Spectral time-domain induced polarization and magnetic surveying – an efficient tool for characterization of solid waste deposits in developing countries

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SUMMARY

Time-domain induced polarization (IP) and magnetic data were acquired to map and characterize the decommissioned, un-engineered, municipal solid waste deposit site of the Kwame Nkrumah University of Science and Technology (KNUST), located in the Kumasi Metropolis of Ghana. Thirteen induced polarization profiles 500-800 m long and twenty-six magnetic profiles 600-800 m long were acquired, and two drillings were carried out in order to help in the interpretation of the geophysical data. The study was carried out with the aim of determining the risk posed by the waste deposit to the quality of the soil and the groundwater system, which is the main potable water supply for the Secondary School, the University Teaching Hospital and the Veterinary School, situated within the catchment area of the site. Full-decay 2-D time-domain IP inversions in terms of Cole-Cole parameters were used for interpreting the polarization data. The chargeability, resistivity, and the normalized chargeability distributions, together with the magnetic results, aided in a full characterization of the site geology, the waste and the associated pollution plume. In particular, clear contrasts in resistivity and in the polarization parameters were found between the saprolite layer and the granite bedrock, the main lithological units of the area.

Furthermore, it was found that the KNUST waste deposit is characterized by a low-chargeability and low-resistivity signature, and that the low-resistivity area spreads out from the waste deposit into the permeable saprolite layer, indicating the presence of a leachate plume. A fracture zone in the granite bedrock, which is at a risk of leachate contamination, was also identified. The research thus provides the information needed for assessing the future impact of the waste on the water quality in the area as well as for designing risk-mitigation actions.

INTRODUCTION

Landfills without leachate collection systems pose a high risk to the ecosystems and to human health. In the past, this was not considered much of a problem because large unused land and abundant natural resources such as water were ready available. However, the ever increasing population in the urban areas due to rural-urban migration has put pressure on land use, increased waste production and the demand for potable water especially in developing countries. As well, there are cases of a redefinition of land use as areas, once considered unsuitable for habitation, such as land used for unengineered waste disposal, have been inhabited by people, disregarding the risk for public health and livelihood (e.g. Wemegah *et al.*, 2014). The pollutants originating from these un-engineered landfills pose a health risk to the people exposed to them and can lead to death in extreme cases. The effect on the quality of life caused by the intake of pollutants from industry and domestic wastes has been reported by Dolk and Vrijheid (2003) and Moore *et al.* (2011). These pollutants tend to accumulate in the soil and finally leach into the underground water system, which is becoming the main source of potable water in most developing countries, due to the ever-increasing pollution of surface water bodies (Barthiban *et al.*, 2012) and the drying out of surface water due to climate change. These problems are mostly compounded by improper management of the waste disposal sites, especially in developing countries like Ghana, because of the lack of capital investment, poor and improper enforcement of existing laws.

In order to improve the situation in some of these areas, there is the need to monitor and determine the impact of the sites on the environmental quality and to provide the appropriate remedies. For large areas, it is very expensive to obtain information on the landfill characterization using only drillings. Thus, a fast, cheap, and non-destructive mapping technique, allowing coverage of the whole area of interest, is a huge benefit.

This study presents the characterization of the un-engineered and decommissioned KNUST waste deposit site in Kumasi, Ghana using TD spectral IP and ground based magnetic survey data. Thirteen induced polarization profiles 500-800 m long and twenty-six magnetic profiles 400-800 m long were acquired, and two boreholes drilled in the site during the case of the work. The research help in the determination of the risk of the KNUST landfill on the quality of soil and groundwater, which is the main source of water supply to the KNUST Secondary School, the Teaching Hospital, and the Veterinary School situated in the area.

METHOD

The decommissioned un-engineered KNUST solid waste deposit (Fig. 1) is situated around the coordinate (660349W, 739177N) projected in the World Geodetic System (WGS84) UTM zone 30 N, 2 km northeast of the main university campus in the Kumasi Metropolis, Ghana. The site covers an approximate area of 600 by 650 m with the main waste deposited around 1/3 of area and was operational from 1998 to 2011. The area is mainly a low lying wetland behind the main demonstration farm of the Agriculture Faculty. Other University facilities located in the area are the KNUST Secondary School forming the northern boundary of the site, the KNUST Teaching Hospital, and the Veterinary School, under construction in the southeastern corner of the area.

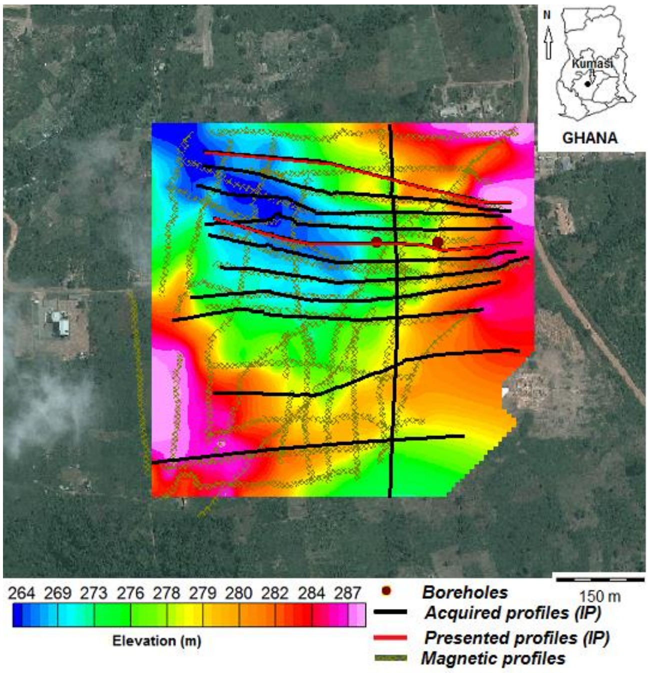

Figure 1: Satellite image of the study area showing the acquired profiles (black and red lines), the borehole positions (dark red circles), the magnetic lines (dark green cross) and the digital elevation map.

The magnetic data were acquired on approximately 5 x 15 m grids, on 22 profiles with lengths ranging between 600 to 800 m (Fig. 1). The gridding of the data was carried out using the minimum curvature algorithm at one-quarter (1/4) of the profile spacing. The analytical signal was applied to the total magnetic intensity data converts the magnetic anomalie directly over the magnetic source as a form of reduction to the pole (e.g. Nabighian, 1984; Ansari and Alamdar, 2009). On the other hand, 13 DCIP profiles with lengths ranging between 500 m to 800 m (Fig. 1) were surveyed. The was done using the gradient array (Dahlin and Zhou, 2006) because of its efficiency with a multi-channel acquisition system, the low geometrical factor, and how it minimizes the effect of electrode polarization (Gazoty *et al.*, 2013). The data was acquired with the Iris Syscal-PRO instrument using 20 gates, approximately log-sampled with gate widths between 10 and 800 ms and 3 stacks in each acquisition, using 4 s current turn on-and-off (Gazoty *et al.*, 2013). The electrode spacing was 5 m.

The DCIP data were processed and inverted in Aarhus Workbench (Auken *et al.*, 2009), a software package that enables the display, processing, and inversion of the data in a GIS environment. The data were processed to remove outliers in the resistivity section as well as in the IP decays. In all about 5% of the DC data and about 13% of the IP data were removed in the processing. The standard deviation on the DC and IP data was computed using 2% and 10% relative values, respectively, plus a noise floor of 1 mV (Gazoty *et al.*, 2013). The full-decay IP data were inverted using the 2-D DC/IP inversion algorithm (Fiandaca *et al.*, 2013; Auken *et al.*, 2014). This gives access to the spectral information contained in the IP decays, retrieved in terms of the Cole-Cole model (Pelton *et al.*, 1978). The inversion Cole-Cole parameters including direct current (DC) resistivity (ρ), chargeability (m_0), the relaxation time (τ), and the frequency factor (C) were based on the complex resistivity (ξ) equation:

$$\xi(\omega) = \rho\left[1 - m_0\left(1 - \frac{1}{1+(i\omega\tau)^C}\right)\right]$$

where ω is the frequency and i is the imaginary unit. With the IP time gates adopted in this study, τ values ranging from tens of milliseconds to several seconds can be resolved (Fiandaca *et al.*, 2012).

RESULTS

The IP and the magnetic datasets acquired were used to delineate the lateral extent of the waste, as well as modelled the waste and plume thicknesses of the site.

The magnetic analytical signal of the research area (Fig. 2) mapped the waste's lateral extent, due to the high magnetic signature of the waste. The main waste was mapped at the central part of the site, with the northern and the western parts of the site recording significant anomalous values. This high magnetic signature is attributed to the high ferrous metal composition of the waste. The uncontrolled nature of the waste deposition at the site is evident in the form of various spots of high magnetic signal observed in various parts of the area.

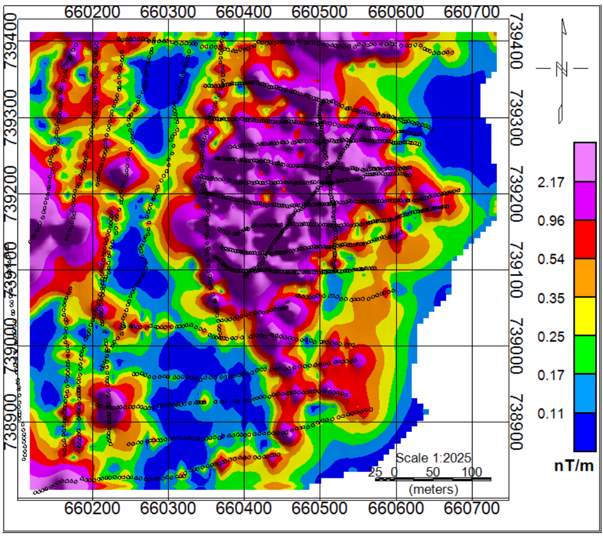

Figure 2: Map of the magnetic analytical signal showing the position of waste with high magnetic signature. Black hollow circles represent the acquisition points.

The inversion results of two exemplary TDIP profiles are presented in Fig. 3 in order to show the features that were considered in developing the above-mentioned models. In particular, profile 1 (Fig. 3a1-f1) is on the edge of the site and shows a distinct reduction of resistivity in the granite bedrock interpreted as a fractured zone; profile 5 (Fig. 3a2-f2) is over the main waste and presents anomalies linked to the waste itself and the resulting pollution plume.

The decreased resistivity values in the vicinity of the waste body, as retrieved by the IP parameters and it correlation and low chargeability values in the saprolite layer, is probably due to an increase in the pore fluid conductivity of the soil due to leachate. In fact, as documented by Lesmes and Frye (2001) and Slater and Lesmes (2002), an increase of the fluid conductivity would imply a reduction of both the resistivity and chargeability values. Consequently, the low resistivity areas can be interpreted as areas polluted by the waste leachate. This interpretation is also corroborated by the thickness of the low resistivity anomalies, which is significantly bigger than the waste thickness, as known from waste site records and confirmed by the borehole loggings (e.g. Fig. 3a). This means that the DC resistivity method alone is not enough for mapping the waste body in this unprotected and un-engineered waste site, where the leachate infiltrates from the waste into the porous subsoil. This interpretation of the low resistivity anomalies suggests that the normalized chargeability is the better parameter linked to the site lithology. In fact, both chargeability (m_0) and resistivity (ρ) decrease when the pore fluid conductivity increases, but their ratio, i.e. the normalized chargeability σm_0, is less affected by the pore fluid conductivity.

The picking surfaces representing the waste and plume bottoms as well as the granitic-saprolite (e.g. Fig. 3) of all the profiles were performed in Aarhus Workbench and the surfaces gridded using Kriging algorithm. The generated interfaces were subtracted from the digital elevation model of the area to generate the waste thickness, plume thickness and geological model of the research site.

CONCLUSIONS

Combined 2-D time-domain spectral IP tomography and magnetic surveying were used in mapping the un-engineered municipal solid waste deposit of the Kwame Nkrumah University of Science and Technology, located in the Kumasi Metropolis of Ghana. The full-decay IP data were inverted using an accurate modelling of the current waveform and of the instrument filter in order to extract the IP spectral information in terms of Cole-Cole parameters, while the analytical signal was computed from the magnetic data.

The magnetic analysis depicted the lateral extent of the landfill, thanks to its high magnetic signature, while the IP investigation retrieved also the thickness of the waste body, together with information on the waste leachate and on the site geology. In particular, it was found that the waste deposit is characterized by a low-chargeability and low-resistivity signature, and that the low-resistivity area spreads out from the waste deposit into the permeable saprolite layer, indicating the presence of a leachate plume. Furthermore, the lithological setup of the site was developed, thanks to the contrast present in both resistivity and IP parameters between the saprolite layer and the granite bedrock, the main lithological units of the area. A fracture zone of the granite bedrock at risk of leachate contamination was also identified.

The outcome of this work is important for planning the future provision of potable water to the institutions located in the area, since groundwater has become the main means of water supply on a regular basis in the Kumasi metropolis in recent years. This is due to the erratic supply of water from the Ghana Water and Sewage Company, which has the potential to endanger the safe running of the facility.

We believe that the full-decay spectral inversion of TDIP data could contribute towards changing the field applications of induced polarization. Data interpretation could evolve from a qualitative description of the soil, able only to discriminate the presence of contrasts in chargeability parameters, towards a quantitative analysis of the investigated media, which could allow soil-type characterization, as done in this study. We also believe that the combination of TDIP and magnetic surveying is a strong and efficient tool for mapping of waste deposits and the host geology in developing countries.

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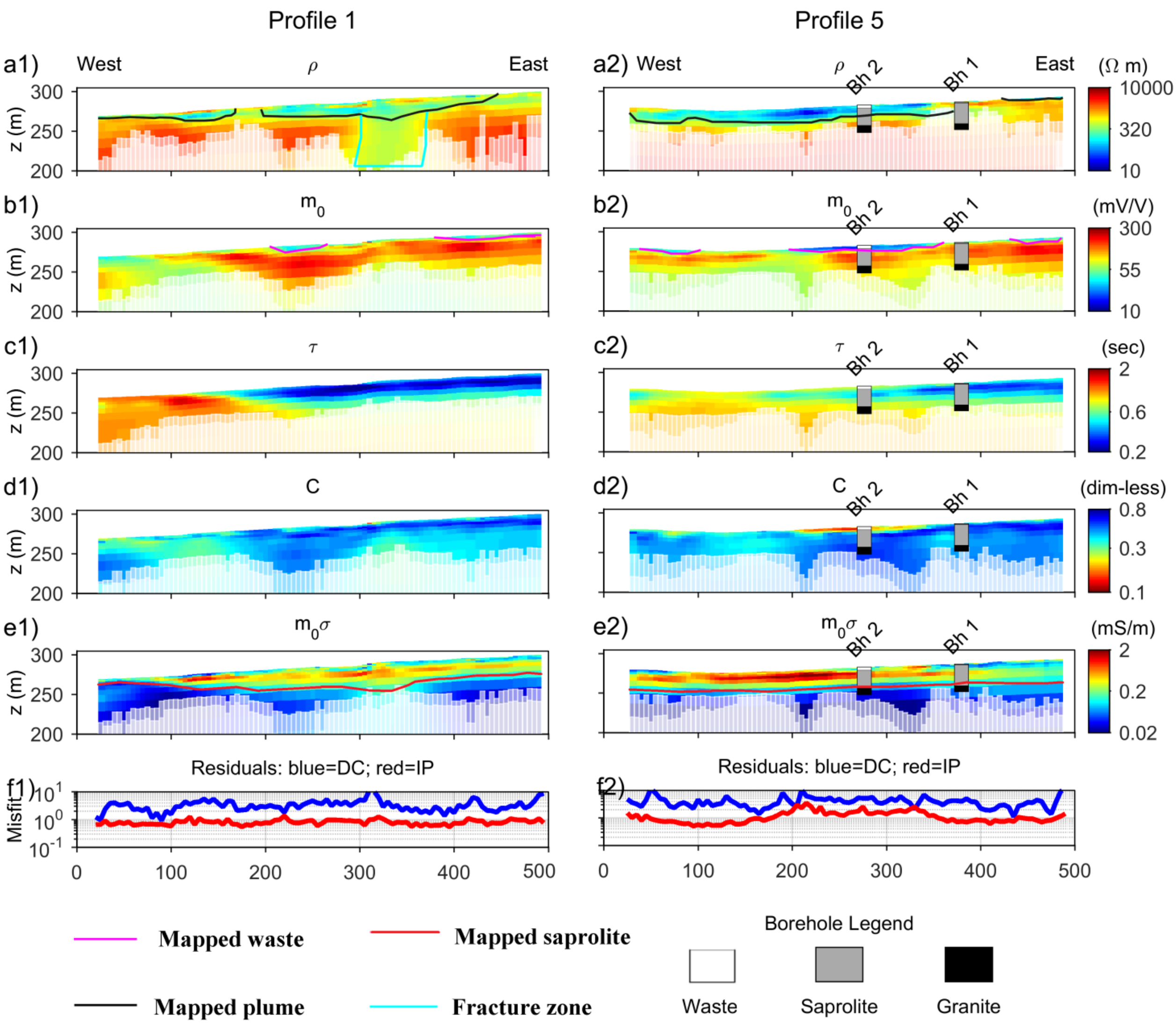

Figure 3: Cole-Cole DCIP parameters of profiles 1 and 5 a) resistivity section showing the picked plume bottom and fracture zone b) chargeability section showing the waste bottom c) relaxation time section d) frequency factor section e) normalized

chargeability section showing the picked saprolite-granite interface f) the DC and the IP misfit section. The depth of investigation is included in all model plots by partially shading poorly resolved areas and fully blanking not resolved model areas.