EXPLORING THE POTENTIAL OF ELECTROMAGNETIC SURFACE MEASUREMENTS FOR THE CHARACTERISATION OF INDUSTRIAL LANDFILLS

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Introduction

Enhanced landfill mining[1] (ELFM) could optimise the economics of landfill remediation. Landfill exploration is considered as a key aspect of ELFM as it can contribute to evaluating the amounts and properties of waste material. Geophysical measurements carried out at the landfill surface offer a non-invasive, non-destructive and rapid approach to the identification of subsurface structures. In contrast to most geophysical studies on landfill sites described in literature, this study does not focus on determining the environmental risks arising from disposed waste. Instead, the ELFM potential of disposed waste is investigated. The aim of this work is to explore the suitability of surface measurements with frequency-domain electromagnetic induction (FDEM) and ground penetrating radar (GPR) measurements for characterising waste layers, and more in particular their geometry and electric properties. The geophysical measurements were made with real-time GPS positioning,[2] followed by trench excavation. Additional trench profile measurements were made to validate the electromagnetic property distributions derived from the surface measurements.

Materials and Methods

Site description The site is part of a former paint factory in Ghent, Belgium, which started its activities in 1958. From 1941, the site was the location of a textile production facility. The investigated area was covered by gravel and used for on-site traffic. On the described site, a transect with a length of 33 m was investigated. In the context of environmental site assessment, previously conducted soil investigations indicated a contamination with heavy metals and polycyclic aromatic hydrocarbons.

FDEM survey The described site was surveyed using a FDEM sensor, in particular a DUALEM-421S[3] (DUALEM Inc., Milton, Canada). This sensor incorporates six transmitter-receiver coil combinations: three in a horizontal co-planar (HCP) configuration, with inter-coil distances of 1 m, 2 m, and 4 m, and three in perpendicular configuration (PRP), with inter-coil distances of 1.1 m, 2.1 m, and 4.1 m. As a rule of thumb, HCP configurations sense the ground to a depth of around 1.5 times the inter-coil distance, while for PRP configurations this factor is 0.5. However, also the electrical conductivity of the subsurface is a determining factor of the actual penetration depth. For surveying, the sensor was fixed on a sled towed by a quad bike. The exact position of the quad bike was recorded using a Trimble differential GPS. The GPS and geophysical data were logged synchronously at respective frequencies of 1 Hz and 4 Hz.

FDEM data processing The recorded GPS data were translated into sensor position data according to the constraint method described in Delefortrie *et al.*[4] The sensor data were then converted into apparent electric conductivity (EC_a) data.[5] Subsequently, the surface data were inverted to obtain a distribution of true electrical conductivity, based on the forward formulations given by Ward and Hohmann.[6] A new FDEM-inversion approach was developed based on the application of an update step of the Ensemble Kalman Filter algorithm,[7] with a one-dimensional, multi-layer conductivity model. From the Bayesian standpoint, the algorithm starts with given prior estimations of electric conductivities in the form of Gaussian probability distributions. The electrical conductivity is constraint to positive values by using logarithmic prior distributions. To avoid abrupt conductivity variations, the conductivity value in a single layer was assigned a minimum correlation with the corresponding values in neighbouring layers. In the update step, measurement data are used to invert the profile or, in Bayesian terminology, to compute samples of the posterior distributions. The mean of the posterior distribution is taken as the final estimate for the inverted, true conductivity; the variance of the posterior distribution serves as a measure of the uncertainty on the estimated conductivity. Using the outlined one-dimensional approach all measurement locations were inverted independently.

GPR survey For the GPR survey, a dual-frequency, time-domain system was used, more specifically a Utility Scan DF impulse GPR, with 300 and 800 MHz as centre frequencies (Geophysical Survey Systems, Inc., Nashua, New Hampshire, USA). A transmitter antenna emits short electromagnetic pulses and, as contrasts in material properties are encountered during propagation into the subsurface, energy is reflected to the surface and recorded at a receiver antenna.[8] The reflections are recorded with their corresponding arrival time. A two-dimensional representation of multiple time series is called a radargram. The GPR survey was conducted along the same transect as the EMI survey.

GPR data processing In a first step, a correction for the so-called time zero, *i.e.* the travel time required for the radar pulse to enter the subsurface after leaving the antenna, was made. Secondly, the recorded travel times were transformed into depths using an estimation for the propagation velocity.[9] Afterwards, a background removal was applied to the GPR data to reduce background noise.[9] As a final step, the amplitudes of all arrival times were normalised by automatic gain control.[9]

Validation data After the surface measurements, a trench of approximately 1 metre depth was excavated along the survey area. A profile description was made based on visual observations. The profile (Figure 3a) showed various, though distinct, layers of different materials, of which seven main types were discriminated. The material occurring at the bottom of the trench (type 3) was identified as, presumably burnt, municipal solid waste. The origin of the above-lying sandy material (type 2) was unclear. Most likely, this waste had an industrial origin, but no further (standard waste material) characterisation was conducted. Three augerings were made in the bottom of the trench (near 2 m, 19 m and 31 m distance along the profile in Figure 3) which allowed to derive the thickness of the municipal solid waste layer and indicated the underlying natural material consisted in clay. Afterwards, additional profile measurements of electrical conductivity (EC_p) and relative dielectric permittivity (RDP) were made with a UGT UMP-1 handheld-sensor (Umwelt-Geräte-Technik GmbH, Muencheberg, Germany) at the locations indicated in Figure 3b and 3c. Since a measurement with the UGT UMP-1 requires penetration of electrodes, not all materials could be investigated.

Results and discussion

The inverted profile and the recorded apparent electric conductivities are shown in Figure 1. Negative values and distinct peaks in the EC_a-data are possibly caused by near-surface metal pieces. Such effects are clearly visible in the inversion result (*e.g.* at 16 m, Figure 1), but are neglected for the overall evaluation of the subsurface structure. For further descriptions of the results, the profile is considered as two separate parts. The part showing complex layering, from 0 m to approximately 10 m distance, and the homogenous part from 10 m to the end of profile, showing three distinct layers. From 0–10 m along the profile, a relatively high electrical conductivity was estimated for the top layers. Below 0.6 m, a layer of lower conductivity is seen, while the conductivity rises again for the bottom layer (approx. at 1.2 to 1.3 m depth). The conductivity at the pit bottom appears to be slightly higher on the homogeneous part of the profile. This observation is consistent with the shape of the EC_a-signal of the HCP2 coil configuration (Figure 1a). The layer of high conductivity at the bottom corresponds to the occurrence of the municipal waste (Figure 3a). The higher conductivity of this waste material was confirmed by the profile measurements of electrical conductivity, as shown in Figure 3b. According to the inversion results, in the homogenous part of the profile, roughly three layers can be discriminated, which agrees with the layering of material 1, 2 and 3 in the profile description (Figure 3a). Additionally, the EC_a signal for the 4 m HCP coil configuration (Figure 1a) suggests that the conductivity at a depth larger than the excavated trench is more homogeneous than at the exposed part. From 2–2.5 m depth downwards, natural clay was found which can be assumed to be more homogeneous.

The results of the GPR survey are shown in Figure 2. For the first 10 meters of the profile, the GPR signal shows strong attenuation as from 0.2–0.3 m depth, indicating the presence of relatively high conductive material. This is consistent with the electrical conductivity distribution estimated from the FDEM inversion. From 10 m onwards, a strong reflection can be observed at a depth of around 0.6 m, slightly inclined towards to the centre of the profile. This strong reflector seems to correspond with the layer boundary between the sandy material and the municipal waste (Figure 3a). A similar RDP contrast was shown by the profile measurements. The boundary between the top layer (type 1) and the sandy layer does not show in the GPR profile, likely because of the similar RDP of the materials.

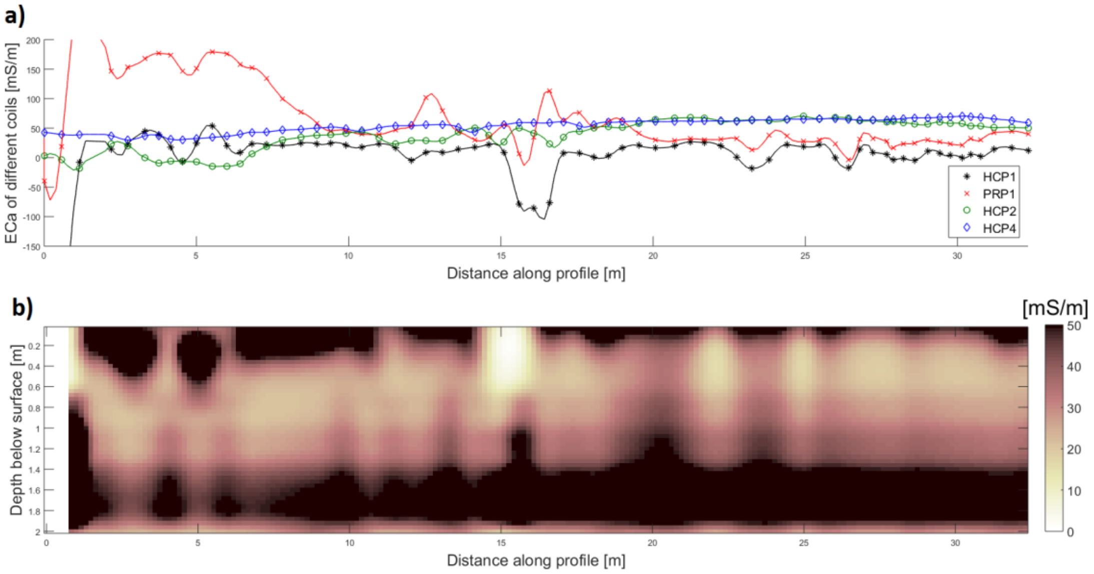

Figure 1: a) FDEM measurement data used for the inversion (PRP2 and PRP4 data neglected to reduce metal artefacts in the inversion results) b) Smoothed inversion results for the electric conductivity

The contrast observed in both RDP and electric conductivity between the sandy material and the municipal waste allows making a good estimation of depth of the waste material type (type 3). This illustrates that both FDEM and GPR can contribute to the characterisation of the spatial distribution of disposed waste materials. The more complex organisation of disposed materials in the first part of the profile could only partly be reconstructed as only the strong contrasts in material properties can be resolved from the surface measurements. The FDEM measurements, representative of relatively large subsurface volumes here appear to provide insufficient (vertical) resolution to discriminate the complex sequence of disposed materials. For GPR, the high-conductive material in the upper 50 cm prohibited to retrieve detailed information from RDP variations at larger depths.

The outlined approach, combining GPR and FDEM measurements with targeted processing, allowed a localisation of different material by relative electric properties and therefore, it is assumed that the approach presents a contribution to determine the ELFM potential of a site.

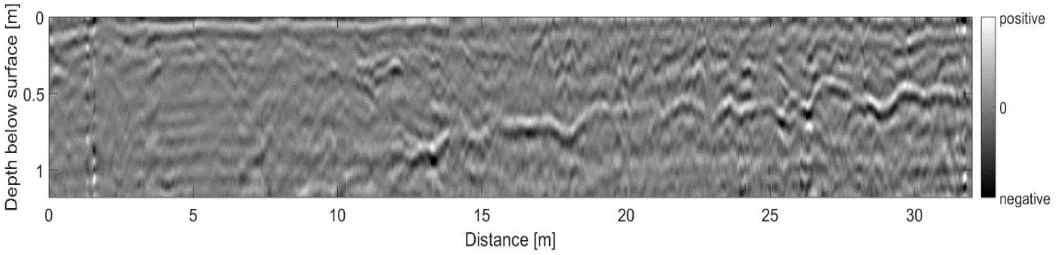

Figure 2: GPR data from the 300 MHz antenna after processing (data from 800 MHz antenna not shown here for brevity)

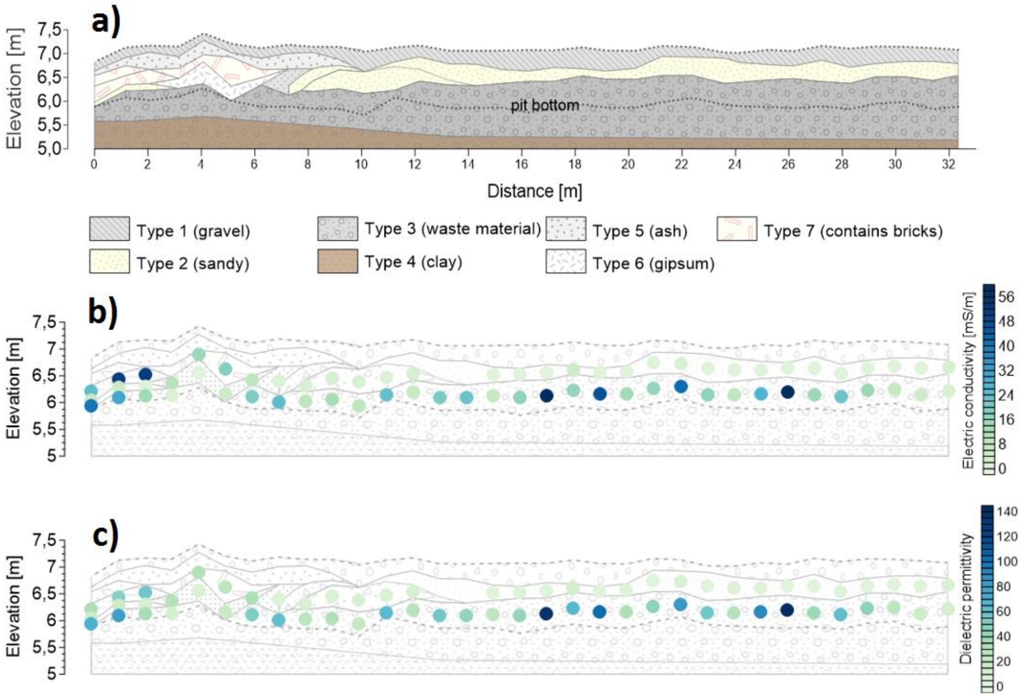

Figure 3: Schematic representation of the profile description made, indicating the main types of material discriminated (c), and profile measurements of electric conductivity EC_p (a) and RDP (b) made with a UGT UMP-1 BT soil moisture meter

Future steps

The EMI data were inverted using only a rough estimate of the subsurface electric conductivity as obtained from the profile measurements. Notwithstanding promising results were achieved using the profile measurements as calibration data, the collection of reliable calibration and validation data sets for FDEM inversion presents an important topic for future research, particularly considering the generally complex subsurface context of landfill sites. Furthermore, FDEM inversion could be optimised by including data of other subsurface properties, such as the magnetic susceptibility.

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