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

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A B S T R A C T

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.

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 960,000 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

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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 (Fig. 1). The 26 ha wide and up to 60 m deep (5.3 million m^3 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 90 s. 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 m^3 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 55 m 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 (e.g. 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:

$$\rho_b = \rho_w \; a \; \theta^{-m} = \sigma_w^{-1} \; a \; \theta^{-m} \tag{1}$$

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