Gravimetric water distribution assessment from geoelectrical methods (ERT and EMI) in municipal solid waste landfill

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ABSTRACT

The gravimetric water content of the waste material is a key parameter in waste biodegradation. Previous studies suggest a correlation between changes in water content and modification of electrical resistivity. This study, based on field work in Mont-Saint-Guibert landfill (Belgium), aimed, on one hand, at characterizing the relationship between gravimetric water content and electrical resistivity and on the other hand, at assessing geoelectrical methods as tools to characterize the gravimetric water distribution in a landfill. Using excavated waste samples obtained after drilling, we investigated the influences of the temperature, the liquid phase conductivity, the compaction and the water content on the electrical resistivity. Our results demonstrate that Archie's law and Campbell's law accurately describe these relationships in municipal solid waste (MSW). Next, we conducted a geophysical survey *in situ* using two techniques: borehole electromagnetics (EM) and electrical resistivity tomography (ERT). First, in order to validate the use of EM, EM values obtained *in situ* were compared to electrical resistivity of excavated waste samples from corresponding depths. The petrophysical laws were used to account for the change of environmental parameters (temperature and compaction). A rather good correlation was obtained between direct measurement on waste samples and borehole electromagnetic data. Second, ERT and EM were used to acquire a spatial distribution of the electrical resistivity. Then, using the petrophysical laws, this information was used to estimate the water content distribution. In summary, our results demonstrate that geoelectrical methods represent a pertinent approach to characterize spatial distribution of water content in municipal landfills when properly interpreted using ground truth data. These methods might therefore prove to be valuable tools in waste biodegradation optimization projects.

KEYWORDS

Electrical resistivity tomography; moisture content; leachate; municipal solid waste; bioreactor landfill; borehole electromagnetic

1. Introduction

In Wallonia (Belgium), about 2500 landfills are present. Dozens of them are recognized as polluted and hundreds of them potentially polluted (SPAQuE, 2003). Although there is no accurate landfill counting in all the European countries, it has been estimates that 960000 landfills exists on the entire continent (27 of the 39 countries collaborating with the European Environmental Agency (van Liedekerke et al., 2014)). These numerous waste disposal sites represents a threat for the environment and public health (air and groundwater pollution), covers valuable lands and brings high exploitation and long duration post-exploitation cost.

Among the possible ways to deal with the waste issue, the concept of landfilling bioreactors has risen in the last several years. These are new landfills designed and equipped to enable the monitoring and manipulation of the humidity and oxygen content in the waste mass. In a landfill bioreactor, the biodegradation of the organic waste is accelerated, which increases the production of landfill gas and shortens the exploitation time. Moreover, biodegradation is more complete, which decreases potential long-term pollution risks and therefore costs of post-exploitation monitoring. Finally, the constant recirculation of leachate (which accumulates in the lower part of the landfill and is reinjected in the upper part) reduces the costs of leachate treatment and evacuation (Audebert, 2015; Reinhart and Townsend, 1997).

An alternative approach is to equip existing municipal landfills in order to monitor the bioreactor-like activities of the landfills. In Belgium, the MINERVE project, aims at transforming existing Belgian municipal landfills into bioreactors so as to optimize the landfill biogas production. An additional objective of the project is to study the landfill mining opportunity of the studied site

Water content is a limiting factor regarding the two objectives. Firstly, the bioreactor-like function of a landfill highly depends on the waste water content, which affects both the completeness and the kinetics of organic waste biodegradation (Benbelkacem et al., 2010; Šan and Onay, 2001). Secondly, the humidity of the material influences the profitability of landfill mining operations. Indeed, the moisture content affects the material separation efficiency (Ford et al., 2013). Any form of material and energy recovery requires mechanical treatment (such as shredding, trommel screen or metal extraction), the efficiency of which is limited by the water content, and may therefore also require an expensive drying process (Fisher, 2013).

In this context, the moisture content of MSW landfills needs to be determined. Drilling followed by waste sample analysis or punctual probes are the most direct ways to measure water content. However, these techniques have proven itself very expensive and only provides punctual information lacking spatial representativeness (Grellier et al., 2006a). Therefore, the interest in indirect geophysical method development to determine water content has grown in the past few years (Imhoff et al., 2007) and has been extensively studied in landfill bioreactors. Among the possible geophysical ways to indirectly assess the moisture content of the waste mass, measuring the electrical resistivity properties of waste has raised as a promising strategy (Grellier, 2005; Grellier et al., 2007, 2006b; Guérin et al., 2004; Imhoff et al., 2007). A possible technique to achieve this is Electrical resistivity tomography (ERT) which provides large scale distribution values of the electrical resistivity of the waste material (Bernstone et al., 2000; Chambers et al., 2006, 2004). Most of the time, time-lapse ERT is used to monitor changes in electrical resistivity linked to leachate content variation during recirculation events or infiltration during rainfall events (Audebert et al., 2014; Clément et al., 2011b, 2010; Grellier et al., 2008, 2006a; Guérin et al., 2004; Morris et al., 2003). However, geophysical methods are not often used to directly measure water content (Grellier et al., 2007).

In our study, we aimed at validating the electrical resistivity measurements as an indicator of water content. Using direct measurements on excavated waste samples, we tried to understand the influence of environmental factors such as temperature, compaction, leachate electrical conductivity (resistivity) and leachate content parameters on electrical resistivity in order to establish a method to correlate the electrical resistivity property of the waste with the moisture content. Once a direct correlation between the electrical resistivity and the water content was established, we tested two electrical geophysical methods to obtain spatially distributed information: the well-established electrical resistivity tomography and, for the first time, borehole electromagnetics. These geophysical techniques both appear as a reliable indirect and cost-effective means to determine the waste water content.

2. Site description and field testing

All field tests are performed on one of the largest engineered landfill of Belgium, located in a former sand quarry in Mont-Saint-Guibert (Figure 1). The 26 ha wide and up to 60 m deep (5,3 million m³ of waste) site is under activity since 1958. Around 3 million tons of waste were landfilled prior to the installation of a bottom high density polyethylene (HDPE) liner in the early 90s. Thereafter, the class 2 technical landfill exploitation license was renewed and 8 million tons were disposed. These are composed of municipal solid waste, non-hazardous and non-toxic industrial waste and bulky waste were disposed, as well as inert waste and clinker, mainly used for cover layers and dam and road stability. The site infrastructure includes a bottom leachate collection system and 200 vertical gas extraction wells. During the past 25 years, more than 1 billion m³ of landfill gas have been produced. The waste is compacted with landfill compactors to conserve free space and maximize the landfill lifespan.

In August 2012, a 32 m long borehole was drilled and equipped with HDPE pipes perforated for the last 12 m. Temperature profiles (distributed temperature sensing method – DTS) and electrical conductivity (borehole EM) were measured inside the boreholes. At the borehole location, the landfill is 55m deep. A first disposal period occurred between 1995 and 2000, when a former ground level was established (still partially in place 10 m below the current ground level). Then, an additional

10 m thick layer of waste was disposed in order to create the final topographic profile of the landfill cell.

In May 2015, an electrical resistivity tomography perpendicular to the landfill ridge was performed on the test site. The southern extremity of the profile is located on more recent waste (late 2009). This is the less known part of the landfill with no boreholes, no leachate sample and no direct measurement of the water table. The middle of the profile is the landfill ridge, characterized by flat topography favoring water infiltration. The slope increases and reaches up to 15% in the northern part.

3. Material and methods

The Electrical resistivity is a suitable physical parameter to study the water content of a landfill (Guérin et al., 2004; Meju, 2006). The bulk resistivity varies with the water content, the composition, the temperature and the compression state of the waste (e.g. Moreau et al., 2010). For the short-term (a recirculation experiment for instance), changes in temperature and water content are the most important effects. For the long-term (several months to several years), changes in the pore water conductivity (resistivity) with maturation and aging of the landfill, as well as the waste settlement, strongly influence the bulk resistivity.

3.1. The electrical resistivity

The electrical resistivity is expected to vary inversely with the moisture content. As electrical current is mainly transported by the liquid phase inside the pores, waste with low moisture content has a high electrical resistivity. The Archie's law (Archie, 1942; Wyllie and Gregory, 1953) describe the evolution of the bulk resistivity with the fluid resistivity, the porosity, the saturation and some coefficients related to the matrix structure. Grellier (2005) and Grellier et al. (2007) proposed a simplified equation for the study of MSW. The volumetric water content replaces the porosity and the saturation which are difficult to measure on waste sample:

$$\rho_b = \rho_w \, a \, \theta^{-m} = \sigma_w^{-1} \, a \, \theta^{-m} \quad (1)$$

Where ρ_b is bulk resistivity; ρ_w is resistivity of the pore fluid; a is the cementation constant; m is an empiric constant and θ is the volumetric water content of the sample.

The influence of temperature on the electrical conductivity can be represented by a linear law based on viscosity theory (Campbell et al., 1948). Generally, a 2% increase of conductivity with every additional degree of temperature is observed. This theory has been validated experimentally for MSW (Grellier, 2005; Grellier et al., 2006b).

$$\sigma = \sigma_{T_{ref}}.\left(1 + c.\left(T - T_{ref}\right)\right) \ where \ c \simeq 2\%/°C \ \ when \ T_{ref} = 25°C \quad (2)$$

Clément et al. (2011a) investigated the contribution of temperature, moisture content and dry density feature to the bulk resistivity of waste. A ten coefficient equation is proposed and the most significant parameters identified by statistical analysis. The moisture content and temperature dominates the signal variation. While assessing the moisture content from the electrical resistivity information, temperature variation cannot be neglected, while dry density variations are less influent.

3.2. Electric and electromagnetic geophysical methods

Electrical and electromagnetic geophysical methods are suitable to characterize waste deposits because of their sensitivity to electrical resistivity (Bernstone et al., 2000; Grellier et al., 2007; Guérin et al., 2004).

The electrical resistivity tomography (ERT) method is widely described in many references (e.g. Dahlin, 2001). An electrical current (I, in Ampere) is injected in the medium with a pair of stainless steel electrodes and the resulting potential difference (ΔV, in Volt) is measured between two other electrodes. This can be done at the laboratory scale (test cells) and at the field scale (ERT). For field surveys, the greater the electrode spacing is, the larger and the deeper the investigated volume. Hundreds or thousands of data are collected with various distances between current and potential electrodes and then inverted with an iterative process to produce a 2D/3D representation of the subsurface electrical resistivity that explains the measured data.

The ERT profile presented in this study is 410 m long (83 electrodes and 5 m electrode spacing). Its extension is limited by road infrastructure around the landfill and the existence of a HDPE membrane. Indeed, quadrupoles with electrodes both inside and outside the landfill are not considered as the current flow would be prevented by the resistive membrane. Pinholes in the geomembrane could even act as secondary electrodes, making the current flow pattern unconventional (De Carlo et al., 2013; Tsourlos et al., 2014). The resistivity data were acquired with a multiple-gradient protocol (Dahlin and Zhou, 2006) to take advantage of the multichannel ability of the ABEM terrameter LS (Figure 2).

The data were inverted with the inversion code CRTomo (Kemna, 2000). The surface topography and the bottom HDPE membrane morphology are included in the inversion grid with homogeneous Neumann conditions (no current flow in normal direction) because the ERT profile is locate too close to the landfill HDPE membrane (both bottom liner and lateral boundary). Indeed, (Audebert et al., 2014) have shown that a minimum distance of 0.64*L from the landfill boundary and 0.58*L from the landfill bottom membrane (L is the ERT line total length) is necessary to neglect boundary effects.

The inversion process is based on the minimization of an objective function of the form (Tikhonov and Arsenin, 1977):

$$\emptyset = \left\| W_d\left(d - f(m)\right)\right\|^2 + \lambda \left\| W_m m + \alpha(m - m_0)\right\|^2 \qquad (3)$$

where the terms on the right hand-side are the data misfit constraint and the reference model constraint (Oldenburg and Li, 1994). In equation 3, W_d is the data weighting matrix, f is the non-linear operator mapping the log resistivities of the model m to the log impedance data set d. W_m is the roughness matrix, λ is the regularization parameter, m_0 is a reference model and α weights the importance of the reference model. W_d contains the error level on the data estimated from reciprocal measurements (LaBrecque et al., 1996). The latter correspond to a measurement with the same electrode quadrupole while exchanging the current electrodes with the potential electrodes. It allows us to estimate the error level related to, among other phenomena, poor contact resistance. An absolute error of 0.0005 Ω and a relative error of 1% (the envelope of the reciprocal error model) is considered during the inversion process (Slater et al., 2000), which provides a conservative error model. The optimization process ends when the error weighted Chi^2 of the data misfit reaches 1 (i.e. the data set is fitted within its error level assessed with reciprocal measurements). The reference model is weighted (α coefficient) according to the faithfulness of the model. A high weight is used for the saturated zone (well-known zones) so that resistivity value stays close to the imposed reference model. A low weight is used for the unsaturated zone (uncertain zones) so that the resistivity values are free to diverge from the reference model. Doing so, the weight given to the reference model is important in zone of low sensitivity for ERT. Caterina et al. (2014) have shown with several examples that including such prior information in the inversion helps to recover realistic resistivity distributions. Similar weighted reference model schemes were already developed by several authors (Blaschek et al., 2008; Karaoulis et al., 2014; Kim et al., 2014; Kim and Tsourlos, 2009; Yi et al., 2003). The λ coefficient is optimized at each iteration to minimize the data misfit. At the last iteration, it is increased to fit exactly the assumed level of noise.

To assess the quality of the ERT image at depth, we used the error weighted cumulative sensitivity matrix (Caterina et al., 2013; Kemna, 2000). Note that when prior information is used, a low sensitivity does not necessarily mean that the model is not reliable; it means that the regularization has more importance than the data in this part of the tomogram (Hermans et al., 2012).

The borehole electromagnetic method provides the bulk electrical conductivity surrounding a borehole using the inductive electromagnetic technique. We used the EM39 from GEONICS. The radius of investigation is about 1m and the measurement is not influenced by the HDPE casing or the fluid properties inside the borehole (McNeill, 1986). The response integrates a vertical interval of about 1m. The EM measurement is strongly disturbed by metallic object in a 3 m radius around the well, resulting in sharp deflection of the signal and sometimes loss of records (Taylor et al., 1989). In September 2012, an electromagnetic log was performed in the boreholes. The EM conductivity values were recorded at a 0.2 m interval in the landfill. In the unsaturated zone, within some depth interval, negative values and very low values (irrelevant in the context of a landfill) were excluded from the data set. An average mobile filter of one meter is applied to the data before interpretation. For paper clarity, all EM measurements are later presented in terms of electrical resistivity.

The basic principle of the distributed temperature sensing (DTS) on fiber optic for borehole fluid logging is described by Hurtig et al. (1994). We used the AP-Sensing linear pro series which operates with a minimum spatial resolution as low as 50 cm and 0.1°C temperature resolution (spatial, temperature and time resolution are interdependent). The borehole temperature log was recorded simultaneously to the EM log.

3.3. Borehole drilling, waste sampling and laboratory measurements

Waste samples studied at the laboratory originate from a single 32 m long borehole performed in August 2012 by auger drilling inside a steel casing. The drill bit was lifted every 4 m in order not to mix all waste samples. The waste material was freed from the auger with a shovel, laid out on a plastic sheet and then subsampled. The structure of the waste was strongly altered by the drilling and sampling process so that the density, the solid matrix structure and the volumetric water content was not representative of *in situ* conditions. Waste temperature was measured during the drilling process whenever possible. The borehole was equipped with HDPE tubing screened on the last 12m. A sample of leachate from the 15 m deep saturated zone was analyzed for the electrical conductivity (resistivity).

Waste samples (30 dm^3) were gathered every 2 m for further analysis. The gravimetric water content is measured on a 1 dm^3 subsample by weighting the mass loss after drying process (5 days at 55 °C). Electrical resistivity laboratory measurements are performed on cylindrical transparent plastic tanks.

The bases of the cylinder are copper current transmission plates. Potential electrodes are located on one generatrix of the cylinder and divide the tank in three equivalent volumes. The bulk electrical resistivity measurement in based on a four point electrodes system. The geometric factor of both tanks is given analytically by the Pouillet law:

$$R = \rho_v \frac{h}{S} \tag{4}$$

Where R is the resistance, ρ_v is the resistivity, S is the surface of the current transmission plates and h is the thickness of waste between the potential electrodes (one third of the cell total length). The relation has been checked experimentally with water of known resistivity. A large cell, 9 dm^3 in volume (0.17 m diameter over 0.396 m in length) was used for electrical resistivity measurement on waste samples issued from the borehole. For practical reasons (the 9 dm^3 cell do not enter our laboratory oven), a 1.5 dm^3 cell (0.08 m diameter over 0.3 m in length) was used for temperature and compression (volumetric water content) experiments.

The bulk resistivity of 13 waste samples originated from one single borehole (Table 1) was measured in 9 dm^3 test cells. The waste sample was compacted manually. The wet density of the sample is measured in order to convert volumetric water content into gravimetric water content (equation 7) and for later compaction state correction (equation 10). Thereafter, the liquid phase conductivity (resistivity) is measured on 100-200 ml leachate sample recovered by pressing the waste with a 15 tons press.

The influence of temperature (10-65°C) on the waste resistivity and the influence of the volumetric leachate content (through the compaction experiment) on the waste resistivity were validated in 1.5 dm^3 cells. The first experiment was conducted on 1 waste sample and 4 leachate samples (presenting different electrical conductivities) with similar results. The second experiment needed 18 waste samples characterized by different water content and compaction state. The driest one contained 28.9% water. No liquid phase could be recovered through manual compaction. The last one (53% of water) represents the largest water content encountered in our waste samples. For each of these three samples, 6 different compaction works were applied (no compaction, 2.5, 5, 10 cm of material added between two manual compaction steps with different compaction pressures between 1 and 10 t/m²) generating 18 different conditions. The waste sample dry density ranged from 0.24 to 0.63.

Geophysicists usually quantify the water content with the volumetric coefficient (θ), defined as the volume of water (V_w) over the total volume (V_{total}) ratio, as it appears directly in the Archie's law. This parameter strongly depends on the sampling procedure.

$$\theta = \frac{V_w}{V_{total}} \tag{5}$$

On the other hand, microbial availability (for methane production) and sorting ability (for material valorization) of the waste depends on the gravimetric water content (w), defined as the weight of water (M_w) over the total sample weight (M_{total}) ratio. This parameter is independent of the density of the waste and can be measured on disturbed samples (providing there is no desaturation).

$$w = \frac{M_w}{M_{total}} \tag{6}$$

The relation between these two humidity parameters is straightforward, but practically, the *in situ* wet density (D_{wet}) of a waste dump is very difficult to measure. The water density (D_w) is taken equal to 1).

$$\frac{\theta}{w} = \frac{v_w}{M_w} * \frac{M_{total}}{v_{total}} = \frac{D_{wet}}{D_w} \approx D_{wet} \tag{7}$$

4. Results

All measurements performed for this study aim at assessing the gravimetric water content of the waste material. In a first approach, direct measurements of water content and bulk electrical resistivity were performed on samples in the laboratory. Then, the ability of geophysical methods (borehole EM and ERT) to provide reliable *in situ* distribution of water content in the waste material is investigated.

4.1. Laboratory

The composition of waste samples looks relatively similar over the entire borehole, except for the upper 2 samples (where silt and waste are mixed) and the samples located at 9 m and 11m composed of a waste, silt and wood mixture (Table 1).

The gravimetric water content and the bulk resistivity of the samples are given in Table 1. The upper 15 m are unsaturated and characterized by a 20-27% gravimetric water content (with two humid levels at 5 and 11 m depth), whereas samples below 15m depth originates from the saturated zone and contain up to 55% of water. The visual humidity observations are not solely influenced by the gravimetric water content but also the volumetric water content, and therefore the waste density. This is the reason why a dense sample with 26% water (sample 19m) seems wetter than a loose sample with 27.5% water (sample 13 m).

The bulk resistivity measured on samples decreases as depth increases (Table 1). The waste density in test cell varied from 0.5 to 1.2 in an erratic behavior. A special care was needed for the measurement on 5, 15 and 25 m depth sample for which the water content was clearly above the retention capacity of the waste. These where energetically homogenized before any subsampling and measurements were performed shortly after to limit sample desaturation.

The leachate conductivity varies from 7500 µS/cm (1.33 $\Omega\cdot$m), for the surface and perched water table, to 36000 µS/cm (0.28 $\Omega\cdot$m) in the saturated zone (Table 1) (Figure 7d). In the unsaturated zone, the leachate conductivity increases with depth. This could be accounted for by the progressive dissolution of salt by the leachate during infiltration (the longer the contact time, the greater the possibility for dissolving waste materials). However, some horizons are characterized by lower conductivities, probably linked to preferential meteoric water arrival and accumulation. Increased infiltration through the landfill cover layer is suspected at positions 220 m, 260 m and 315 (on ERT profile at figure 5) due to flat topography or the existence of dams impeding the runoff process. In contrast to the unsaturated zone, the leachate conductivity is more stable in the saturated zone (excepted for sample 19m) and close to the mean leachate conductivity measured in the well after equipment (34000 µS/cm; 0.29 Ω·m) (Figure 7 d).

The influence of temperature on the conductivity of 4 leachates and 1 waste samples was investigated by performing one heating and cooling cycle in a laboratory oven. The temperature increased from 10°C to 65°C, and then decreased again to check the reversibility of the process. For the tested range of temperatures, a linear law based on the viscosity theory (Campbell et al., 1948) fits the experimental data with a 2.101% increase of conductivity per degree of temperature (reference temperature at 20°C; $R^2 = 1$).

$$\sigma = \sigma_{20°C}.\left(1 + c.\left(T - 20°C\right)\right) \, where \; c = 2.101\%/°C \qquad (8)$$

Using this relation, the *in situ* bulk resistivity (at the *in situ* temperature state) can be calculated from bulk resistivity measurements performed in the laboratory at 20°C.

Next, the variation of the waste bulk resistivity with the volumetric water content was investigated using reconstituted waste samples. For that purpose, three waste samples with different gravimetric water content were prepared by adding different quantities of leachate to a preliminary oven dried homogenized waste material originating from the 6 boreholes presented in figure 1. The entire range of gravimetric water content observed in our samples (Figure 3) is covered. Figure 3 presents the electrical resistivity data as a function of the volumetric water content, computed from the gravimetric water content and the sample weight.

The waste resistivity appeared dominated by the volumetric water content. Indeed, two samples with identical volumetric water content but different compression states and gravimetric water contents are characterized by an identical bulk resistivity (Figure 3). Although the dry solid density, the porosity and the tortuosity change with the compression state, the relation between the electrical resistivity and the volumetric water content is describe by a single function derived from Archie's law (equation 1).

$$\rho_b = \rho_w \, a \, \theta^{-m} = 0.42 * \; 1.53 * \;\; \theta^{-2.101} \qquad (9)$$

Where ρ_w = 0.42 Ω·m (or σ_w= 24000 µS/cm) is the electrical resistivity of the liquid phase measured with a conductivity probe, while a and m constants of the power law optimize the R^2 (0.99).

Assuming that the gravimetric water content is unchanged by the compression process (the compaction was stopped when saturation was reached), the volumetric water content is proportional to the wet density of the sample (equation 7). Based on these observations, Archie's law (equation 1) expressed for the *in situ* wet density condition, divided by the same law expressed for the laboratory wet density condition, can be used to reproduce the bulk resistivity representative of the *in situ* compaction state from the laboratory bulk resistivity result and the *in situ* and laboratory wet density ratio (equation 10).

$$\rho_{b\ in\ situ} = \rho_{b\ lab} * \left(\frac{\theta_{in\ situ}}{\theta_{lab}}\right)^{-m} = \rho_{b\ lab} * \left(\frac{D_{in\ situ}}{D_{lab}}\right)^{-m} \qquad (10)$$

4.2. Uncorrected field results

An ERT tomography was acquired in May 2015, 32 months after the borehole acquisition. No major change for the depth of water level and leachate conductivity was seen from 2012 to 2015. The topographical features and the cover layer remain the same, no recirculation process occurred in that specific zone, so that the perched water table highlighted in borehole data in 2012 is expected to remain today.

The depth of investigation of the surface ERT is limited to 15-20m. Due to the high electrical conductivity of the leachate, the model sensitivity rapidly decreases in depth (Figure 4). Due to the high electrical conductivity of the leachate, the model sensitivity rapidly decreases in depth (Figure 4). In low sensitivity regions, a change of the model resistivity will have little or no influence on the simulated data. This is typically found at greater depths. In those regions, the model resistivity are not controlled by the measured data but by the reference or starting model used in the inversion (Hermans et al., 2012). The latter corresponds to a homogeneous value equal to the waste resistivity at depth (in the saturated zone) used to reproduce correct values below the water table.

On the inverted ERT profile (Figure 5) the saturated and unsaturated zones are clearly seen. Below 15 m, the saturated zone is characterized by a very low (1-2 Ω·m) and homogeneous resistivity. In between, the unsaturated zone is characterized by a heterogeneous resistivity (10-30 Ω·m) that could likely reflect local changes in the water content. Due to the weighted reference model constraint, the depth to the saturated zone is consistent with the borehole data, even if the electrical resistivity gradient is sharper in borehole data than with geophysical data acquired from the surface (vertical resolution decreases with depth for surface ERT while it remains constant for borehole EM). Some perched water tables are visible under the landfill ridge (position 220 m along ERT profile) where a circulation drain is installed and at the exact position of our borehole (figure 1; figure 5).

Regarding the borehole EM data (Figure 6b), the saturated zone is 15 m deep (confirmed by water table measurement) and is characterized by homogeneous resistivity of about 1 Ω·m. The unsaturated zone is more heterogeneous. A more sandy-silty layer is found at a 10m depth and corresponds to a former impervious cover layer dating back from 2002. Above this layer, a less resistive layer is visible at 5 m depth. In two vertical intervals (around 3 m and 7 m depth), a lot of EM39 data had to be discarded, probably due to higher metal content in the waste material.

Three individual temperature measurement were performed in the well. During the drilling process, the temperature was recorded by ourselves with a min/max thermometer. Data are available at depth 3, 7, 19, 23, 27 and 31. These are in good accordance with DTS data measured after borehole equipment but are missing around the unsaturated / saturated zones interface. The temperature was also recorded by the drillers every time the drilling head was removed for waste sampling. Measurements are always lower than DTS measures and are very heterogeneous. Finally, DTS measurements are performed after the borehole equipment. DTS-measured temperature changes inside the borehole are very smooth (Figure 6a). The saturated zone is nearly homogeneous with temperature change between 57 and 61°C. The humid zone (10-15 m deep) is also characterized by high temperature. The temperature gradient between the outside (25°C) and the 12 m deep temperature (59°C) is nearly constant. In comparison with temperatures measured by the drillers during the drilling process, temperature measurements in the borehole appear higher but also smoother. This suggests that measurements taken during the drilling process are less reliable, potentially because temperature probes are not placed in correct conditions, or because the probe does not have enough time to reach an equilibrium. However, this also clearly shows that after borehole equipment, the liquid and gas inside the casing undergo mixing and the temperature heterogeneities will not be depicted by DTS measurement inside the well tubing.

4.3. Interpretation

Gravimetric water content increases while electrical resistivity (measured by ERT and by EM39) decreases with depth. However, the laboratory results cannot be directly compared to field data. First, the laboratory measurements were conducted at a room temperature of 20 °C while the *in situ* temperatures vary from 25 to 65°C. Second, the waste density in test cell somehow varied from 0.5 to 1.2 kg/dm^3. In order to compare data from different techniques collected *in situ* and in the laboratory, the data need to be corrected for temperature and compression state (equations 8 and 10). A first strategy would be to bring laboratory measurements to *in situ* environmental conditions. This way, laboratory data could validate EM39 and ERT data. Another strategy would be to correct EM39 log and ERT profiles in order to remove the effect of temperature and density and thus infer respectively the gravimetric water content profile and section (Grellier et al., 2007).

4.3.1. Correction of laboratory results to reflect *in situ* conditions

In the laboratory, resistivity measurements were performed at a constant temperature of 20°C (used for the reference temperature of equation 8). A 2.101% conductivity increase with every degree of temperature is considered (equation 8). The temperature correction is based on the DTS measurements performed in the borehole. The correction to apply is small close to the surface (air temperature close to 20°C) but is significant at depth (nearly 50% conductivity increase – 33% resistivity decrease – in the saturated zone; Figure 6c).

Regarding the compaction correction (equation 10), an *in situ* density of 0.9 at surface and 1.3-1.5 in the saturated zone (with a gradient density in between) is retained (Figure 6a). This density profile is based on “undisturbed waste sample” gathered at the same place in 2002 by the “bucket augering” technique (smoothed by average mean). This range of density corresponds to normal to high compaction rate (Zekkos et al., 2005). At low depth, the *in situ* density is smaller and easily reproduced in the laboratory. In the saturated zone, densities are higher but the compression state is also accurately reproduced in the laboratory. Reasons for this (e.g. preconsolidation strength, water content, change of elasticity or particles size with aging of the waste) has not been investigated in this study. The correction is predominant at intermediate depth (Figure 6c) where *in situ* densities are non-satisfactorily reproducible in test cells.

While only a rough resistivity decrease with depth is observed on raw data (see section 4.1), a much refined interpretation can be done from corrected data. Once the temperature (equation 8) and compression (equation 10) correction applied, EM39 data correlate well with laboratory data (Figure 6b). In depth between 10 and 12 meters, the fit is not reliable. This issue might be explained by a potential contamination of the waste sample during the drillings, which would originate in the change in the casing diameter before the excavation of this particular sample. This hypothesis is supported by the fact that both laboratory measurements (of water content and resistivity) are correlated and differ from the *in situ* data. In order to compute the coefficient of determination, laboratory measurement is compared to the more similar EM39 resistivity value in a small vertical range (+- 20 cm) around sample position. Sample 11 m is probably contaminated and is discarded from the data set. Doing so, the R^2 value is 0.85. Sample 9 m, located to a sharp vertical contrast of resistivity (EM39 data) largely contributes to the R^2 deterioration. The uncertainty on the vertical position of the sample 9 m could explain this observation. Indeed, the electrical resistivity value of the sample 9 m is similar to the resistivity value of EM39 at 9.6 m depth. When sample 9 m is discarded from the data set, the R^2 value reaches 1.

4.3.2. Correction of *in situ* results to match laboratory conditions

The gravimetric water content of the waste mass was computed from the electrical resistivity *in situ* data. First, the coefficients deduced for the Archie's law and Campbell law (equation 8, 9 and 10) were used to compute the volumetric water content. Thereafter, the volumetric water content was divided by the waste density to deduce the gravimetric water content (equation7). The same process was applied to transform laboratory electrical resistivity data. The density taken into account is the waste density inside the test cell.

For the leachate conductivity vertical profile, three different options were tested (Figure 7 a,b,c). The first correction was applied with the real leachate conductivities measured on the liquid phase of the sample (Table 1). This correction generated an optimal match between in situ and laboratory data that validates the petrophysical laws described above. However, this correction is only valid locally, for the EM39 data acquired in the same borehole (Figure 7a). Very humid level at 5, 11 and 15 m depth are depicted in both data sets. The sample at 5 m is very humid but still relatively resistive because the liquid phase of the sample is less conductive (more resistive) that the leachate. If we do not consider this information, we could interpret the 5m depth layer as humid while it is saturated. Laboratory analyses of the sample at 11m differ from in situ measurements. In this case, sample contamination is suspected, more credits is given to EM39 data. Using real leachate conductivity (the best correction we can reach so far), there is a strong correlation between measured water content and computed water content from different methods (Figure 7a). The coefficient of determination between direct and indirect water content measurement in the laboratory is rather high. The quality of this fit is independent of the field temperature and density condition. However, the accuracy of the liquid phase conductivity measurement and the gravimetric direct measurement representativeness (very small samples were dried out) could explain the correlation factor (R^2 = 0.79; table 2).

Practically, once the petrophysical laws deduced for the site, our objective is to avoid the waste sampling and subsequent laboratory analyses. Supposing we only have geophysical data and do not have access to the liquid phase conductivity in the unsaturated zone, the average leachate conductivity of 34000 µS/cm measured in the borehole could be used for the correction (Figure 7b). Provided that the leachate conductivity can be measured in several boreholes, the method can be used to correct 2D/3D ERT tomographies. In our case, leachate conductivity varies between 30000 and 34000 µS/cm in the different boreholes. Using a constant leachate conductivity value for the correction provides us with an excellent fit in the saturated zone because the leachate conductivity variations are small. In the unsaturated zone, the leachate conductivity is overestimated and therefore, the computed water content is underestimated. For example, the liquid phase of the 5m-sample is 8000 µS/cm, which is 4 times lower than the leachate conductivity measured in the well. As a consequence, the computed water content is half the real humidity value ($2=4^{1/m}$). This layer appears as dry (<30% humidity) while it is saturated above retention capacity and landfill mining process and waste separation could be unexpectedly problematic in that zone. The coefficient of determination for the entire data set is 0.54 (Table 2).

In a third intermediate solution, a conductivity gradient between the surface and the saturated zone and a homogeneous liquid phase in the saturated zone is considered (Figure 7c). This hypothesis is pertinently supported by our liquid phase conductivity measurements (Table 1). With the last solution, the sample 5m is recognized as highly saturated. However, the sample 11m is not. The leachate conductivity gradient hypothesis is therefore a compromise, generating more reliable humidity data than the constant leachate hypothesis and that can be used at other location than the borehole. The coefficient of determination is higher than for the constant liquid phase conductivity hypotheses (R^2 = 0.67; table 2). A clearer improvement is observed on the average gravimetric water content of the unsaturated zone with 29, 25, 23 and 16 % for the direct measurement, the real liquid phase conductivity, the gradient liquid phase conductivity and the constant liquid phase conductivity respectively.

4.4. Mapping gravimetric water content from geophysical data

While studying leachate recirculation process or the landfill mining opportunity of an entire site, there is a real interest in providing spatially distributed values for the gravimetric water content. The electrical resistivity tomography is the best suited geophysical method to produce 2D/3D images of the underground electrical resistivity (later converted into water content) (Clément et al., 2010; Grellier, 2005; Grellier et al., 2007; Guérin et al., 2004; Imhoff et al., 2007).

Following the procedure described in section 2.3.2, the gravimetric water content was computed from the ERT profile. For that purpose, the density, the temperature and the liquid phase conductivity distribution on the entire 2D profile had to be known. In this study, the vertical logs observed around the borehole are extrapolated to the entire field. The leachate conductivity in the saturated zone was checked in 5 other boreholes (leachate conductivity ranges from 27000 to 34000 µS/cm) on the landfill. However, none of these boreholes is located on the south eastern part of the ERT profile. The gravimetric water 2D distribution is illustrated in Figure 8. There is a clear distinction between the saturated (30-35 % water) and the unsaturated zone (10-30% water). Under the landfill ridge and the drilling zone, some humid pockets of waste are visible, probably resulting from water infiltration trough the capping. At 10 meter depth, a nearly continuum of dry waste is visible (except under the landfill ridge). This layer reaches the surface after position 330m (towards the north-west). The existence of this low humidity layer is confirmed at the drilling position by borehole EM and laboratory data. We suspect a very low vertical permeability layer, with no clear evidence of it in the drillings cuttings, between the perched water table (at 5 m depth) and rather dry deeper layers.

The electrical resistivity information extracted from the ERT profile at the borehole location was compared to EM borehole data and laboratory corrected measurements (Figure 9a). ERT data appears generally higher and smoother. The perched water table at 5 m depth is clearly visible but the resistivity contrast with the other layers is reduced. The resistive layer at 10 m depth is correctly retrieved but the extremely low resistivity layer at 15 m depth is not. In the saturated zone, as the sensitivity decreases with depth, the resulting tomography is constrained by the reference model. Below 20 m depth, the model matches the reference model (1 $\Omega\cdot$m). The gravimetric water content extracted from the ERT profile at the borehole location with the gradient liquid phase conductivity hypothesis is illustrated in Figure 9b. The humid level at 5 m depth is clearly visible but the value is much lower. This is not unexpected since the real leachate conductivity (quite low) is not taken into account in the correction process. At 10 m depth, a dry level is present. The ERT data are in accordance with EM39 values. The waste sample analyses differs but are supposed to be contaminated at that specific depth. At that depth, a thin low resistivity horizon would probably not have been visible in the ERT profile due to the smoothness constraint used for the inversion stabilization. For the same reason, the extremely low resistivity horizon at 15 m depth visible on EM39 data and laboratory measurements is not visible on the ERT data.

5. Discussion

The results of this study show that the water content of municipal solid waste can be estimated from its bulk resistivity, provided that some parameters, namely the temperature, the density and the liquid phase conductivity, are known or estimated. Petrophysical laws describing the influence of these parameters on the bulk resistivity of a waste sample where determined through laboratory experimentation and were successfully used to correct resistivity measurement over the entire length of the borehole. These results are also supported by previous reports showing that electrical resistivity tomography can be successfully converted into gravimetric water content distribution in a less complex environment (Grellier et al., 2007, 2006b).

The rather good correlation between direct (weight loss trough drying process) and indirect methods (resistivity measurement in laboratory, ERT and borehole electromagnetics *in situ*) to measure the gravimetric water content suggests that empirical models are sufficient to describe the resistivity variation in the range of temperature and density encountered in a landfill. However the petrophysical laws probably need to be recalibrated for other landfills or even different zones of the same landfill.

An estimation of the temperature, density and leachate conductivity distribution in the entire landfill is needed to convert resistivity in water content. While these parameters are measured with a high precision in a laboratory, the *in situ* parameters are generally poorly described. In the literature, the density and leachate conductivity is often considered as a constant (e.g., Grellier et al., 2007) as a first approximation. This study shows that the distribution of these parameters is better described by gradient in the unsaturated zone and constant in the saturated zone. This situation is a reasonable assumption already made for temperature (measure in a borehole) and density (averaged data) and can be used for both ERT and borehole EM data interpretation. However, the leachate conductivity gradient is probably strongly site dependent and varies with the rainfall events on the area, the type of cover layer (silt, clay, HDPE membrane) or the inclination of the ground level. While assessing the gravimetric water content from geoelectrical methods, the limiting factor is the evaluation of the waste resistivity, temperature and density profiles rather than the petrophysical law itself.

The metallic content of the waste material might be a limiting factor for the use of borehole electromagnetics. In this study, the method was successfully used after removal of outliers originating from high metallic content zones. The metal content in municipal solid waste all around the world is estimated to 3, 2-3 and 6 % in lower, middle and upper income countries (Hoornweg and Bhada-Tata, 2012). In the present case, the content is limited to 3.5% in weight, resulting from efficient Belgian waste sorting policy. The method need further validation for high metallic content landfills, whereas regarding global statistics, it should be reliable on most sites.

The quality of the ERT inversion in such a complex media is a real challenge. For this study, we had to impose the water table depth in the prior model of the ERT inversion in order to produce plausible resistivity values. If we impose an incorrect water table as prior information in the reference model constraint, the inversion still converges but to impossible values. Likewise, if we do not guide the inversion process by imposing the saturated zone electrical resistivity, the saturated zone is retrieved with a resistivity value of 3-4 Ω·m (instead of 1 Ω·m). While the structural interpretation is still straightforward, conversion to water content through petrophysical laws would lead to low humidity values (15-20 %) in the saturated zones. Ground truth data are mandatory to ensure the quality of inversion results. Borehole EM data could also be used as prior information to further improve the ERT inversion (e.g. Caterina et al., 2014).

With increasing projects of leachate recirculation process, there is an increasing demand for time-lapse monitoring of water content inside a landfill. The observation of resistivity changes appears less challenging than direct correlation between resistivity and water content. However, the interpretation of monitoring data is difficult due to the multiple factors influencing the resistivity. Waste maturation involves changes in leachate salinity, settlement (and therefore change in saturation), and heat production trough microbial activity. Recirculation or infiltration or fresh leachate / water process imply changes in leachate salinity, temperature and saturation. Theoretically, borehole measurements could be repeated from time to time to provide time-lapse high vertical resolution information. In practice, boreholes are rapidly sheared due to differential settlement of the waste. In the specific study, the borehole integrity was no more ensured after a few months.

6. Conclusions

A borehole has been drilled on a municipal landfill site of Belgium. Waste samples were collected every 2 meters and analyzed for the gravimetric water content and the bulk electrical resistivity. We validated the use of long-established petrophysical laws to describe the influence of the temperature, the compaction and the volumetric water content on the waste resistivity of the waste material. Empirical parameters for these laws were defined to allow the calculation of the gravimetric water content from the bulk electrical resistivity, the temperature, the density and the liquid phase electrical conductivity information.

With the electrical resistivity tomography (or ERT) and borehole electromagnetics (or EM), we have shown that, on one hand, bulk electrical resistivity measured on waste sample (in the laboratory) and in the borehole present an excellent correlation once the data are corrected for their temperature and compaction environment. On the other hand, we have established that two geophysical methods, ERT and borehole EM, can be used to estimate the moisture content over large areas, provided that environmental parameters measured at one place are proved to be representatives of the entire site or that this parameters are known at several location in the landfill.

Given the importance of the water content of the waste material for the biodegradation of the organic waste biodegradation process and in a later phase of the landfill exploitation, the feasibility of landfill mining, the present methodology opens perspective for large scale site characterization.

7. Acknowledgements

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Figure

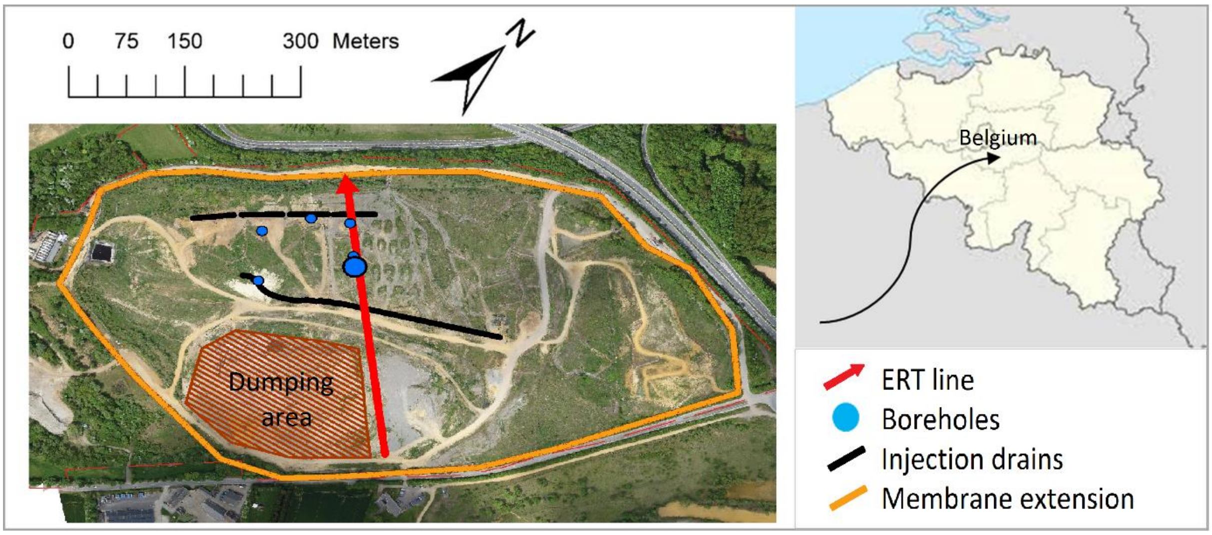

Figure 1: Location of Mont-Saint-Guibert engineered landfill (Belgium). The geophysical survey layout is depicted as a red arrow; boreholes location as blue dots (oversized for the borehole described in the present paper); Injection drains as black lines and the HDPE membrane extension as orange contour.

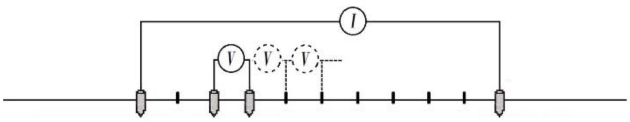

Figure 2: The multiple-gradient electrode protocol electrode configuration

SAMPLE DEPTH (M)	LABORATORY RESULTS (20°C)			VISUAL OBSERVATION		LEACHATE CONDUCTIVITY (µS/CM)
	Grav. Water content	Bulk resistivity (Ω·m)	Sample density	Humidity	Composition	
1	0.245	86.03	0.87	dry	Silt + waste	7500
3	0.273	63.62	0.673	dry	Waste + silt	14750
5	0.477	10.13	0.99	> retention capacity	waste	8000
7	0.239	25.04	0.754	dry	waste	23000
9	0.214	82.59	0.617	dry	Silt + wood + waste	24300
11	0.471	28.14	0.557	humid	Silt + wood + waste	11760
13	0.275	31.63	0.736	dry	waste	17370
15	0.557	1.926	0.935	> retention capacity	waste	30850
17	0.368	13.69	0.641	Very humid	waste	31800
19	0.259	8.56	1.049	humid	waste	17200
21	*Lost sample*					
23	0.360	4.737	0.934	Very humid	waste	30800
25	0.375	1.898	1.047	> retention capacity	waste	32000
27	*Lost sample*					
29	0.341	1.813	1.173	Very humid	waste	36000
31	*Lost sample*					

Table 1: observation and measures made in the laboratory on waste samples collected during drilling process. The gravimetric water content is measured after drying a 1 dm³ waste sample, the bulk resistivity and the waste wet density are measured on a 9 dm³ waste sample.

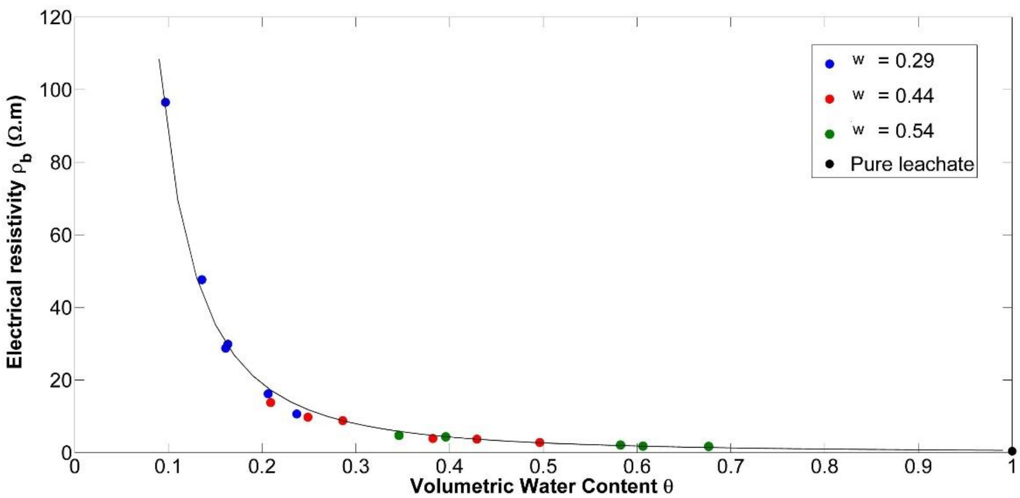

*Figure 3 : Bulk electrical resistivity of a waste sample as a function of the volumetric water content. 18 samples are tested (3 gravimetric water content * 6 compression states). The volumetric water content 100% stand for the pure leachate resitivity.*

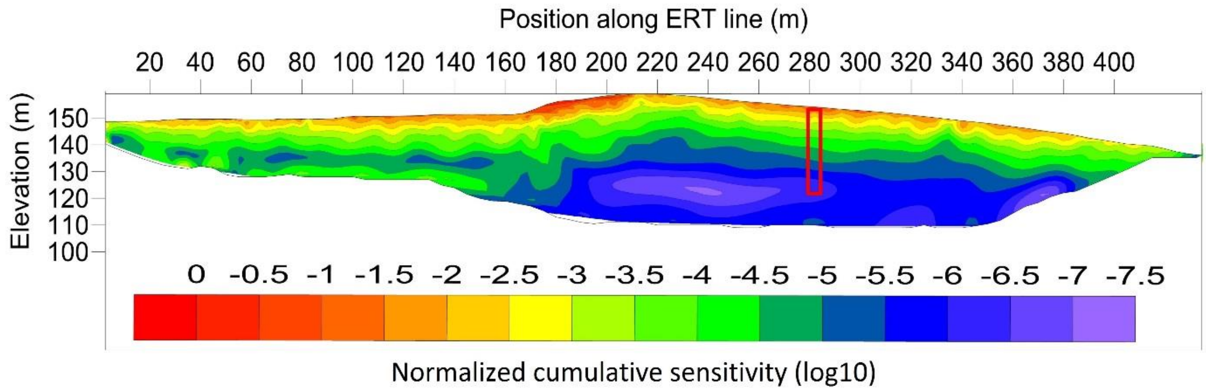

Figure 4: cumulative sensitivity value (log10). The sensitivity value rapidly decrease with depth due to the high electrical conductivity of the leachate.

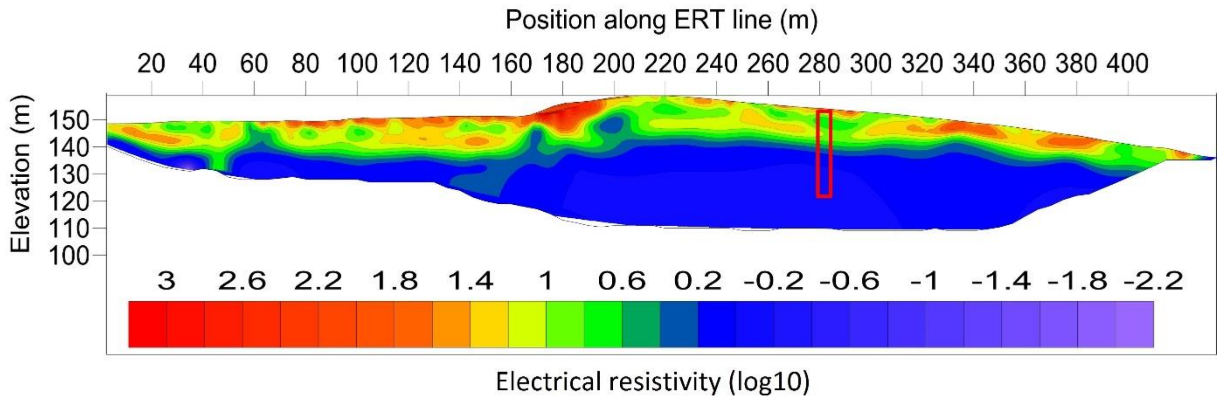

Figure 5: Electrical resistivity tomography (log10 of electrical resistivity) crossing the landfill from the SE border to the NW border. The inversion process ended with an error weighted Chi² equal to 1 (see section 3.2.) and a final regularization parameter (λ) equal to 0.7.

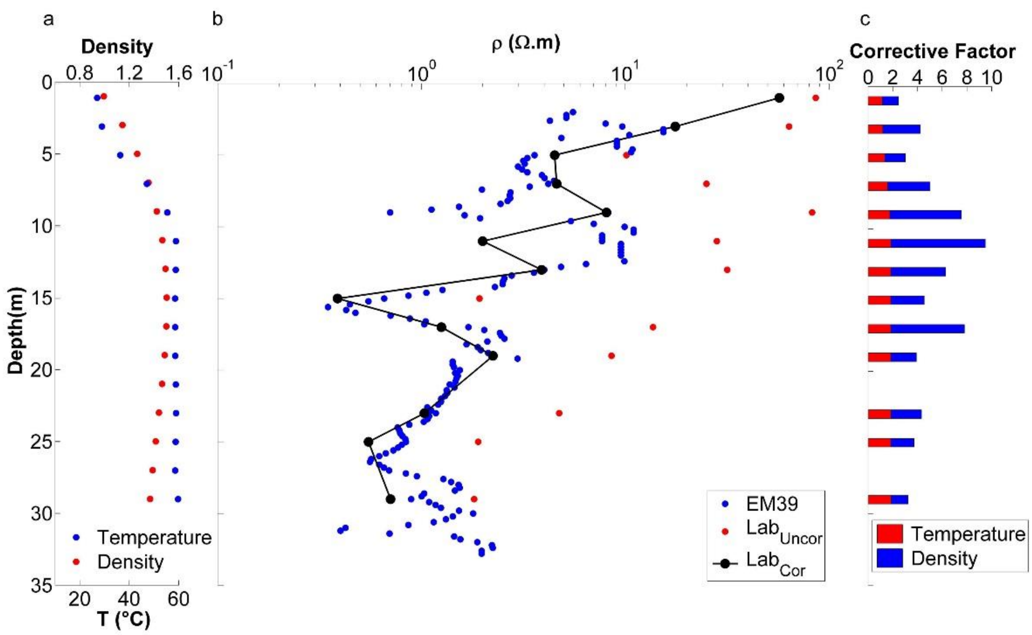

Figure 6: resistivity measurement in borehole K6 and measurement correction: a. in situ temperature and density profils; b. electrical geophysical method (borehole EM) vs bulk resistivity measured on waste sample (uncorrected and corrected); c. relative importance of the temperature and the compaction correction.

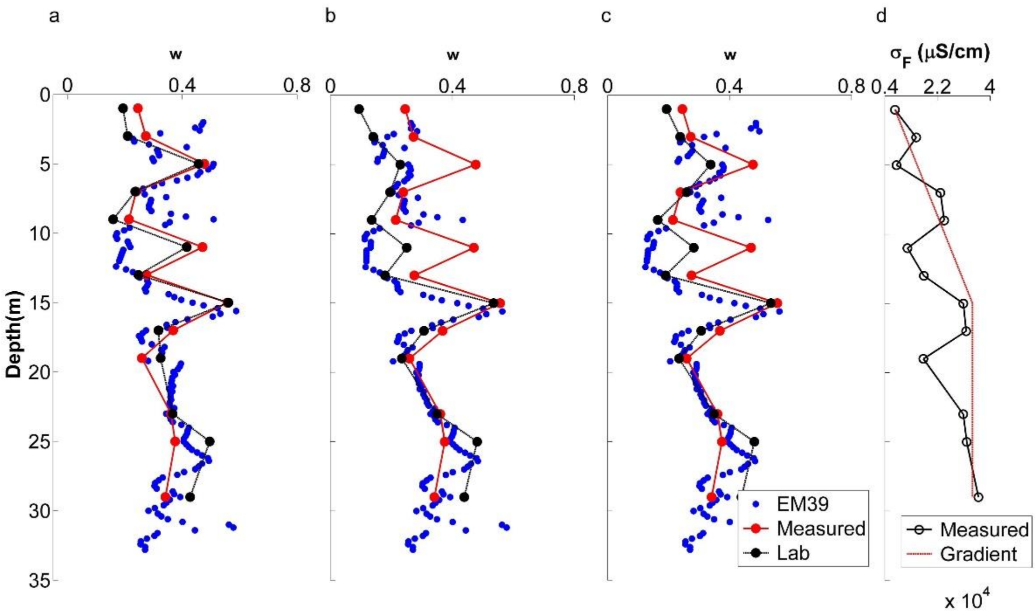

Figure 7: Waste gravimetric water content for three methods (direct measurement in the laboratory, from resistivity measures in laboratory and from borehole EM in situ) and three hypothesis for the liquid phase conductivity: a. measured liquid phase conductivity; b. constant liquid phase conductivity; c. liquid phase conductivity gradient in the unsaturated zone; d. measured liquid phase conductivity and gradient / constant liquid phase conductivity hypothesis

Coefficient of determination (R^2)	*Hypothesis on the liquid phase conductivity*		
	Real	**Gradient**	**Constant**
Indirect laboratory VS direct laboratory	0.79	0.67	0.54
EM39 VS direct laboratory	0.89	0.79	0.54

Table 2: correlation between the gravimetric water content values computed with three different method: direct laboratory measurement (mass loss trough drying process), indirect laboratory measurements (bulk electrical resistivity measured on waste sample) and borehole EM (EM39).

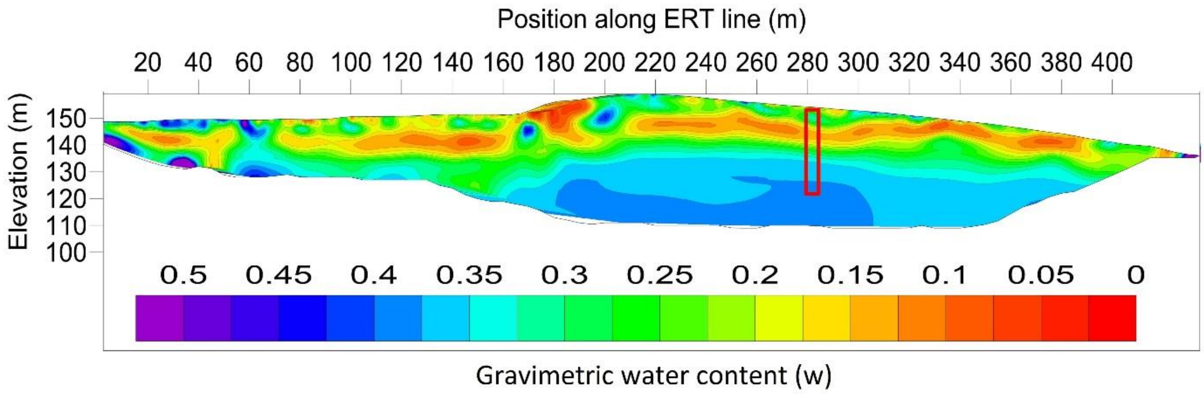

Figure 8: Gravimetric water content inside the landfill. Humidity value are calculated from the electrical resistivity tomography and temperature / density condition measured in situ. For the liquid phase conductivity, the conductivity gradient hypothesis is used in the unsaturated zone.

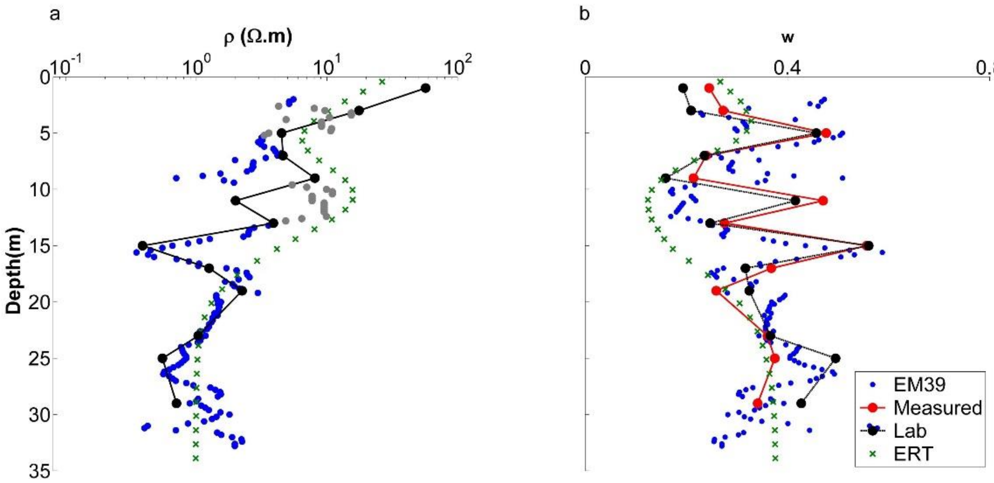

Figure 9 : a. electrical resistivity distribution around the borehole; b. gravimetric water distribution around the borehole

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