

Mapping of landfills using time-domain spectral induced polarization data: the Eskelund case study

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ABSTRACT

This study uses time-domain induced polarization data for the delineation and characterization of the former landfill site at Eskelund, Denmark. With optimized acquisition parameters combined with a new inversion algorithm, we use the full content of the decay curve and retrieve spectral information from time-domain IP data. Thirteen IP/DC profiles were collected in the area, supplemented by el-log drilling for accurate correlation between the geophysics and the lithology. The data were inverted using a laterally constrained 1D inversion considering the full decay curves to retrieve the four Cole-Cole parameters. For all profiles, the results reveal a highly chargeable unit that shows a very good agreement to the findings from 15 boreholes covering the area, where the extent of the waste deposits was measured. The thickness and depth of surface measurements were furthermore validated by el-log measurements giving *in situ* values, for which the Cole-Cole parameters were computed. The 3D shape of the waste body was pinpointed and well-defined. The inversion of the IP data also shows a strong correlation with the initial stage of the waste dump and its composition combining an aerial map with acquired results.

INTRODUCTION

Landfills are the primary choice for municipal solid waste disposal in many parts of the world (Morris and Barlaz 2011), as landfilling is seen as an easy and low-cost waste management option. Even though waste management policies have considerably evolved in the last decades (e.g., Butt *et al.* 2008) the reliance on landfills and the type of buried waste still vary from one country to another. During the process of waste degradation, landfills yield to waste products found in three phases: solid degraded waste, liquids from leachate and gas, usually referred to as landfill gas. Many landfills operational between 1950–1980 were designed without any kind of capture system underneath, leading to percolation through the waste and into the underlying geological layers and aquifer systems (Christensen *et al.* 1993; Kjeldsen *et al.* 1998a; Kjeldsen *et al.* 1998b; Christensen *et al.* 2001; Poulsen 2002). For large areas, it is very expensive to gain information on the landfill delineation using only drillings. Thus, having a fast, cheap and non-destructive mapping technique allowing coverage of the whole area of interest would be a huge benefit. Although the mapping of the waste body is a target itself (for instance for the recognition and delineation of buried and forgotten landfills), it is also very relevant to assess the cover layer and the layers below the waste, to assess and identify potential pollution threats. The goal of this work is to character-

ize the spatial boundaries of the former Eskelund landfill, Denmark, by a dense coverage in IP and DC resistivity.

Resistivity can be a relevant parameter for landfill delineation, since a significant contrast in resistivity occurs between the waste deposits and the cover layer (Aristodemou and Thomas-Betts 2000; Leroux *et al.* 2007; see also Clément *et al.* 2010; Clément *et al.* 2011 for commonly found values). However, the DC resistivity signal is strongly dependent on the pore fluid, which introduces large uncertainties in landfill delineation (Carlson *et al.* 2001). Sometimes, the resistivity of the waste can be altered by saturating fluids through some geochemical process and therefore a resistivity contrast can be observed between the waste and the surroundings. However, if the water table is located within the waste layer, the method can lead to some ambiguities.

Recently, new applications of induced polarization have emerged in environmental geophysics, including the detection and mapping of a contaminant, both at the field scale (Vanhala 1997; Kemna *et al.* 2004; Sogade *et al.* 2006; Flores-Oroszco *et al.* 2011; Flores-Oroszco *et al.* 2012) and at the laboratory scale (Vanhala 1992; Abdel Aal *et al.* 2006; Cassiani *et al.* 2009), or for the geological discrimination of clay contents (Schmutz *et al.* 2011; Gazoty *et al.* 2012). In the time domain, the induced polarization method has been successfully applied to landfill characterization, often displaying a chargeable unit related to the waste body (Carlson *et al.* 2001; Johansson *et al.* 2007; Leroux

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et al. 2010; Gazoty *et al.* 2012). The time-domain field operation is simple and robust when applying standard multi-channel acquisition systems. Furthermore, new approaches dealing with optimized acquisition parameters make it possible to get the full benefit of the technique and estimate the reliability of the data (Gazoty *et al.* 2012). The standard procedure for inverting time-domain IP data commonly involves the use of the integral chargeability only, which is very restrictive. Some inversion algorithms using the entire time decay have been proposed – Yuval and Oldenburg (1997) and Hönig and Tezkan (2007) presented 2D inversions of TDIP (time-domain induced polarization) data with synthetic and field data applications. Some other papers deal with extracting spectral content from time-domain IP data (Tong *et al.* 2006; Tarasov and Titov 2007; Titov *et al.* 2010); however, these approaches do not take into account the shape of the transmitter waveform and the receiver transfer function. In 2012, Fiandaca *et al.* presented a new algorithm for inverting TDIP data where they used the full decay curve for retrieving the spectral information of the data in terms of Cole-Cole parameters. In this inversion algorithm, the transmitter waveform, in terms of duration of current pulses and stack size is accurately modelled, as well as the effect of filters sometimes present in the instruments. Because of these improvements, one can take advantage of the TDIP method and use the spectral information as it is performed for SIP data.

METHODOLOGY

Basic principles of time-domain induced polarization

The IP signal is measured as a function of time or frequency. In the following we limit the discussion to time-domain IP data (one can refer to Keller and Frischknecht 1966; Sumner 1976 or Binley and Kemna 2005 for a more developed theory). TDIP consists in measuring a voltage decay resulting from an exciting current pulse. Figure 1 summarizes the basic principles of TDIP signal acquisition and all the following denotations refer to this figure. Immediately after the current is turned on, a potential, V_i ,

raises across the potential electrodes (Fig. 1a). After a charge-up effect, the primary voltage, V_{DC} , is measured for the computation of the direct current resistivity just before the current is turned off. When the current is turned off, the voltage drops to a secondary level, V_s and then decays with time during the relaxation period. This decay curve is characteristic of the medium (in terms of initial magnitude, slope and relaxation time) and represents the target of TDIP (see Fig. 1b).

Because of inductive coupling occurring after the current shut-off, a time gap or delay is applied before performing the measurements. The signal decay is usually integrated over n time windows or gates for the computation of chargeability M . The integral chargeability [mV/V] is defined as follows (Schön 1996; Slater and Lesmes 2002):

$$Ma_i = \frac{1}{V_{DC} [t_{i+1} - t_i]} \int_{t_i}^{t_{i+1}} V_{ip} dt \quad (1)$$

where V_{ip} is the intrinsic or secondary potential [mV] that can be seen as the transient response resulting from ground polarization after the current is shut-off. t_i and t_{i+1} are the open and close times(s) for the gate over which the signal is integrated.

There are different ways of defining the gate length. With log-gating, which is usually done for transient electromagnetic measurements, the secondary potential is integrated over time intervals whose length increases logarithmically with time (Effersø *et al.* 1999, Christiansen *et al.* 2006). This way of integrating the IP signal yields a significant increase of the signal-to-noise ratio by decreasing the standard deviation of the noise with time by a factor of the square root of the gate length (Munkholm and Auken 1996). If linearly distributed gates are used, the signal-to-noise ratio will decrease significantly for later times.

Inversion of surface TDIP

In this study we present some results obtained by using a new implementation of the 1D-LCI (laterally constrained inversion) algorithm for TDIP data (Fiandaca *et al.* 2012). With this new

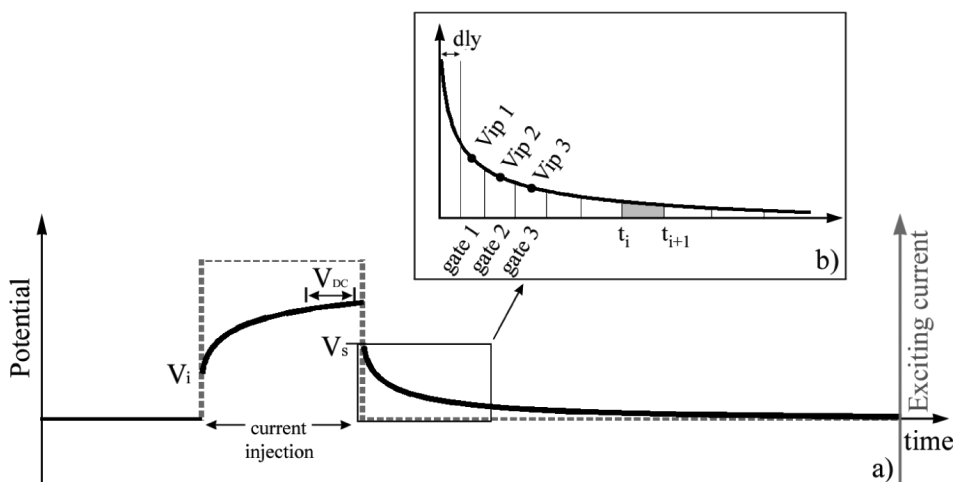


FIGURE 1

Basic principles of time-domain IP acquisition. The length of the measuring gates increases logarithmically with time following a log-gating sampling. M_a defined in equation (1) is the area under the decay curve between t_i and t_{i+1} , normalized by V_{DC} and $(t_{i+1} - t_i)$.

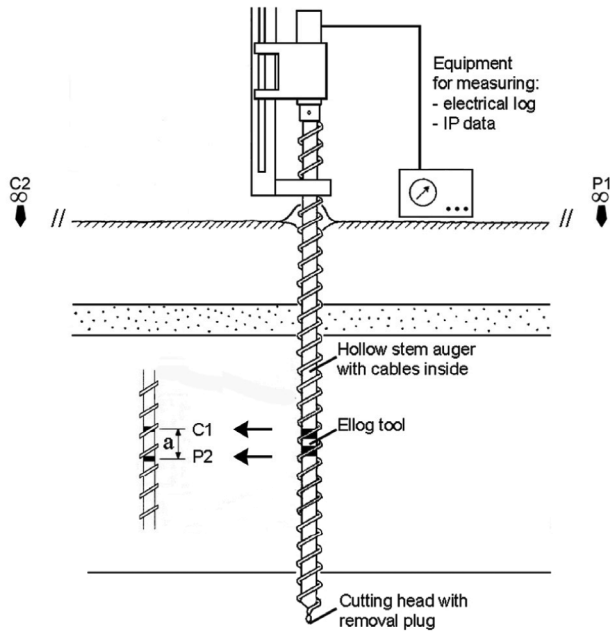


FIGURE 2

The el-log instrument for the measurement of *in situ* IP-DC data. P are the potential electrodes, while C are the current electrodes. The distance a is equal to 20 cm. Modified from Sørensen and Larsen (1999).

code, the time-domain forward response is computed for a layered medium via a Hankel transform of the frequency-dependent Cole-Cole impedance (Pelton *et al.* 1978). The inversion part is carried out with the 1D-LCI implementation (Auken *et al.* 2005) to retrieve the four Cole-Cole parameters (resistivity, c , τ and M_0), for each layer, with the stopping criterion being the relative change in the objective function below 0.7%. This new code uses the full IP decay curve to assess the spectral content of the IP phenomenon, allowing for a detailed description of the sub-soil. Furthermore, it implements full-waveform modelling by taking into account the number of stacks used during the measurement procedure as well as the pulse duration for the charge-up effect. If the waveform modelling is ignored the final M_0 magnitude is strongly underestimated (up to several hundred per cent, see Fiandaca *et al.* 2012). The inversion procedure is complemented by a full uncertainty analysis of the model parameters supporting quantitative evaluation of the inversion result in terms of determination. The analysis is computed by taking the square root of the diagonal elements of the covariance matrix, C_{est} , of the last iteration of the linearized inverse problem, following Tarantola and Valette (1982). Because the model parameters are represented as logarithms, the analysis gives a standard deviation factor (STDF) for the i th parameter m_i defined as follows (see Auker *et al.* 2005):

$$STDF(m_i) = \exp(\sqrt{C_{est(i,i)}}) \quad (2)$$

In other words, under log-normal assumption, it is 68% likely that the i th model parameter m_i falls in the interval:

$$\frac{m_i}{STDF(m_i)} < m_i < m_i \cdot STDF(m_i) \quad (3)$$

Low values in the analysis indicate better parameter determination. Due to the large number of constraints on the model we will, in this case, only use the numbers relatively. The computation of the uncertainty analysis enhances the reliability of the models and avoids some over-interpretation or misleading of the different features present in the inverted sections.

Measurement of undisturbed resistivity and IP formation using the el-log method

The el-log (Sørensen and Larsen 1999) is a high-resolution electrical logging technique (Fig. 2), allowing detailed mapping of the formation resistivity similar to what can be obtained from cone penetration tests. With the el-log design, the apparent formation resistivity and chargeability are measured by means of electrodes that are integrated with the hollow-stem flight auger. The measuring electrodes are embedded in insulating material with connections to the measuring instrument on the ground through cables inside the drill stem. The el-log ensures a very accurate lithological delineation and provides a unique correlation between the borehole information and the geophysical measurements. It enables the assignment of *in situ* values of resistivity and chargeability to the geological layers and can be used in environmental studies for the identification and characterization of the waste layer. A description of the specific acquisition parameters used for this study is provided further in the manuscript.

Inversion of el-log data and forward computation of the IP response

As mentioned above, the el-log measurements allowed the collection of *in situ* chargeabilities $M(t)$. In order to retrieve the same model space as surface measurements, the IP data were inverted for the computation of the Cole-Cole parameters for each decay and thus allowing direct comparison with the ground-based data inverted by the 1D-LCI code. Because the electrode spacing was small compared to the expected lithological variations (20 cm against tens of metres), in this study the el-log forward response is expressed in terms of a full-space solution. Pelton *et al.* (1978) showed that the time-domain intrinsic chargeability curves for a full space solution in terms of Cole-Cole parameters can be described by

$$M(t) = M_0 \sum_{n=0}^{\infty} \frac{(-1)^n \left(\frac{t}{\tau}\right)^{nc}}{\Gamma(1+nc)} \quad (4)$$

where τ [s], c [dimensionless] and M_0 [mV/V] are the Cole-Cole decay parameters, M_0 being the magnitude of the chargeability taken at $t = t_0$, first time point of the transient decay curve after the time delay, τ a time constant that characterizes the decay and c a constant that controls the frequency dependence and is

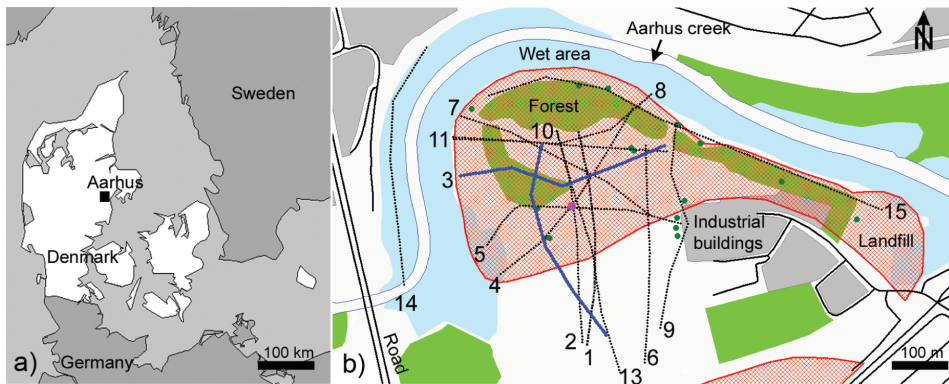


FIGURE 3

The survey area. a) Location of Aarhus at the east coast of Denmark. b) IP/DC measurements performed in the Eskelund landfill (red hatched area), ranging from 355–700 m. The pink dot shows the el-log drilling location and the green dots are the boreholes. The blue sections are further shown in Figs 7 and 8.

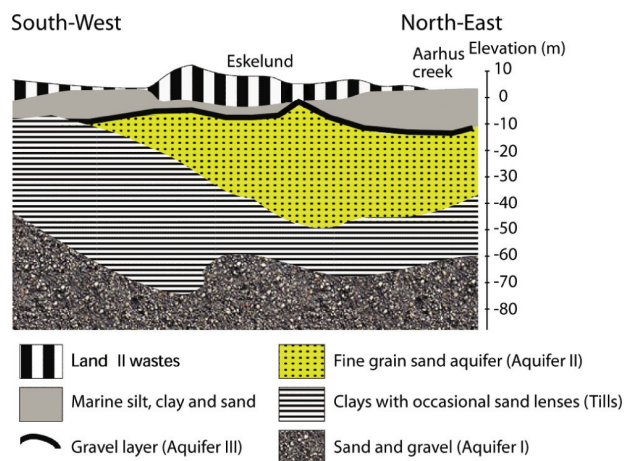


FIGURE 4
Conceptual cross-section showing the geology of the area.

bounded between the values of 0–1; Γ is the Gamma function. In terms of physical properties, M_0 describes the polarization magnitude and τ the relaxation time. Luo and Zhang (1998) and Pelton *et al.* (1978) showed that M_0 and τ depend on the quantity of polarizable elements and their size, respectively, whereas c depends on the size distribution of the polarizable elements (Vanhala 1997; Luo and Zhang 1998).

For $t/\tau < 10$, the formula for a homogeneous full-space described in equation (4) can be used for the forward problem computation. However, because of the slow convergence of expression (4) when $t/\tau > 10$, Ghorbani *et al.* (2007) suggested the use of the expression given by Guptasarma (1982) instead:

$$M(t) = M_0 \sum_{n=1}^{\infty} \frac{(-1)^{n+1} \left(\frac{t}{\tau}\right)^{-nc}}{\Gamma(1-nc)} \quad (5)$$

In this study, the forward response is computed over a full decay including both expressions (4) and (5) in the algorithm, by evaluating the ratio t/τ for each time gate and by defining $M(t)$ accordingly.

The IP data set is inverted using a Gauss-Newton algorithm, with vertical roughness constraints on the Cole-Cole parameters and adaptive damping similar to the implementation of Auken

and Christiansen (2004). Also, full waveform modelling was implemented following Fiandaca *et al.* (2012) allowing a consistent and reliable comparison with ground-based data.

THE ESKELUND FIELD CASE

The present study aims at characterizing the spatial boundaries of the former Eskelund landfill. This dump site was active from 1950–1980 and is located in the vicinity of Aarhus, Denmark (Fig. 3a). It belongs to a complex of four landfills, covering an area of approximately 150 000 m². The site was established in the meadows adjacent to Aarhus River, which was moved several times to the north allowing more space for the deposits. The landfill has been uncontrolled and was established without any kind of membranes, leachate capture or isolation systems. The waste mainly consists in domestic waste but also industrial waste including oils and chemical waste. Its composition can be very different from one place to another within the landfill, as deposits were first stored according to their content and burnt afterwards at some places. Because of the overburden of the waste, the landfill partially collapsed, causing a flat area currently below sea level.

Numerous geochemical surveys and underground water samples show contamination resulting from water seepage through the landfill. The contamination levels vary depending on the location, probably because of differences in the waste content. The substratum of the waste mainly consists of mud and silt, which provides only slight protection from the leachate (Fig. 4).

A dense coverage of DC/TDIP sections together with the fast and robust interpretation technique as described above, allows a detailed delineation of the waste body and the investigation of the waste signature content in terms of Cole-Cole parameters. It gives evidence of, for the very first time at the site, the 3D volume of the in-fill materials and we gain knowledge about the overall geological setting. By performing a correlation between ground-based measurements and *in situ* IP/DC measurements from an el-log, we aim at improving the spatial characterization of the waste body by producing 3D maps of the inversion parameters and by comparing the results to a large number of existing drillings.

The survey

The area was investigated with the collection of 13 IP/DC profiles ranging from 355–700 m (Fig. 3b), all with stainless steel electrodes 5 m spaced and 1410–2550 quadrupoles, respectively. The survey was performed using the gradient array (Dahlin and Zhou 2006) because of its efficiency on a multi-channel acquisition system and because it minimizes the effect of electrode polarization (Dahlin *et al.* 2002). The maximum distance set between the current electrodes was 320 m. The gradient array protocol was implemented on a Syscal-Pro instrument (Iris Instruments) for the measurement of 10 simultaneous channels. The on- and off-time lengths for the time decay measurements were set to 4 s (also called 50% duty cycle) and the data were acquired using logarithmic spaced gates with approximately eight gates per decade from 20 ms to 4 s, with a total of 20 gates.

The survey was completed by *in situ* resistivity and TDIP measurements with the el-log instrument. The TDIP measurement sequence was set up in a pole-pole configuration with a 4 s-on/4 s-off square wave and log-gated windows sampling the decay. Note that the el-log design enables to get around the issue of electrode polarization because the potential electrodes

are never used for current injection. The IP data were collected every half metre by stopping the rotation of the stem and directly connecting the Syscal-Pro instrument. Total drill depth was 24 metres.

The data quality was globally very high (see examples in Fig. 5). The number of stacks for both the IP and DC measurements was set-up to be in a range of 3–6 with a threshold for the standard deviation fixed at 5 mV/V in chargeability. However, for the *in situ* measurements, the number of stacks required was not above 3–4.

Surface DC/IP

Careful attention was paid to the data quality: the full data set was imported into the Aarhus Workbench (Auken *et al.* 2009), where it is possible to display and process both raw DC and IP data in connection to a GIS. For the DC data, it is possible to reject the outliers visualized in a regular pseudo-section (Fig. 6a) and the corresponding IP data are automatically removed (Fig. 6b). For the IP data, it is possible to plot any time-decay curve, as well as the pseudo-sections for each gate. In this way, outliers were manually removed, as well as negative data and aberrant curves. Figure 6(c,d) shows typical decay curves. For

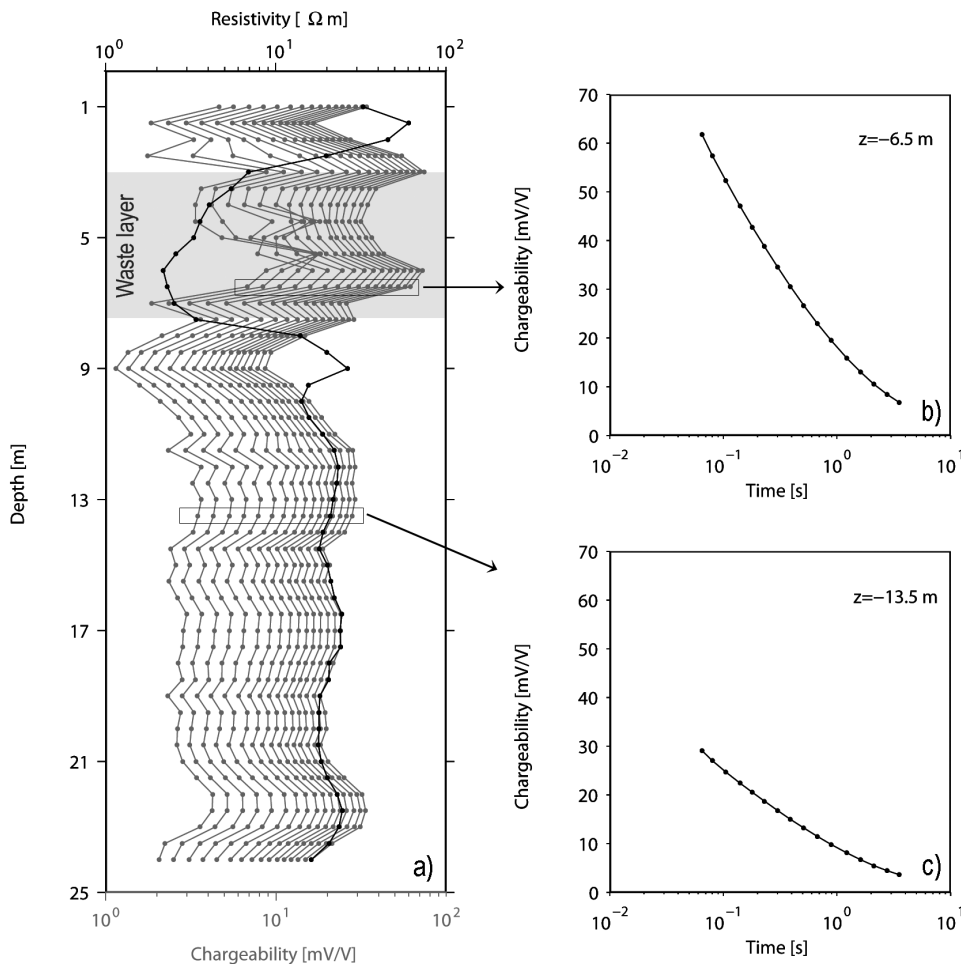


FIGURE 5

Data obtained with el-log drilling (refer to Fig. 3b for the location). a) Resistivity (black curves) and IP (grey curves) data. Each grey curve corresponds to a gate for the measurement of time-domain IP. b) and c) Examples of high-quality decay curves obtained from the el-log.

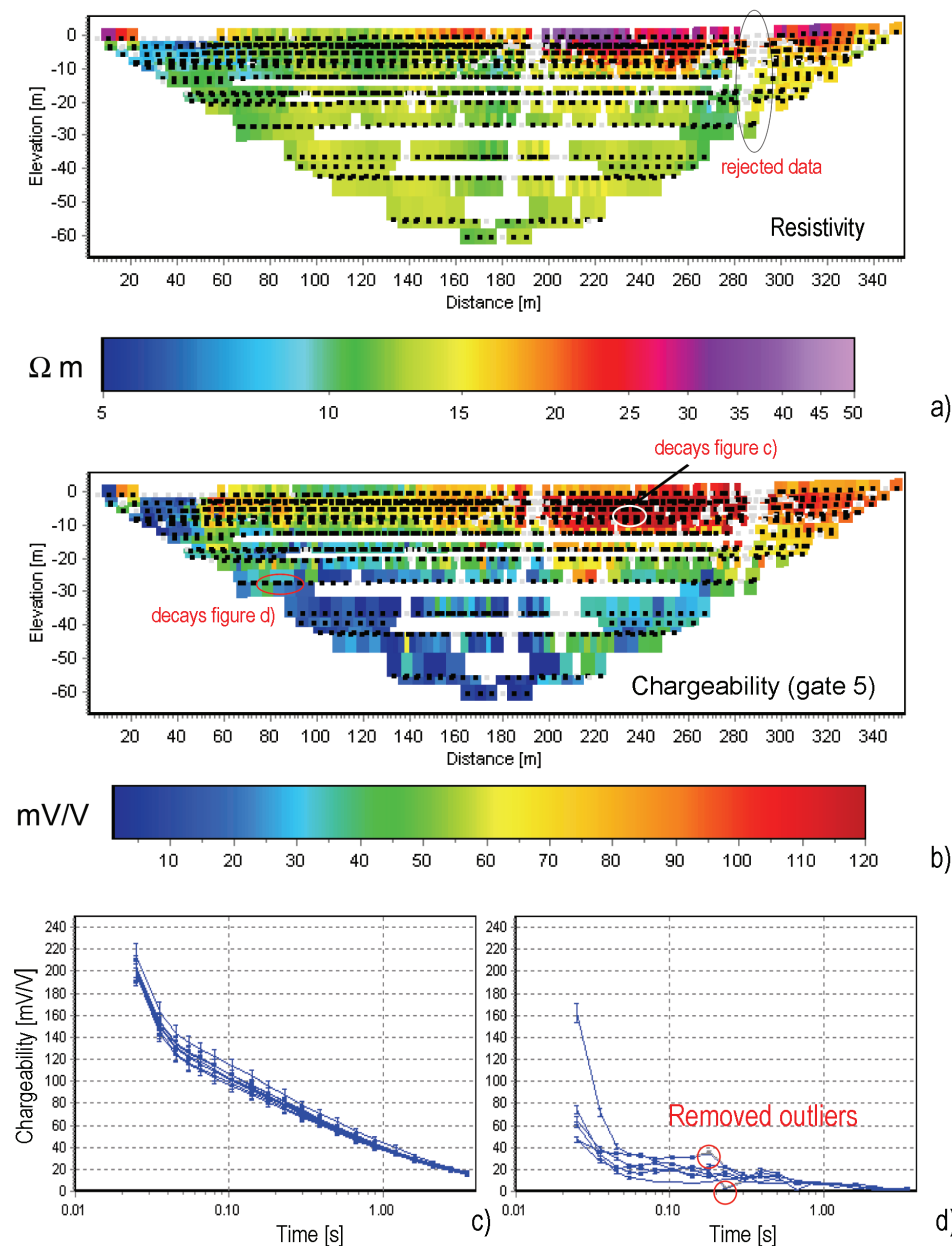


FIGURE 6

Example of data processing. a) Resistivity pseudo-section. b) Chargeability pseudo-section displaying time-domain values for gate 5. c) and d) Examples of decay curves obtained at the site, with removed outliers.

profile 3, for instance, 88% of the DC data were kept, whereas 87% of data over the 20 gates were kept for the IP data.

The inversion results for two perpendicular sections are presented in Fig. 7 and Fig. 8. Profile number 10 (Fig. 7) displays a clear discontinuity in IP and DC at the south boundary of the landfill, with a resistive body and a low-chargeable unit outside the area. Within the landfill, the inverted section clearly shows a chargeable unit of a few hundreds of mV/V, in agreement with the waste layer identified in the boreholes, matching both the thickness and the depth. It is important to note that at some places, the waste layer is saturated and hence displays a signature in both IP and DC, e.g., at the northern part of profile 10, around borehole B1.

However, the DC section cannot be used to identify the waste layer that is clear from the lateral variations seen in profile 10. Contrary, the IP section displays a systematic signature in IP throughout the waste layer. This example demonstrates the complementarity of IP and DC resistivity, as the joint application of both allows the shape of the waste body to be delineated with high accuracy and reliability. In this example, the lateral thickness variations of the waste body can also be retrieved all along the section, which is verified by the three boreholes.

The different sections in Fig. 8 show all the parameters delivered by the 1D-LCI inversion. As shown in Fig. 7, the waste layer is characterized by a high- M_0 signal in the range

of 200 mV/V, depending on the location in the section. Again, there is a good agreement between this layer and the waste layer displayed by the two boreholes on the edges. The uncertainty analysis performed for all parameters is displayed in Fig. 8(a2-d2). Despite for the resistivity values, which have a higher sensitivity at depth than the three other Cole-Cole parameters, it is very clear that the shallow part containing the landfill is very well determined (down to -10 m in elevation) and the features observed in the inverted sections are reliable. Below the landfill however, the uncertainty increases significantly and the values observed in the c , τ and M_0 sections match the starting models. Despite this, Fig. 8 shows the relevance of the parameter M_0 in comparison with c and τ for the landfill characterization. These two parameters can be linked

to some well-known physical properties of the rock matrix and their inversion shows a very good match between the different sections all over the landfill. However, in our survey it turns out that their values and signatures are more complex to interpret and do not provide systematic evidence of the waste body as does the parameter M_0 . In the following part we choose to display only M_0 .

Figure 9 compiles the results from M_0 for all sections containing boreholes. Some lateral discontinuities appear along several transects (e.g., profiles 5, 7, 9 and 13), which were identified as 2D artefacts due to the 1D LCI. However, the presence of the waste and its thickness is identified by all the induced polarization sections and matches the borehole information almost perfectly wherever present.

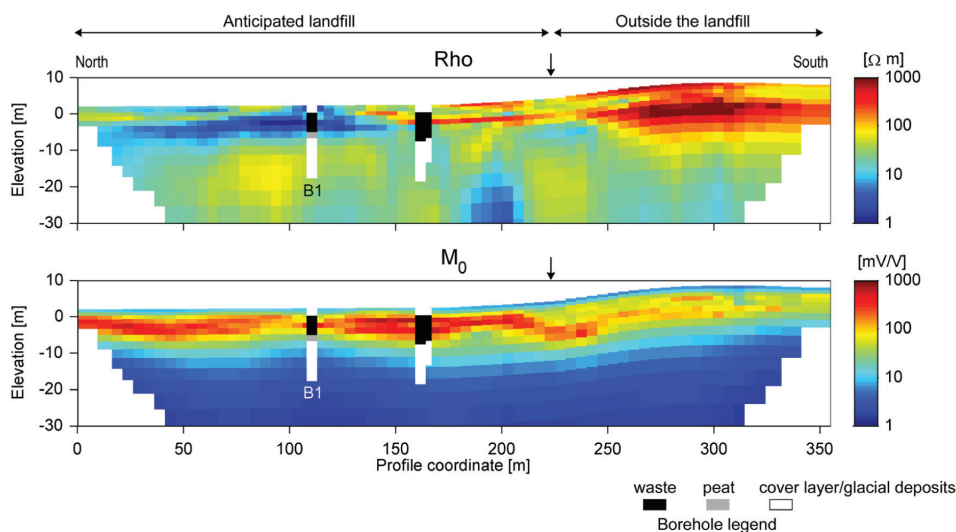


FIGURE 7

Results from a 1D laterally constrained inversion for profile 10 (highlighted on the map in Fig. 3) with superimposed boreholes. Top: resistivity section. Bottom: chargeability section M_0 .

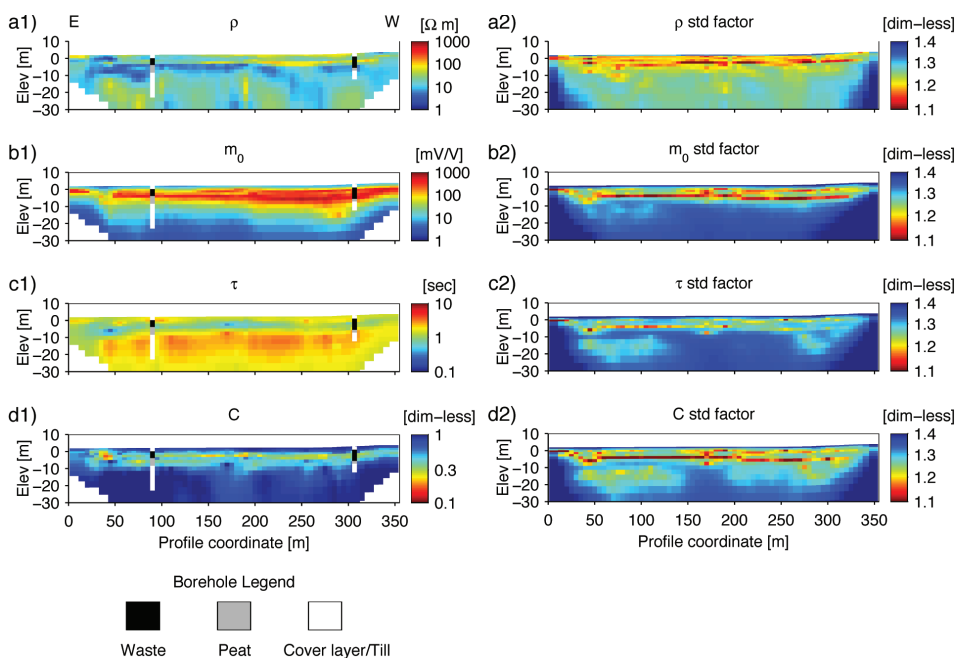


FIGURE 8

Results from a 1D laterally constrained inversion for profile 3 (highlighted on the map in Fig. 3) with superimposed boreholes. a) Resistivity with corresponding uncertainty analysis. b) M_0 with corresponding uncertainty analysis. c) τ with corresponding uncertainty analysis. d) c with corresponding uncertainty analysis.

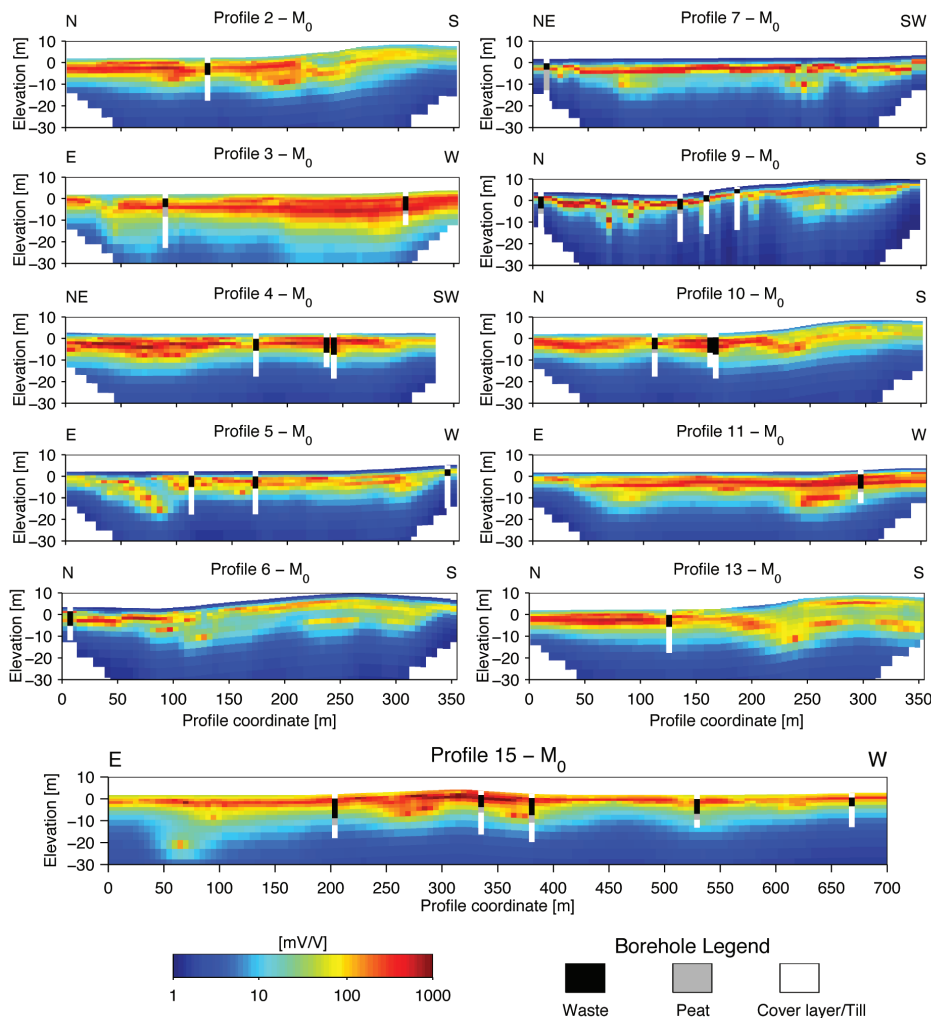


FIGURE 9

Inversion results of chargeability, M_0 , for all sections containing boreholes. Note the agreement between the waste and the chargeable unit in all sections.

***In situ* measurements and comparison with surface inversion**

The five first gates from the *in situ* measurements (until 70 ms) were removed for the IP data because they are affected by a 10 Hz low-pass filter in the Syscal-Pro Instrument and the filter characteristic has not been implemented yet in the el-log inversion scheme. Only a few outliers were rejected and 94% of the collected data were used for the inversion. The acquired data in Fig. 5 show a distinct chargeable layer corresponding to the expected waste location, between 2.5–8 m depth. This chargeable unit is clearly anti-correlated to a low-resistive body, whose resistivity decreases to $1 \Omega \text{ m}$. Even though this decrease in resistivity is rather homogeneous within the waste layer, the chargeability plot reveals more details with two distinct peaks of 80 mV/V in apparent chargeability at 3 m and 6 m depth, respectively. It is difficult at this stage to determine whether the differences in IP reflect differences in the waste content, or other variations within the waste layer. Drill samples characterized the layer above the waste (between 1–2.5 m depth) as a clay rich cover layer and the layer below (between 8–24 m depth) as a mixed clay-sand layer.

The el-log data were inverted as described in the methodology section. M_0 and resistivity parameters are shown in Figs 10 and 11, respectively. In order to validate the results from the surface measurements, we extracted 1D models from the inverted surface sections crossing the el-log position. We then compared the results from the inversions of the two data sets, both for M_0 and resistivity (Fig. 10 and Fig. 11). From all soundings, a highly chargeable unit close to 250 mV/V coinciding with the waste layer can be retrieved. Profiles 2, 4 and 13 even display the two peaks in M_0 with a depth identified with the el-log, at 3 and 6 m. Profile 5 only identifies the second highly chargeable unit at 6 m depth. However, this section contains the lowest data quality of the survey, with quite high noise levels. Overall, the information provided by the two methods is in very good agreement and the results within the waste layer from the surface measurements are validated by the el-log, both in terms of depth and magnitude. Beyond 8 m depth, the results do not coincide, which is explained by the decreasing determination of the surface measurements with depth (see Fig. 8a2-d2), causing the inversion result to return slowly to the starting model. This means that the

el-log results are more reliable at depth. The resistivity results shown in Fig. 11 enhance the conductive structure of the waste body. The el-log measurements reveal a rather homogeneous conductive layer (5 m thick), whereas the surface measurements suggest a slightly higher resistivity at 4 m depth. The most conductive part at 6 m of a few Ω m is however retrieved and reached by the surface measurements and below 8 m depth the results are also in good agreement suggesting a higher depth of investigation for resistivity than for M_0 .

The comparison of parameters c and τ shows a good correlation between el-log and surface inversion models as well: the el-log validates the results from the surface measurements and confirms the magnitudes of parameters obtained by the two methods.

Spatial characterization of the landfill

When checking the reliability of the results, it was shown that the IP surface measurements allowed defining the waste body with a high accuracy, in terms of magnitude (after comparison with the el-log), depths and thicknesses (after comparison with the el-log and all the boreholes). The results from all 2D sections were merged to provide an estimate of the 3D body and to check inter-profile consistency (Fig. 12).

The depths and thicknesses of the chargeable units agree very well between all the sections. Furthermore, it seems that the M_0 value varies 2–3 times within the waste layer. To interpret this, the relevant M_0 isosurface was computed and superimposed on an aerial picture from 1966. Figure 13 shows the contemporary landfill delineation in green, which was defined according to observations from aerial pictures and information taken from reports and communications. It appears that the highest signal in M_0 (above 350 mV/V) occurs in the north-eastern part of the area, coinciding with the oldest waste, dumped in 1966. This waste is known to be mostly sludge from water treatment as well as waste from a gas work, with cyanide containing coal residuals.

The second M_0 hot-spot located to the south (cf. black star on Fig. 13) does not coincide with the first temporal stage of the landfill, as it stands clearly outside the boundaries defined by the green contour. However, this location fits with a current deposit of iron coming from metal-springs and railway tracks. In addition, if we analyse the distribution of the parameter τ on the map, we observe a spatial consistency of high values of M_0 , present in the northern-east part of the area, as well as precisely on top of the current metal dump.

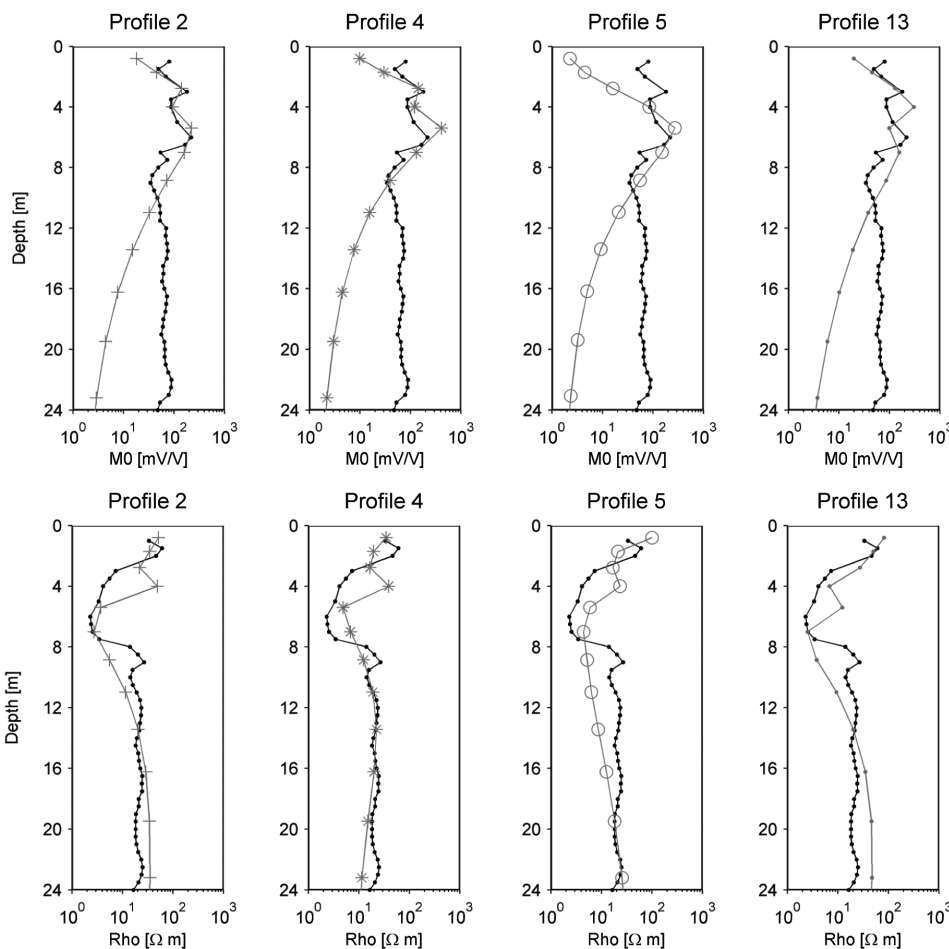


FIGURE 10

Inverted IP data from the el-log (black) in comparison with 1D LCI for several models extracted from the inverted surface measurements crossing the el-log (grey).

FIGURE 11

Inverted DC data from the el-log (black) in comparison with 1D LCI for several models extracted from the surface measurements crossing the el-log (grey).

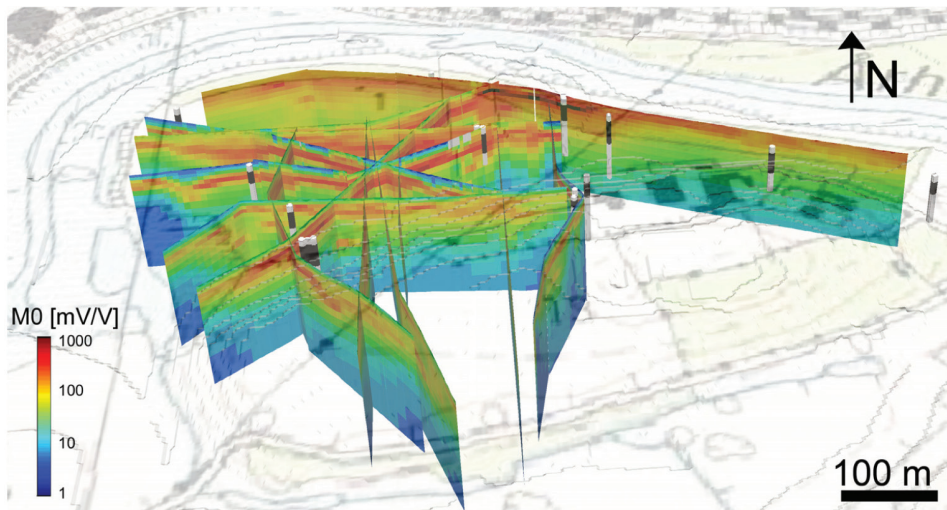


FIGURE 12
3D characterization of the landfill area: gathered 2D sections in chargeability with boreholes.

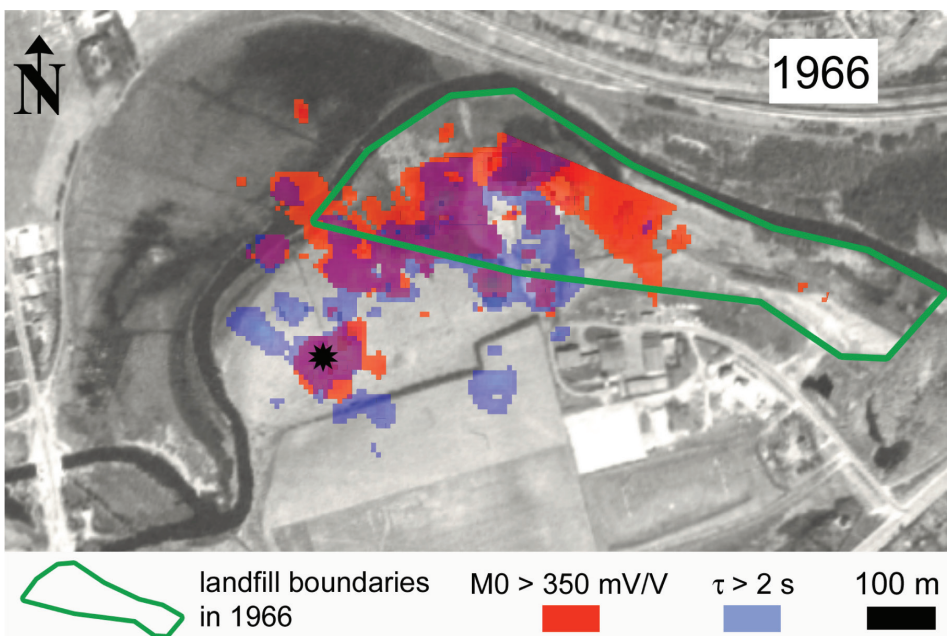


FIGURE 13
Aerial picture from Eskelund taken in 1966 (<http://geomidt.flyfotoarkivet.dk>) with superimposed isosurfaces of chargeability M_0 above 350 mV/V and parameter τ above 2 s.

DISCUSSION

The present study mainly focused on results of the M_0 parameter, because a straightforward correlation between the waste content, identified with surface and *in situ* measurements, as well as borehole information was possible. Indeed, M_0 indicates how polarizable the medium is and whether there is a signature in chargeability or not. In our case, the inverted sections showed a high chargeability M_0 , in the range of several hundreds of mV/V, fitting the expected dump site location, as validated by borehole comparison. The high M_0 magnitude is likely related to the metallic content of common refuse, disseminated as small and discontinuous particles (Weller *et al.* 2000).

The 1D-LCI code was able to restore the waste layer at the right location, even when quite strong lateral variations were present, which is a very promising result. The quality of the inverted sec-

tions presented in this paper could also be attested by the very good match between the surface and *in situ* measurements, as the retrieved Cole-Cole parameters were in the same range of magnitude with the two methods. Moreover, there was a perfect agreement between all information provided by the 2D sections wherever they crossed each other, even though each single section was inverted individually, i.e., without any spatial constraints.

Regarding τ and c , it is known from literature that they are relevant parameters for providing significant information at the pore scale, as they can be linked with some hydrogeological parameters as hydraulic conductivity. In the present case, some background modellings identified a water divide between the abstraction wells and the landfill. Groundwater seems to flow towards the east and then to surface water at a creek located further west. Regarding the hydraulic conductivity, it is known

that due to the complex geology of glacial till, sand, postglacial sand, silt and peat, the hydraulic conductivity varies significantly, both horizontally and vertically. It was then very difficult to interpret τ and c parameters in terms of hydraulic conductivity or with a petrophysical explanation and such a step would constitute a full study by itself. In this study, we chose to focus on landfill delineation and characterization.

When analysing carefully the spatial distribution of the M_0 parameter (Fig. 13), we found that high values of M_0 were present at some specific locations. The first high-chargeable area fits the eldest part of the waste, containing sludge and coal. This observation concurs with Leroux *et al.* (2010) who reported a significant difference in the IP signal according to the different types of waste and the organic content in particular. The second high-chargeable area, more in the south-west direction, on top of metal spring deposits, also fits a high value of τ (above 2 s). This observation is in agreement with Seigel *et al.* (1997) who described a high chargeability, in the range of several hundreds of mV/V, in mineral exploration and used τ for discriminating above different mineral deposit assemblages; for massive pyritic sulphides and cultural sources like fences and grounded power lines, they reported τ values in a range of 1–10 and above, which is very consistent with the values shown in this study. Therefore, as a major outcome in the use of TDIP, it seems that we cannot only delineate the waste body itself but possibly also distinguish between different types of waste within the waste layer. We can track some spatial advancement in time of the landfill and delineate the final boundaries with a high accuracy.

CONCLUSION

The effectiveness of IP in the mapping of landfill areas is a good alternative to the implementation of drillings, in terms of time and costs. The Eskelund study clearly evidences the complementarity of IP and DC resistivity, as the joint application of both allows pointing out the shape of the waste body with a high accuracy and in perfect agreement with borehole information. With the el-log, it was possible to make a very accurate correlation between the geology and the geophysics and to allocate a peak M_0 value to the waste layer in the range of 250 mV/V, whereas higher values are also retrieved from the inversion of surface data. The inversion of the IP data and the analysis of the spatial distribution of different Cole-Cole parameters also show that it was possible to identify patterns that coincide with the first temporal stage of the landfill and discriminate among metal deposits from the rest of the waste. This is a very promising result in the application of the 1D-LCI inversion code and this study shows the entire benefit of applying the combined DC/IP with boreholes and el-log.

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