Journal of Applied Geophysics 138 (2017) 1–8

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Detailed landfill leachate plume mapping using 2D and 3D electrical resistivity tomography - with correlation to ionic strength measured in screens

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ARTICLE INFO

Article history:
Received 28 August 2016
Received in revised form 16 December 2016
Accepted 14 January 2017
Available online 15 January 2017

Keywords:
Large scale 3D ERT
Landfill
Leachate plume
Ionic strength
Hydrogeophysics

ABSTRACT

Leaching of organic and inorganic contamination from landfills is a serious environmental problem as surface water and aquifers are affected. In order to assess these risks and investigate the migration of leachate from the landfill, 2D and large scale 3D electrical resistivity tomography were used at a heavily contaminated landfill in Grindsted, Denmark. The inverted 2D profiles describe both the variations along the groundwater flow as well as the plume extension across the flow directions. The 3D inversion model shows the variability in the low resistivity anomaly pattern corresponding to differences in the ionic strength of the landfill leachate. Chemical data from boreholes agree well with the observations indicating a leachate plume which gradually sinks and increases in size while migrating from the landfill in the groundwater flow direction. Overall results show that the resistivity method has been very successful in delineating the landfill leachate plume and that good correlation exists between the resistivity model and leachate ionic strength.

1. Introduction

Groundwater contamination is one of the most serious environmental risks, especially in and around areas with an industrial history. The sources of contaminations are either called point source contamination or areal contamination. Point source contaminations include landfills, industrial waste disposal sites, accidental spills, leaking gasoline storage tanks, etc. Areal contaminations are for instance the chemicals used in agriculture such as fertilizers and pesticides. Among the point source contaminations, landfills with various types of solid waste are quite common and can potentially generate contaminated leachate plumes (Barker et al., 1986; Baxter, 1985; Bjerg et al., 1999; Christensen et al., 2001; Cozzarelli et al., 2011). Over time some of the landfill waste materials degrade and dissolve, and as water perches through landfill leachate with inorganic and organic constituents are generated. Often the older landfills do not have a leachate collection or liners beneath the landfill which may result in leachate contaminating groundwater down-gradient from the landfill.

The migration of a leachate plume can potentially contaminate aquifers and surface waters for decades and thus poses a long term serious risk to the health and environment (Bjerg et al., 2014; Bjerg et al., 1999). To evaluate these risks, an understanding of the interaction between the surrounding aquifers and the contaminant plume leaching from the landfill is becoming increasingly pertinent. Hence, a main target in field investigations of landfills is mapping and characterizing the contaminant plume. The most common techniques used for this purpose include geological and hydrogeological characterization of aquifer properties by use of borehole information, as well as chemical analyses of soil and water samples. However, these techniques provide limited spatial information, which might lead to incomplete site investigation and inadequate remedial designs. Geophysical measurements minimize this spatial information gap as they can provide extensive lateral coverage with high-resolution information.

Non-invasive geophysical methods have been used extensively to investigate the composition and structure of the subsurface, and in particular electrical resistivity tomography (ERT) has been used for studying the landfills and related contaminated sites (Casado et al., 2015; Konstantaki et al., 2015; Slater and Binley, 2006; Vargemezis et al., 2015; Wang et al., 2015). The application of ERT for the study of the landfill sites addresses two main complimentary issues: (1) Mapping of extent of landfill sources (Bernstone et al., 2000; Ogilvy et al., 2002); and (2) Identification and mapping of landfill leachate plumes (Acworth and Jorstad, 2006; Perozzi and Holliger, 2008; Zume et al., 2006). Hence, surface ERT methods can be used for characterizing the landfill and leachate migration, in case of an increased ion concentration in the groundwater. In this paper, we will study a landfill with a detailed site characterization and plume monitoring and show that combined

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http://dx.doi.org/10.1016/j.jappgeo.2017.01.019

use of 2D and large-scale 3D ERT data enables detailed imaging of a heterogeneous flow pattern of a contaminated groundwater leachate. The 3D layout contains a very large number of electrodes, which enables a hitherto unseen spatial coverage while maintaining a high resolution.

Inorganic constituents such as chloride, hydrogen carbonate, ammonium, and potassium are often present in landfill leachate contaminated groundwater (Christensen et al., 2001). This causes an increase in the electrical conductivity (EC) of the contaminated groundwater resulting in a resistivity contrast between the contaminated zone and the host aquifer, which makes it detectable by surface resistivity surveys. Multichannel measurements (Dahlin and Zhou, 2006) have made the ERT method robust, faster and more convenient to perform in the field. 2D inversion codes (Auken et al., 2014a; Loke and Barker, 1996b) are available and can produce high resolution subsurface resistivity images. However, in the case of three-dimensional (3D) resistivity structures, such as a landfill leachate plume, 2D resistivity methods may be insufficient, which then calls for 3D resistivity techniques both for data acquisition as well as data processing and inversion.

Three dimensional (3D) measurements are generally carried out by deploying the electrodes in parallel lines or by using a regular grid. Though, many instruments can handle only a limited number of electrodes (typically 64–128), which limits the areal coverage that can be obtained (Dahlin et al., 2002). For larger coverage, more electrodes are needed which puts demands on the switching capabilities of the system. A flexible and expandable 3D acquisition system using a set of parallel cables in a fish-bone structure was presented by Auken et al. (2014b). Here, we will apply a further developed version of this system to a landfill leachate plume for the first time.

3D modeling and inversion of resistivity data is generally based on finite difference (Loke and Barker, 1996a; Park and Van, 1991; Zhang et al., 1995) and finite element methods (Sasaki, 1994; Yi et al., 2001). Most of these algorithms are based on Gauss-Newton techniques for optimization and do not consider the surface topography. (Günther et al., 2006) have presented an algorithm based on unstructured tetrahedral meshes and finite element forward calculation. The algorithm also incorporates the surface topography and can be applied to large scale 3D problems as encountered in practice.

In the present study we use and demonstrate an extended and improved version of the flexible and expandable 3D system (Auken et al., 2014b) in combination with the inversion algorithm by Günther et al. (2006). The aim of the study is to delineate and describe the leachate plume migrating from a landfill and compare with field observations of water quality in the landfill leachate plume.

The measurements were carried out at a Grindsted landfill site in the southern part of Jutland, Denmark (Kjeldsen et al., 1998a; Bjerg et al., 1995). The landfill was pre-investigated by 2D ERT profiles and 2D resistivity models were also used to compare with the inorganic water chemistry obtained from water sampling of boreholes in the landfill leachate plume.

2. Study area and background description

2.1. Grindsted landfill

The Grindsted landfill site is located on top of a flat glacial outwash plain (Fig. 1; Heron et al., 1998). Between 1930 and 1977 approximately 300,000 tons of waste was deposited over an area of 10 ha, most of it between 1960 and 1970 (Kjeldsen et al., 1998b). There is no leachate collection or liner beneath the landfill. The deposited waste consists of municipal solid waste, industrial waste, sewage treatment waste, and demolition waste. The landfill source has been subject to a number of investigations (Kjeldsen et al., 1998b), which suggest that there is a pronounced spatial variability in the leachate and that the landfill can be divided into strong and medium leachate zones (Fig. 1). The concentration of chloride, ammonium, and dissolved organic carbon (DOC) in the strongest leachate zones is typically 20–40 times higher than in the weak leachate zones. The waste in the northern part originates from a local pharmaceutical factory site, which deposited liquid industrial waste in a lagoon. The waste had very high ion content and chemical waste residues including pharmaceutical compounds. The waste in the southern part is mainly demolition waste, while the remaining part of the landfill hosts municipal household waste, demolition waste and smaller amounts of chemical waste. The described differences in waste composition are clearly reflected in EC values for water samples collected in the groundwater just below the landfill (Table 1).

2.2. Geology and hydrogeology

The geology of the area consists primarily of sand where the upper 10–12 m are divided into Quaternary and Tertiary sand layers separated by discontinuous silt and sand layers (Heron et al., 1998). Below is a 1 m clay layer underlain by a more regional micaceous sand layer, which is approximately 65 m thick and confined by a low permeable clay layer at a depth of approximately 80 m. Three thin lignite layers are present in the micaceous sand unit.

Investigations of hydraulic conductivity and hydraulic gradient show that an average linear groundwater flow velocity is 50 m per year for the glaciofluvial sand (0–6 m) and 10 m per year for the upper Tertiary sands (8–12 m below surface) (Albrechtsen et al., 1999; Bjerg et al., 1995; Lonborg et al., 2006; Rugge et al., 1999). The lower parts of the Tertiary deposits have presumably higher flow velocities, but the data is scarce (Barlebo et al., 1998). The groundwater iso-potential map (Fig. 1) based on data from (Orbicon, 2013) suggests that the overall groundwater flow is north-westerly and that the flow has a diverging pattern indicated by a semi-circular iso-potential line. The flow field shows some temporal variation, which can enhance spreading of contamination (Kjeldsen et al., 1998b).

3. System setup and data acquisition

Before setting up the 3D system we investigated the area using three 2D profiles as shown in Fig. 1. These data were collected using a four-cable setup with roll-along (Dahlin and Zhou, 2006). A gradient array type of protocol was used. Profile 1 and 2 are 600 m long each and profile 3 is 400 m long. Total 1800 quadrupoles were collected for long profiles and 691 quadrupoles were collected for short profile.

The 3D ERT system used for this study was originally designed for a monitoring study (Auken et al., 2014b), which consisted a 64 channel Syscal resistivity meter, field PC and six switch boxes developed inhouse. The original system has been modified and migrated to an ABEM LS terrameter (www.abem.se). The whole system was powered by an uninterrupted power supply (UPS) consisting of a gasoline powered AC generator, three 120 Ah 12 V car batteries and a power management control unit. The control system always charged one battery and used the other for acquisition. Batteries were swapped automatically by the control unit.

Fig. 2 shows the various components of the 3D system where seven parallel lines (63 electrodes in each) are handled by six switch boxes. Each line consisted of four cables where 5 m electrode spacing was used for the two inner cables (21 electrodes in each where one electrode was shared between two cable) and 10 m spacing was used for the two outer cables (11 electrodes in each), making each line 410 m long. Profiles were seperated 25 m apart hence making total coverage 410 m by 150 m. Switch boxes were connected in the middle of the profiles and controlled by a PC which enables automatic selection of desired combinations of cables for data acquisition. The array of measurements (protocols) for each four cable combination was preloaded in the LS Terrameter and executed sequentially by the PC.