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Understanding leachate flow in municipal solid waste landfills by combining time-lapse ERT and subsurface flow modelling – Part II: Constraint methodology of hydrodynamic models

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ABSTRACT

Leachate recirculation is a key process in the operation of municipal solid waste landfills as bioreactors. To ensure optimal water content distribution, bioreactor operators need tools to design leachate injection systems. Prediction of leachate flow by subsurface flow modelling could provide useful information for the design of such systems. However, hydrodynamic models require additional data to constrain them and to assess hydrodynamic parameters. Electrical resistivity tomography (ERT) is a suitable method to study leachate infiltration at the landfill scale. It can provide spatially distributed information which is useful for constraining hydrodynamic models. However, this geophysical method does not allow ERT users to directly measure water content in waste. The MICS (multiple inversions and clustering strategy) methodology was proposed to delineate the infiltration area precisely during time-lapse ERT survey in order to avoid the use of empirical petrophysical relationships, which are not adapted to a heterogeneous medium such as waste.

The infiltration shapes and hydrodynamic information extracted with MICS were used to constrain hydrodynamic models in assessing parameters. The constraint methodology developed in this paper was tested on two hydrodynamic models: an equilibrium model where, flow within the waste medium is estimated using a single continuum approach and a non-equilibrium model where flow is estimated using a dual continuum approach. The latter represents leachate flows into fractures. Finally, this methodology provides insight to identify the advantages and limitations of hydrodynamic models. Furthermore, we suggest an explanation for the large volume detected by MICS when a small volume of leachate is injected.

1. Introduction

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

To reduce the impact of the landfill on the environment, the bioreactor concept has been developed for more than a decade in Europe (Reinhart and Townsend, 1998). This concept is based on leachate recirculation through a leachate injection system (LIS).

However, controlling the quantity of injected leachate remains a challenge (El-Fadel et al., 1996; Rosqvist and Destouni, 2000; Zeiss, 1997). Indeed, 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 hydraulic empirical laws, which generally are not based on experimental observation of the leachate flow inside the waste.

In recent decades, several hydrodynamic models for landfills have been developed and could help LIS design by predicting the volume of waste wetted by the injection process. The prevailing approach for modelling leachate flow in solid waste media is based

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on the assumption of a homogenous porous media (Demetracopoulos et al., 1986; Khire and Mukherjee, 2007; Korfiatis et al., 1984; Straub and Lynch, 1982). In these studies, a single continuum model represents waste and leachate flow is simulated by solving the Richards equation (Richards, 1931).

Because of the large heterogeneities observed in MSW, the assumption of an equilibrium model can be challenged. In addition, preferential flows are believed to be the reason why the single continuum approach considering homogeneous medium may not be in agreement with field observations (Ehrig, 1983; Uguccioni and Zeiss, 1997). A classical way is to represent preferential flows by distributed model parameters with the resolution of a single continuum model.

Another possibility, which is often described in soil science, consists in representing preferential flows by: (i) a dual continuum approach to represent the medium and (ii) the resolution of dual porosity or dual permeability models for water flow simulation (Gerke and Van Genuchten, 1993). This approach assumes that the porous medium is divided into two interacting pore domains, the first one corresponding to fractures (or macropores) with rapid water flow and the second one corresponding to the surrounding matrix domain (or micropores) with slow water movement. While dual porosity models assume that water in the matrix is stagnant, dual permeability models allow water flow in the matrix as well. To our knowledge, the dual porosity model was only used by Tinet et al. (2011) to simulate 1D leachate flow into the unsaturated waste column while the dual permeability model was used by Han et al. (2011) in columns filled with newspapers. In both cases, a dual continuum model was introduced because the single continuum approach (the Richards equation) failed to describe the experiments. A similar concept was used by Rosqvist and Destouni (2000), Beaven et al. (2003), Rosqvist et al. (2005), Woodman et al. (2005) and Woodman et al. (2011) to model the contaminant transport in saturated conditions, with the so-called Mobile-ImMobile (MIM) transport model, corresponding to the dual porosity model or the BIModal advection model (BIM), corresponding to the dual permeability model. The MSW medium has therefore been described as a system composed of a matrix linked to fractures (macropores), which enables complex exchanges of contaminant during leachate flow. It allowed reproducing experimental observations (at the laboratory scale), while the single continuum model (advection dispersion equation) did not.

The main drawback of the dual continuum approach is the definition of the hydrodynamic parameters (porosity and permeability) of each continuum (fractures and matrix) and of the parameters ruling the fluxes exchanged between the two different continua.

Therefore, additional information is required to calibrate hydrodynamic models with an appropriate range of hydrodynamic parameters.

The determination of hydrodynamic parameters (i.e. moisture retention properties, porosity, hydraulic conductivity, density) is somewhat difficult in landfills because of the heterogeneity of the porous waste medium (Bendz et al., 1998; McCreanor and Reinhart, 2000). Many researchers have assessed hydrodynamic parameters on waste samples at the laboratory scale (Benson and Wang, 1998; Breitmeyer et al., 2008; Kazimoglu et al., 2005; Korfiatis et al., 1984; Orta de Velasquez et al., 2003; Powrie and Beaven, 1999; Staub et al., 2009; Stoltz et al., 2012; Tinet et al., 2011; Zornberg et al., 1999). In these studies, water content measurements were taken: (i) using gravimetric methods or (ii) introducing moisture sensors into waste samples (such as neutron probes, time domain reflectometry [TDR] or time domain transmissivity [TDT]). The waste hydrodynamic parameters of these samples were assessed to improve the hydrodynamic models used to predict leachate flow. However, hydrodynamic parameters determined at a small scale in the laboratory may not be appropriate to characterize full waste deposit cells, because of the heterogeneous nature of this medium (Fellner et al., 2009). Waste materials at the laboratory scale are generally shredded or sieved to a smaller grain size and waste confinement in cells may undergo edge effects. Moreover, compaction of waste into 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; Stoltz et al., 2010). This anisotropy is not always taken into account at the laboratory scale in the assessment of hydrodynamic parameters.

Moreover, as 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).

For all these reasons, other techniques are required to assess hydrodynamic parameters of waste at the field scale.

Many studies have shown that electrical resistivity tomography (ERT) is a suitable method to provide spatial information on leachate flow at the field scale (Clément et al., 2011a, 2010; Grellier et al., 2008; Guérin et al., 2004; 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 variation. Indeed, the leachate injection process implies an increase in water content and consequently a corresponding decrease in electrical resistivity. ERT time-lapse monitoring consists in conducting the same ERT surveys several times at the same place (Daily et al., 1992), namely, before, during and after the leachate injection period. However, this geophysical method does not allow ERT users to directly measure water content and assess hydrodynamic parameters.

In hydrology, several studies have combined ERT measurements and subsurface flow modelling to constrain hydrodynamic models and assess the hydrodynamic parameters of a sandstone medium (Binley et al., 2002; Cassiani and Binley, 2005). The two papers used an inversion approach to derive hydrodynamic parameters from ERT measurements (combined with radar). This approach is based on two steps. First, the interpreted resistivity data resulting from the inversion process were converted to water content using Archie's petrophysical relationship (Archie, 1942). Second, water content data from ERT and water content simulated by hydrodynamic models were compared to constrain hydrodynamic models and assess hydrodynamic parameters. More recently, Beaujean et al. (2014) also proposed a coupled inversion approach to assess hydrodynamic parameters from ERT measurements and showed the importance of taking into account the variable resolution of ERT images.

Many approaches are based on the use of a calibrated petrophysical relationship (i.e. with one parameter set), which seems to be appropriate for a relatively homogeneous medium such as sandstone. However, the studied medium is often highly heterogeneous in particular, waste.

Grellier et al. (2005) and Dumont et al. (2016) attempted to calibrate Archie's law for waste in assessing the related in-laboratory parameters. The calibrated law was then used on field data sets to assess waste water content from resistivity (Grellier et al., 2008; Dumont et al., 2016; Ling et al., 2012). As mentioned above, the use of one calibrated Archie's law for the entire landfill is probably not appropriate. Moreover, it can be assumed that Archie's law calibrated at the laboratory scale is ill suited to assessing water content at the field scale for the above-mentioned reasons