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Understanding leachate flow in municipal solid waste landfills by combining time-lapse ERT and subsurface flow modelling – Part I: Analysis of infiltration shape on two different waste deposit cells

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ABSTRACT

Landfill bioreactors are based on an acceleration of in-situ waste biodegradation by performing leachate recirculation. To quantify the water content and to evaluate the leachate injection system, in-situ methods are required to obtain spatially distributed information, usually electrical resistivity tomography (ERT). In a previous study, the MICS (multiple inversions and clustering strategy) methodology was proposed to improve the hydrodynamic interpretation of ERT results by a precise delimitation of the infiltration area. In this study, MICS was applied on two ERT time-lapse data sets recorded on different waste deposit cells in order to compare the hydrodynamic behaviour of leachate flow between the two cells. This comparison is based on an analysis of: (i) the volume of wetted waste assessed by MICS and the wetting rate, (ii) the infiltration shapes and (iii) the pore volume used by the leachate flow. This paper shows that leachate hydrodynamic behaviour is comparable from one waste deposit cell to another with: (i) a high leachate infiltration speed at the beginning of the infiltration, which decreases with time, (ii) a horizontal anisotropy of the leachate infiltration shape and (iii) a very small fraction of the pore volume used by the leachate flow. This hydrodynamic information derived from MICS results can be useful for subsurface flow modelling used to predict leachate flow at the landfill scale.

1. Introduction

This is the first of two related papers that attempt to improve the understanding of leachate flow in municipal solid waste landfills (MSWL) by time-lapse ERT and subsurface flow modelling.

Over the last 30 years, waste production has been continuously increasing throughout the world. Waste management is a major challenge worldwide, requiring the reduction of its environmental impacts as well as the preservation of natural resources. Different waste treatment technologies have been developed such as recycling, biological treatment (i.e. anaerobic digestion and composting), incineration and storage. Of the total amount of household waste collected in France, approximately 25% is stored in municipal solid waste landfills (MSWL) (Ademe, 2014). To reduce their impact on the environment, the bioreactor concept has been studied and tested since 1970 in the US and for more than a decade in Europe (Reinhart and Townsend, 1998). This concept is based on the optimization of water content distribution in the waste landfill, which enhances waste biodegradation (Reinhart and Al-Yousfi, 1996). It involves leachate recirculation, which consists in collecting leachate from the drainage system on top of the bottom composite liner and reinjecting it underneath the landfill cover.

Using landfills as bioreactors has many advantages: (i) biogas production (Barlaz et al., 1990; Findikakis et al., 1988) and thus renewable energy production increases, (ii) the decomposition of waste is enhanced, shortening the post-exploitation period and thereby reducing the overall cost and the potentiality of negative environmental consequences (Barlaz and Reinhart, 2004; Imhoff et al., 2007) and (iii) the leachate treatment cost is reduced. Indeed, the volume of leachate to be treated decreases since a part of the leachate is retained by waste (Warith, 2002).

However, controlling the quantity of injected leachate through a leachate injection system (LIS) remains a challenge (El-Fadel et al., 1996; Rosqvist and Destouni, 2000; Zeiss, 1997). Indeed,

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bioreactor operators need to design LIS to ensure optimal water content distribution into the waste deposit cell, as recommended by Reinhart and Townsend (1998). In the best cases, operators use empirical hydraulic laws, which generally do not consider leachate flow behaviour into the waste medium.

However, to design LIS, one must understand leachate flow into the waste medium. For this reason, many experimental studies at the laboratory scale were conducted to study leachate infiltration into waste samples (Benson and Wang, 1998; Breitmeyer et al., 2008; Kazimoglu et al., 2005; Korfiatis et al., 1984; Orta de Velasquez et al., 2003; Staub et al., 2009; Stoltz et al., 2012; Tinet et al., 2011; Zornberg et al., 1999). In these studies, the authors measured water content with moisture sensors or using gravimetric methods. The sensors used were neutron probes, time domain reflectometry (TDR) or time domain transmissivity (TDT) sensors (Imhoff et al., 2007), which are classically used in hydrology. Then waste hydrodynamic properties of waste samples (i.e. porosity, hydraulic conductivity, density) were assessed to provide hydrodynamic models predicting leachate flow, useful for the design of LIS.

However, since sensor measurements provide only local information, it is difficult and costly to obtain good representativeness of the water content's spatial distribution, because of the high heterogeneity of waste and the large number of probes, that would be required to instrument the landfill. Poor contact between probes and waste is also a problem currently encountered in these measurements (Grellier et al., 2006). Moreover, hydrodynamic properties determined at a small scale in the laboratory are not appropriate for characterizing full waste deposit cells, once again because of the heterogeneous nature of this medium (Fellner et al., 2009). Waste samples at the laboratory scale are generally shredded at a smaller grain size and the boundary conditions differ from those at the field scale. Moreover, compaction of waste in layers during landfilling leads to anisotropy within the landfill (Beaven et al., 2008; Fellner and Brunner, 2010). Consequently, hydraulic conductivity in the horizontal direction is potentially at least one order of magnitude greater than in the vertical direction (Landva et al., 1998; Powrie and Beaven, 1999), which is generally not the case in laboratory experiments.

For all these reasons, other techniques than those previously mentioned are required to improve the understanding of leachate flow and to assess waste hydrodynamic properties at the field scale.

Many studies have shown that electrical resistivity tomography (ERT) can be a suitable method to study leachate infiltration at the waste landfill scale (Grellier et al., 2008; Guérin et al., 2004; Jolly et al., 2011; Mondelli et al., 2007; Moreau et al., 2003; Morris et al., 2003; Olofsson et al., 2006; Rosqvist et al., 2003). Time-lapse ERT can be used to monitor changes in electrical resistivity related to leachate content variations. Indeed, the leachate injection process implies an increase in water content and consequently a corresponding decrease in electrical resistivity.

Time-lapse ERT monitoring consists in performing identical ERT surveys several times at the same location with the same ERT quadripoles (Daily et al., 1992), namely, before, during and after the leachate injection period.

Time-lapse monitoring can be used because water content variations can be considered as the most influent parameters on electrical resistivity variations at the field scale during a short event of leachate recirculation. Indeed, the difference in temperature between injected leachate around 20 °C and the waste medium at 50–60 °C could be another influent parameter on resistivity variations. However, the temperature sensors installed in the landfill measured a maximum decrease of 5 °C during the leachate injection experiment, leading to maximum 10% changes in electrical conductivity (Dumont et al., 2016). This can be explained by the volume of injected leachate, which does not exceed 100 m^3, whereas the total volume of the waste deposit cell is greater than 60000 m^3. Thus, we can consider that the variation in temperature due to leachate injection will have a smaller influence on resistivity variations than the water content, with expected bulk resistivity changes of 50% or more. Moreover, since leachate is injected for a short period, less than 1 day, and after the closure of the waste deposit cell during the anaerobic degradation phase, waste biodegradation and density variation can be ignored.

Time-lapse ERT monitoring can provide spatial information on the shape and size of the infiltration area and the corresponding volume of waste wetted by the injection process (Clément et al., 2011). The delimitation of the infiltration area at the landfill scale could thus provide useful information for subsurface flow modelling.

However, it is not easy to delineate the leachate infiltration area precisely from time-lapse ERT results, due to: (i) the choice of inversion parameters, which greatly influence the inversion results (Audebert et al., 2014; Bazin and Pfaffhuber, 2013; Nguyen et al., 2007; Wagner et al., 2013) and (ii) the smoothness-constrained regularization method, which tends to smooth the resistivity models (DeGroot-Hedlin and Constable, 1990; Günther et al., 2006) and consequently the infiltration contour (Clément et al., 2011).

In their paper, Clément et al. (2011) attempted to determine the appropriate isocontour of resistivity variation that minimizes the difference between the volume of wetted waste extracted from ERT and the volume of leachate injected. However, the choice of this isocontour is related to the inversion parameter set used. The authors concluded that the selection of one isocontour to delimit the infiltration area is straightforwardly related to waste and leachate characteristics (resistivity, temperature, porosity, saturation). Thus, the isocontour identified in their study could not be generalized to other landfill sites.

To improve the delimitation of the infiltration area, Audebert et al. (2014) proposed a new methodology, called MICS (multiple inversions and clustering strategy), which allows a razor-sharp delineation of the infiltration. In this paper, MICS was assessed on many numerical data sets to determine this methodology's advantages, limitations and conditions of use. MICS was then assessed in the field for one ERT time-lapse monitoring of leachate injection including two time steps. Then the MICS results were compared to data obtained from the frequency domain electromagnetic method (FDEM). This first application validated the use of the MICS methodology on a field data set and opened up many research perspectives for the study of leachate infiltration dynamics.

To our knowledge, no study has yet attempted to detect similarities or divergences of leachate flow features between different waste deposit cells and injection experiments.

Therefore, the aim of this first paper is to improve our understanding of leachate flow by an analysis of ERT infiltration delimitation obtained with MICS for two leachate injection experiments conducted on two different waste deposit cells including five time steps.

The use of MICS on two ERT time-lapse monitoring will allow a comparison of the hydrodynamic behaviour of leachate flow between the two waste deposit cells. This comparison will be based on the analysis of: (i) the volume of wetted waste assessed by MICS and the wetting rate, (ii) the infiltration shapes and (iii) the pore volume used by the leachate flow.

Given that this study is only based on two waste deposit cells of the same landfill site, the results obtained were also compared with literature data in order to identify global trends in the hydrodynamic behaviour of leachate flow into the waste.