al. used tomography to monitor subsoil stability near a foundation excavation [13]. Shin et al. used this method for early detection of dam failure by characterizing temporal changes in subsurface behaviors [14]. Neyamadpour showed that it is possible to use ERT to study the vertical and horizontal extension of existing cracks in the structure of a road covered with asphaltic sandstone [15]. Studies such as the works of Martínez-Pagán proved that the ERT method has been very effective and suitable for providing sufficient information on the subsoil of shallow cavities [16]. However, to our knowledge, the method has never been used to monitor and anticipate damage caused by pipe ramming. The objective of the present study is to highlight the contribution of ERT in the diagnostic potential damages caused by pipe-ramming under roads. The study will focus on verifying whether the pipe ramming does not accentuate the formation of cavities or flow paths within these terrains. Such a study will therefore be of practical use for engineers and geotechnicians working in the construction and public works sector. This study was conducted on the national road N°4 in Burkina Faso where

Corresponding Author: Hamma Fabien Yonli, Tel: +22671409576
Email: fabienyonli@yahoo.fr

pipe ramming is one of the trenchless pipe laying techniques that have become widespread in recent years. The time elapsed between the pipe ramming works and the investigations of this study is three (03) months.

Experimental

Study site

The study site is located in Burkina Faso on the national road N°4 (Figure 1), about thirty km from the capital Ouagadougou, in the locality of Boudtenga, in a geological context of crystalline basement. The dominant formations are made up of schists, granites and basalts as shown in Figure 1.

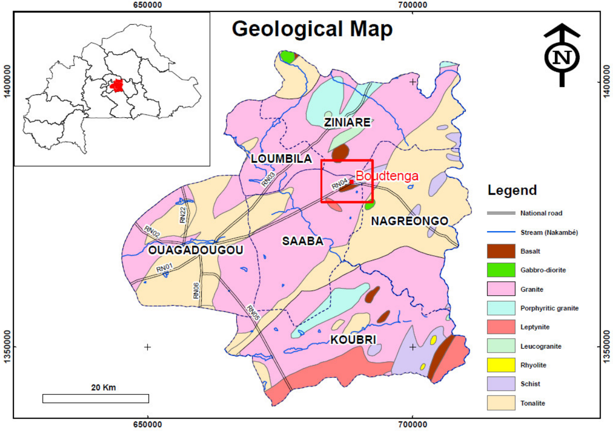

Figure 1: Geological map of the study area

Pipe ramming was conducted there in order to pass various networks under the roadway, namely: electric cables and optical fiber inserted in PVC casings. This work required the construction of temporary excavations on both sides of the road.

The first excavation called insertion pit was carried out on the north side of the road in an anthropized environment. The relief is flat and indurated on the surface with the presence of altered lateritic shells, and sandy and clayey soils originating from the saprolite. On the south side where the second excavation was carried out, qualified as receiving pit, the relief is very indurated and characterized by the presence of witness mounds.

Both pits are located a few tens of meters from the foot of the roadway embankments; the height difference measured between the roadway and the natural ground is respectively 1.20 m on the side of the insertion pit and 0.80 m on the side of the receiving pit.

Visual observations show that the excavated grounds appear to have been used to backfill the pits. However, these grounds show evidence of subsidence and the appearance of cracks favorable to surface water infiltration inside the pits (Figures 2.A and 2.B). The situation is all the more worrying as runoff water from the roadway is easily routed to the pits because of the slope of the embankments.

Strategy of geophysical prospection

The strategy of prospection chosen in this study has consisted of conducting four (04) electrical resistivity profiles as shown in Figure 2.

In a first step, two (02) electrical profiles, namely profiles 1 and 4, were carried out upstream of the pits, about thirty meters away. This strategy aims to assess the properties of the medium that have not been influenced by the pipe ramming. These profiles will thus provide, for each side of the investigated road, the reference situation for a comparison with other profiles.

The second step consisted in conducting electrical profiles (profiles 2 and 3) downstream of the pits, along the road, at the top of the embankments. This position makes it possible to assess the modifications of the properties of the formations underlying the embankment which would have been potentially influenced by the presence of the pipe ramming.

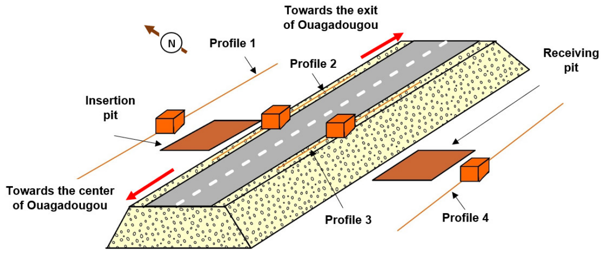

Figure 2: Illustration of the locations of ERT profiles conducted on the field

Data acquisition

Principle

Electrical resistivity tomography consists to align a set of electrodes of constant spacing (electrical resistivity profile) in order to perform a series of apparent electrical resistivity measurements. A sequence of measurements is prepared in advance using ELECTRII software and imported into the memory of a resistivity meter. This sequence of measurements is a small execution program indicating the sequence of quadrupoles to be considered to perform the resistivity measurements (Figure 3). Measurements are made at several horizontal positions and at several depths.

For each quadrupole considered, the potential difference ΔV and the electric current intensity I are measured. The apparent resistivity ρ is then calculated by applying to the ratio ΔV/I a multiplier coefficient K according to the formula:

$$\rho = K\frac{\Delta V}{I} \quad (1)$$

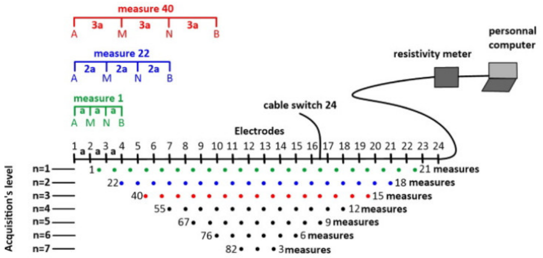

Figure 3: Procedure for acquiring a dataset with several quadrupoles using an automatic electrical resistivity meter [17]

Once installed in the memory of the resistivity meter, the protocol allows it to independently perform the series of programmed unit measurements. The apparent resistivity values obtained for each of the measurement quadrupoles are plotted in a vertical plane called pseudo-section of apparent resistivity.

Choice of measurements configuration on the field

All the profiles were conducted using the Wenner α and Wenner β electrodes array. These arrays have been conducted because their the combination makes possible to assess both the horizontal and vertical heterogeneities of the subsoil. The profiles were obtained by aligning 72 electrodes spaced 1 m apart and centered laterally on the pits (Figure 4). Such an approach allows us to obtain an investigation depth of about 10 m at the center of the device.

Figure 4: Implementation of an electrical resistivity profile downstream of the insertion pit

The measurement device used in this study is the SYSCAL R1⁺ 72 Switch, which is a resistivity meter presented in a compact block and making it possible to read the current intensities, the potentials and to directly calculate the apparent resistivities of the ground. It is powered by an external battery and two internal batteries. Reels of electrical cables are used to connect the device to the electrodes for injecting current and measuring the potential difference.

Data processing

Data pre-processing

Raw data from the resistivity meter undergoes pre-processing with the Prosys II software. Some parameters of the dataset have been filtered in order to avoid errors in the modeling process. In this study, these constraints have been considered: positive apparent resistivity, maximum standard deviation equal to 10%.

Elimination of outliers

After filtering data under Prosys II, they are processed with the X2ipi software. X2ipi made it possible to eliminate some outliers that would have escaped the filter. This consisted in identifying the data which have orders of magnitude different from those of the neighboring data.

Data inversion and classification

After pre-processing and elimination of outliers, the next step has consisted in carrying out a data inversion, that is to say proposing a model of true resistivities called section of electrical resistivity which corresponds to the realities of the field [18]. This step was performed using RES2DINV software. Data inversion started with the determination of an initial model and its iterative improvement using the differences between the observations and the responses calculated with respect to the parameters of the model.

In order to facilitate the analysis and interpretation of the geophysical models obtained after inversion, the interpreted resistivities are grouped into classes of resistivity taking into account the geological context of the study area.

The quality of the data inversion is assessed by the Root Mean Square (RMS) which measures the difference between the calculated apparent electrical resistivities (x_{model}) and the measured electrical resistivities (x_{data}).

$$RMS = \sqrt{\sum_{i=1}^{N}((x_{data,i} - x_{model,i})/x_{data,i})^2/N} \qquad (2)$$

where N represents the total number of measurements.

Results and Discussion

In total, four (4) profiles of 71 m each, with an investigation depth of 10 m, made it possible to carry out all the geophysical prospecting on the Boudtenga site. The following sections show the different results obtained for each pit after data inversion.

Observations on resistivity variability at the insertion pit side

Figure 5 shows the electrical resistivity section upstream of the insertion pit (section from profile 1). Given the distance between the electrical profile and the insertion pit, it can be assumed that this part of the study site was not considerably influenced by the pipe ramming. The section of electrical resistivity makes it possible to perceive a very resistant environment characterized by electrical resistivities greater than 400 ohm.m, in line with the presence of laterite from the surface. In the geological context of crystalline basement, beyond 400 ohm.m, we have to deal with the presence of massive rocks of relatively low porosity and whose alteration is not deep [19-20]. At the east of this profile, however, there are formations of lower resistivity below 400 ohm.m which are more characteristic of alterites.

Figure 6 shows the electrical resistivity section slightly downstream of the insertion pit (section from profile 2 made on the roadway). In general way, the center of the section is less electrically resistant compare to the reference case. On the surface, up to about 1.20 m deep, this situation is easy to understand given the presence of a disturbed layer of soil (compacted road embankment) with lower resistivity. At a deeper level, however, low electrical resistivity values are noticed, such values are related to the presence of wet materials

This situation is all the more noticeable in the center of the electrical profile, at a depth of about 2.4 m, where the lowest resistivities are recorded. These resistivities are lower than 50 ohm.m. Such low resistivities are due to the presence of a very porous medium (beginning of a formation of cavity) and very humid which is not seen on the reference profile (profile 1). Taking into account the fact that the profile was centered on the insertion pit, we can deduce that the poorly clogged excavation of the insertion pit has favored the infiltration of water and has lead to a degradation of the structure towards the zone crossed by the pipe ramming. Therefore, the bearing capacity of the formations underlying the road has been altered. This seems all the more true since the zone of weakness in the center of the section of profile 2 is located at the estimated depth of 2.4 m where the pipe ramming was conducted.

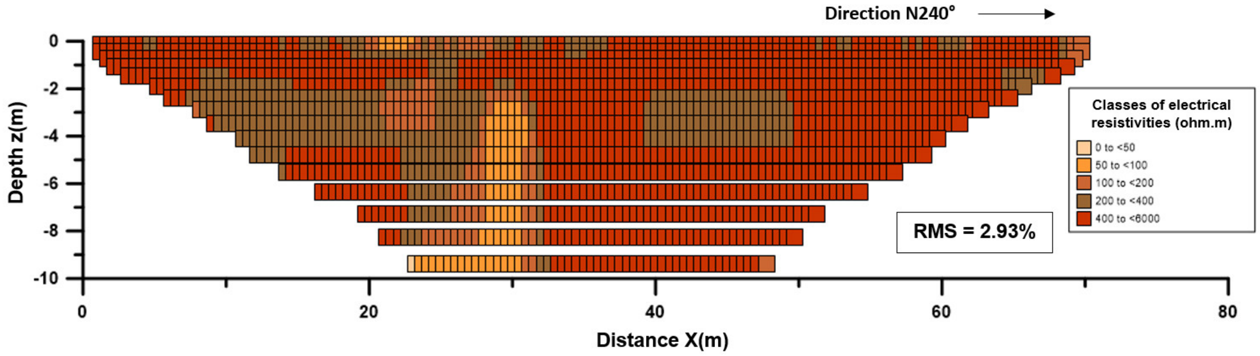

Figure 5: Electrical resistivity section from profile 1 (upstream of the insertion pit)

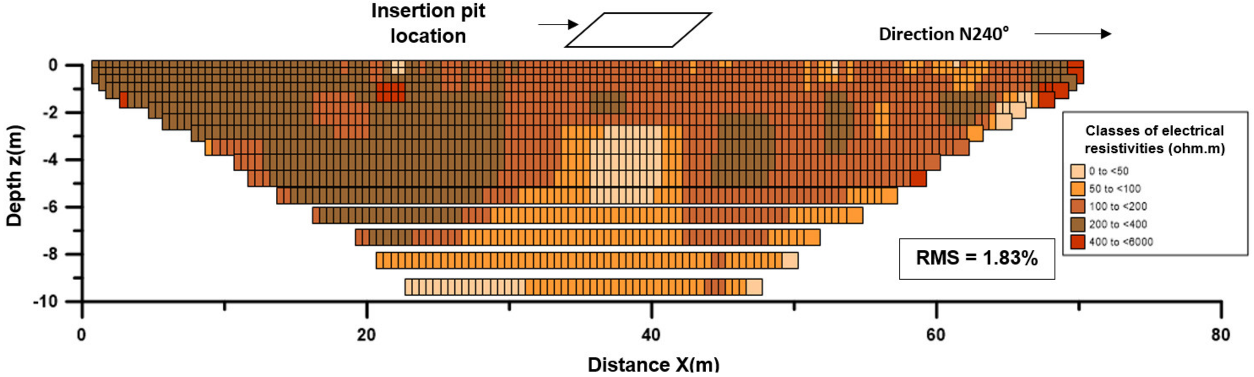

Figure 6: Electrical resistivity section from profile 2 (downstream of the insertion pit)

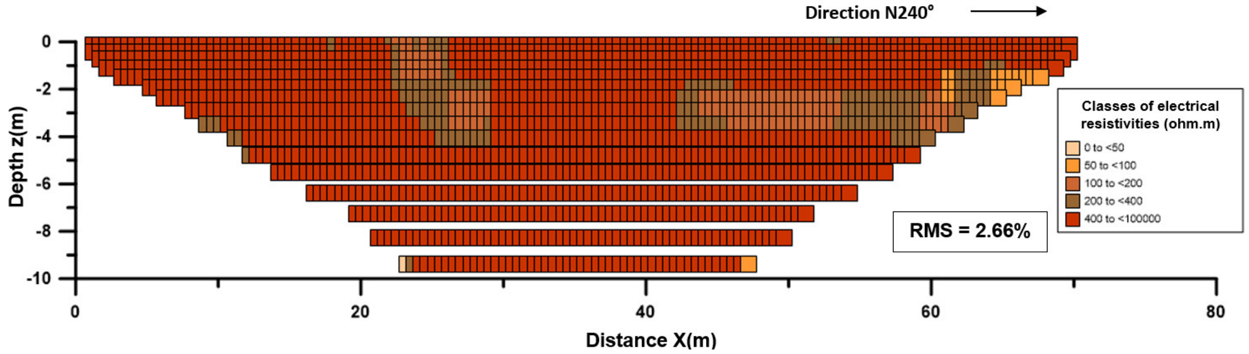

Figure 7: Electrical resistivity section from profile 4 (upstream of the receiving pit)

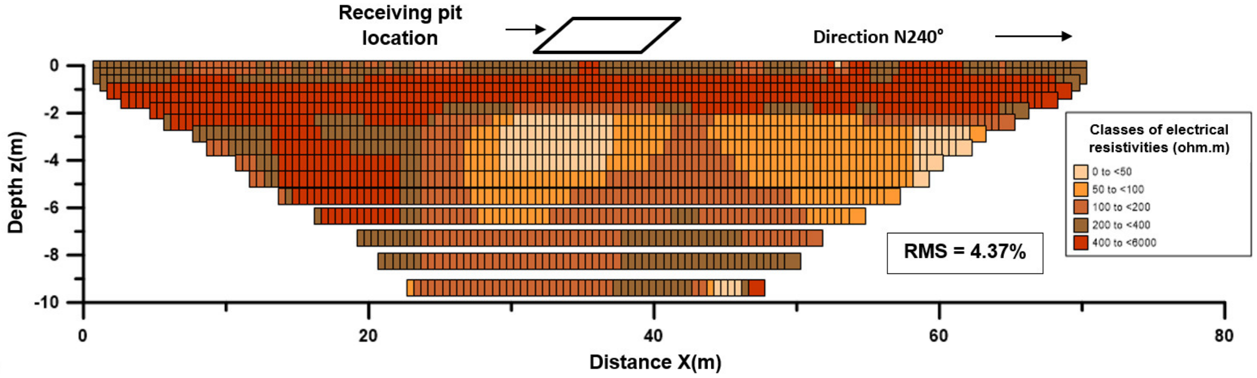

Figure 8: Electrical resistivity section from profile 3 (downstream of the receiving pit)

Observation on resistivity variability at the receiving pit side

Figure 7 shows the electrical resistivity section upstream of the receiving pit (section from profile 4). It reveals that, on the south side of the road, the medium consists of a very electrically resistant environment with electrical resistivity values mostly above 400 ohm.m. As for the electrical resistivity section of profile 1, these values are indicative of a medium with very low porosity consisting of altered lateritic shell.

Figure 8 shows the electrical resistivity section slightly downstream of the receiving pit, profile conducted on the roadway (profile 3). This profile makes it possible to distinguish in the superficial thickness of about 1 m, a layer of resistivity between 200 and 400 ohm.m which corresponds to the compacted road embankment. This compartment thus overlays the lateritic shell which extends over approximately 1.5 m in thickness. The profile then shows that at about 2 m depth, very low electrical resistivities are recorded in the central part (0 to 50 ohm.m). at this location close to the pipe ramming, the structure of altered materials has been affected. The poorly sealed excavation has favored the infiltration of rainwater and its circulation towards the area crossed by the pipe ramming and has given rise to a very wet and highly porous environment (beginning of a formation of cavity). This infiltration also seems to be propagating in depth and also on the western side of the profile where we note the presence of highly conductive layers (resistivities lower than 100 ohm.m) which contrast strongly with the resistant superficial medium above 2 m depth. Note that the depth of 2 m corresponds to the estimated depth of the pipe ramming zone from the level of the roadway.

Discussion

The application of Electrical Resistivity Tomography in Burkina Faso has already proven itself in the sense that it made it possible to image geological formations and to explain the behavior of aquifers in a crystalline basement environment [21-23]. The combination of the Wenner α and Wenner β devices for electrodes spaced 5 m apart and used by Soro [19]; Outoumbe has allowed to observe the presence of discontinuities over an investigation depth of 60 m, and to well describe the alteration profile of hard rock aquifers [22]. Geological conceptual models have been proposed on this basis facilitating the comprehension of such media.

This study shows that the method is also suitable for applications in the field of civil engineering provided that the inter-electrode spacing is reduced in order to have a good resolution of the surface fringe of one to a few tens of meters which is the zone of interest in this type of application. The ratio of outliers after data processing is less than 1% for all electrical resistivity sections: the data can be considered good at the end of this step. Furthermore, the RMS values obtained ranging from 1.83% to 4.37% are low compared to those obtained by Soro [19] which vary between 4.8% and 13.2%. Such values attest the quality of the models obtained.

Conclusions

At the end of the geophysical investigation on the site of the Boudtenga, the electrical profiles conducted on the roadway near the insertion and receiving pits, show in their central parts, a modification of the structure of the underlying formations. At a depth of about 2 m, an environment of very low electrical resistivity is observed, which corresponds to the presence of a porous and very humid material which gradually extends laterally and in depth.

In view of the observations made in the field, the pits have probably been poorly clogged, making the zone of pipe ramming a preferential flow zone below the roadway. These soils underlying the roadway are therefore likely to settle under the weight of road loads and thus lead to subsidence or even collapse on the surface if they are not properly sealed.

As a recommendation, the pits made during the pipe ramming should be plugged in the future with carefully compacted materials to avoid possible infiltration of runoff water drained by the roadway. In addition, to better anticipate disasters likely to occur, we recommend carrying out Electrical Resistivity Tomography tests, before conducting pipe ramming operations and then after the end of these operations. This would allow a temporal monitoring of the properties of the formations underlying the roadway.

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