Original article

Application of ground penetrating radar in mapping and monitoring landfill sites

T. Splajt · G. Ferrier · L.E. Frostick

Abstract The internal structure and the integrity of the containment walls are aspects of landfill site management that need to be continuously monitored. Monitoring currently involves construction of boreholes and chemical analyses of surface samples which are time-consuming and expensive. The applicability of ground penetrating radar (GPR) as an aid to monitoring these processes has been investigated. GPR surveys have successfully resolved the shallow depth soil and geological structure, identified the structure and history of the waste input, defined the water table in three dimensions and identified leachout breakout points in the impermeable lining of the landfill edges. Integration of the results of GPR surveys with data from surface surveys and boreholes could provide landfill operators, environmental agencies and commercial companies with a cost-effective monitoring methodology and a mechanism for enhancing contaminant migration modelling.

Keywords Ground penetrating radar · Leachate · Landfill

Introduction

The environmental impact of landfill sites is of major concern in developed countries due to their increasing development adjacent to urban areas (Meju 2000). Abandoned landfill sites where the type and volume of the fill and the nature of the site boundaries may be unknown are also of concern (Meju 2000). The generation and dispersion of leachate from landfills is slow, unsteady, non-uniform and sometimes discontinuous depending on the degree of compaction of the fill, seasonal changes in water supply to the system and changes in the capping and contaminant walls (Brun and Engesgaard 2002). Continuous monitoring, both at the surface and underground, is therefore required to satisfy the risk assessment of landfill leachate (Butt and Oduyemi 2003). The assessment of the actual or potential degradation of groundwater resources at contaminated sites involves a combination of investigations that are both time-consuming and costly (Asante-Duah 1996). There is therefore a requirement for rapid, non-invasive, cost-effective methodologies to (1) aid landfill managers to position additional boreholes, (2) focus field sampling surveys at areas most affected by leachate migration (Abbaspour and others 2000), (3) monitor the compaction processes occurring in a landfill, (4) identify subsurface structure in abandoned landfills where information might be limited or absent and (5) as inputs to leachate migration modelling (Fatta and others 2002).

In most situations shallow seismic reflection and ground penetrating radar (GPR) methods have been demonstrated to be more useful than magnetometric and geoelectrical methods (Meju 2000) as landfill mapping tools (Ali and Hill 1991; Peters and others 1994; De Iaco and others 2003). GPRs provide high-resolution images of the dielectric properties of the top few tens of meters of the earth which can be used to detect liquid organic contaminants (Nobes 1996), obtain models of the large-scale architecture of the subsurface (Reynolds and Taylor 1992; Trenholme and Bentley 1998) and assist in estimating hydro-geological properties such as water content, porosity and permeability (Knight 2001).

The aim of this study was to investigate the applicability of GPRs in resolving the internal structure and shallow-depth geology of a landfill site and also to identify leachate breakout points in the contaminant wall.

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Materials and methods

Study site

The study site is located in eastern England, covers 40 ha and is divided into 15 cells (Fig. 1). Cells 1 to 6 are unlined

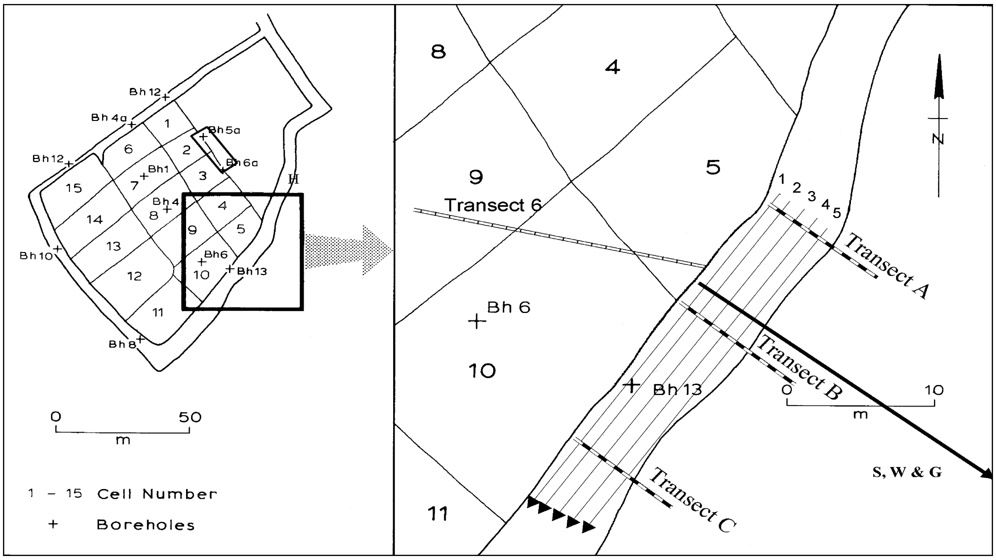

Fig. 1
Map of landfill site indicating cell and borehole locations and GPR and spectroscopy survey lines. Transects *1* to *6* are the GPR survey lines, and direction of survey is indicated by the *arrow*. Transects *A*, *B* and *C* are the chlorophyll survey lines and the *S, W & G* survey line is the soil, water and grass heavy metal concentration survey line

and capped, cells 7 to 10 are lined and capped, while cells 11 to 15 are working cells. Leachate had been observed escaping continuously from cells 5, 10 and 11 since 1997, with a marked increase noted after rainfall.

GPR data acquisition

After discussion with the managers of the landfill site, analysis of aerial photographs and preliminary field investigations, the section adjacent to cells 2 and 3 was selected as being the most likely area unaffected by leachate contamination of the soil, shown as area H in Fig. 1, while the section adjacent to cells 5, 10 and 11 was selected as being the most likely area representative of areas affected by leachate, shown in the close-up section of Fig. 1. Five GPR survey lines were arranged parallel to the edges of the two representative sections separated by approximately 1.5 m (transects 1 to 5 in Fig. 1). An additional survey line was acquired approximately perpendicular to the edge of the landfill site (transect 6 in Fig. 1). The GPR surveys were carried out in August 1999 under sunny and dry conditions using PulseEKKO 100 and 1000 GPRs (produced by Sensor and Software Ltd.). A range of antennas (50, 100, 200, 225 and 450 MHz), a 'reflection' mode of operation and a fixed offset profile mode were employed.

Surface sampling

To aid the analysis of the GPR survey data, five surface samplings transects were carried out away from the landfill edge at cells 5 and 10. Three transects (A, B and C in Fig. 1) sampled chlorophyll and heavy metal concentrations in the vegetation for a distance of 10 m. A fourth sample survey line sampled the heavy metal concentration of the soil and the grass for a distance of 30 m from the landfill edge (transect S, W & G in Fig. 1), while a fifth sample survey line sampled the heavy metal concentration of the surface water for a distance of 50 m from the landfill edge (transect S, W & G in Fig. 1). Chlorophyll-a concentrations in the foliar samples were determined using acetone extraction and analysis by spectrophotometry.

GPR data processing

Calibration of the unprocessed radar data was carried out using the EKKO and Slicer 3D software packages. The GPR image depths were validated to 0.06 m/ns using the geological profiles from the preliminary study and drilling logs from boreholes 13, 5a and 6a and the methods described by Davis and Annan (1989), Reynolds and Taylor (1992), Padaraze and Forde (1994) and Forde (1996). Interpretation of the images was carried out according to the procedures outlined by Annan and Cosway (1992) and Annan (1993).

Results

Laboratory analyses

Vegetation samples from the section unaffected by leachate contamination (area H in Fig. 1) showed a minimum, mean and maximum chlorophyll concentration of 814, 844 and 931 μg/kg respectively. In the section affected by leachate contamination, anomalously high concentrations of a number of heavy metals were present in the vegetation, soil and surface water up to 10 m from the edge of the landfill adjacent to cells 5 and 10 (Figs. 2, 3, 4).

GPR interpretation

The interpretation the GPR data was carried out using existing information on the site, including shallow-depth geology, water-table heights, waste disposal records, and previous research on the variable attenuation and reflection behaviour of radar waves with different soil and rock types, pore water compositions and water saturation levels (Peters and others 1994; Liner and Liner 1995; Meju 2000; Liu and others 2002; A.P. Annan, Sensor and Software Ltd., personal communication, 2000).

Mapping the internal structure of the landfill site

The first objective of the study was to determine whether GPR data could identify the structure and dimensions of

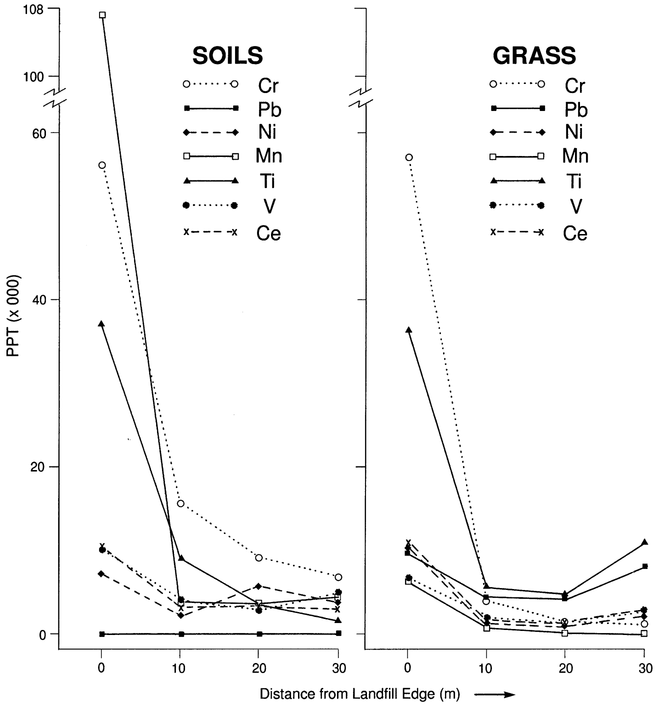

Fig. 2
Heavy metal concentrations in soil and grass from transect S, W & G (location shown in Fig. 1)

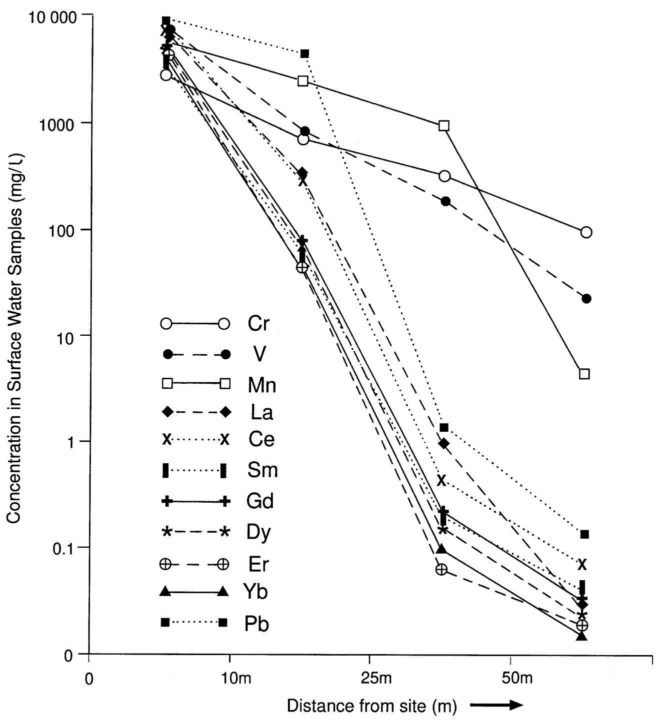

Fig. 3
Heavy metal concentrations in surface water from transect S, W & G (location shown in Fig. 1)

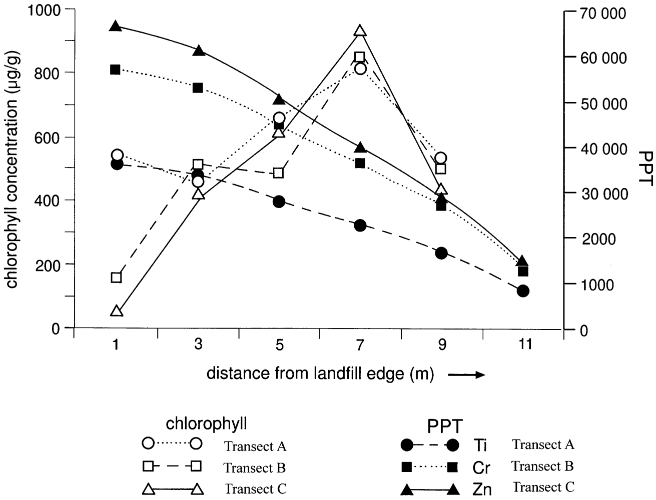

Fig. 4
Heavy metal concentration and chlorophyll concentration (µg/g) from transects A, B and C (locations shown in Fig. 1)

the buried waste, cap thickness and water table within the landfill. GPR surveys, using 50-, 100-, 200- and 450-MHz antennas, were carried out across three cells (5, 9 and 10) along transect 6 (Fig. 1). Due to differences in the age of the buried waste in each cell, some differences in the degree of compaction are likely to have occurred, causing slight differences in pore space and water saturation. After analysis of the whole GPR data set the 450-MHz data were found to be the most useful. Both the surface of and the contacts between the buried waste in the different cells gave subtle but distinct reflections (Fig. 5). The surface of the water table was clearly identifiable due to both the strong reflection from the surface and the distinct contrast in the strength of the strata reflections above and below the water table (Fig. 5). The relatively shallow depth of the landfill (2–3 m) combined with the relatively slight differences in dielectric constant between the waste in the different cells and the waste and soil are the most probable reasons for the higher-frequency GPR data being more useful.

Mapping the shallow-depth geology of the landfill site

The second objective of the study was to determine whether GPR data could resolve the shallow-depth geology below the landfill site. GPR surveys, using 50-, 100-, 200- and 450-MHz antennas, were carried out along transect 1 approximately parallel to the edge of the landfill site at cells 5 and 10 (Fig. 1).
After analyses of the complete data set the 450-MHz data were found to be the most useful. Three areas with significantly higher reflectance and more clearly defined layering were resolved down to a depth of 4 m (Fig. 6). After comparison with borehole data, these areas were identified as being most likely to be sand-gravel lenses. The surface of the water table again gave a strong reflection, and a distinct contrast in the strength of the strata reflections above and below the water table and away from the sand-gravel lenses was apparent (Fig. 6). The relatively shallow depth of the landfill (2–3 m) combined with the relatively slight differences in dielectric constant (caused

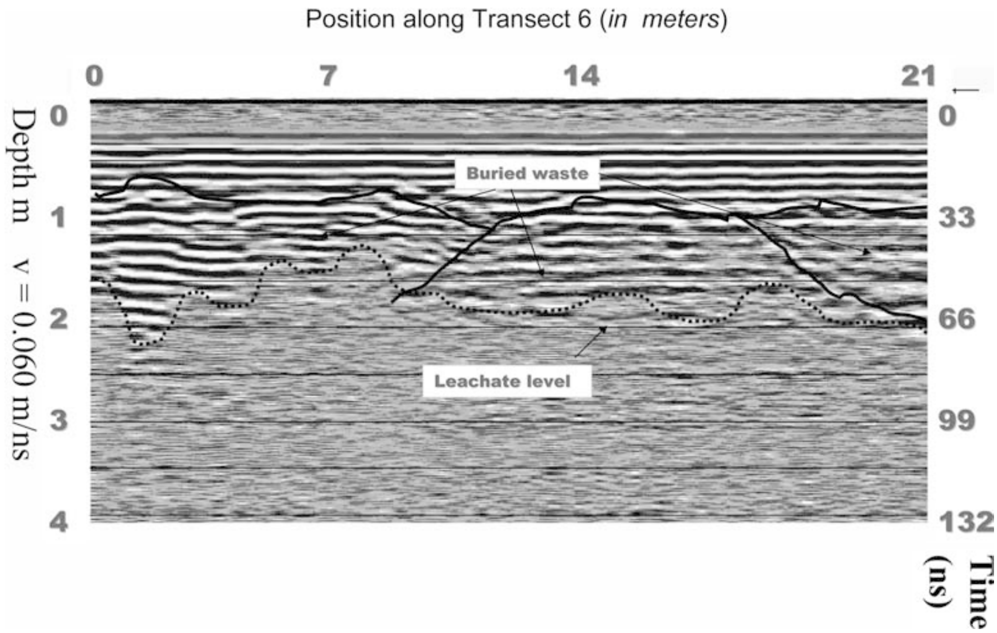

Fig. 5
GPR image (450-MHz) identifying the structure and dimensions of buried waste along transect 6 (location shown in Fig. 1)

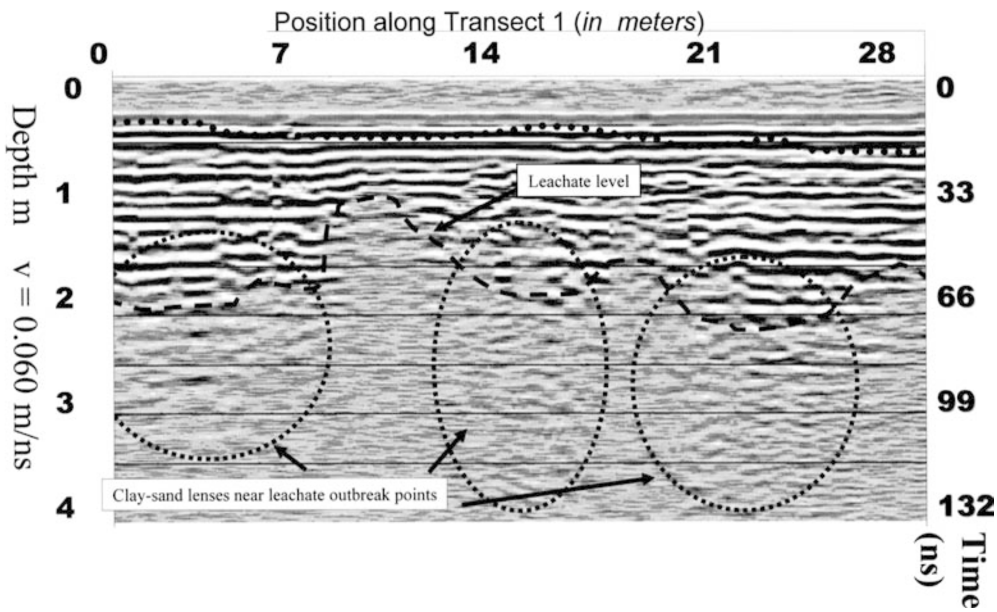

Fig. 6
GPR image (450-MHz) along transect 1 showing sand-gravel lenses parallel to the outer edges of cells 5 and 10 (location shown in Fig. 1)

by the difference in pore volume) between the sand and the sand-gravel areas are the most probable reasons for the higher-frequency GPR data being more useful.

Location of leachate breakout points along the landfill containment walls

Transect 5, shown in Fig. 1, identified an anomalous feature, 2 m wide and 12 m in depth, in the 50-, 100- and 200-MHz GPR images. The 50- and 100-MHz images identified the same depth and extent of the anomalous feature; however, the 100-MHz image gave much higher detail (Fig. 7). The anomalous feature was weak and poorly defined in the 200-MHz images. The survey area soil consisted of very dry sandy soil which the radar signal could penetrate to a considerable depth. At the anomalous feature the radar signal does not penetrate the soil smoothly but is seen to be absorbed in a distinct vertical strip approximately 12 m in depth and 2 m wide. This effect is most probably due to the pore water conductivity increasing due to the presence of leachate contaminant from the landfill, causing the radar signals to be more strongly absorbed and hence the signal penetration decreases.

Discussion

The utility of GPR in landfill mapping and monitoring applications has been demonstrated. This study has shown

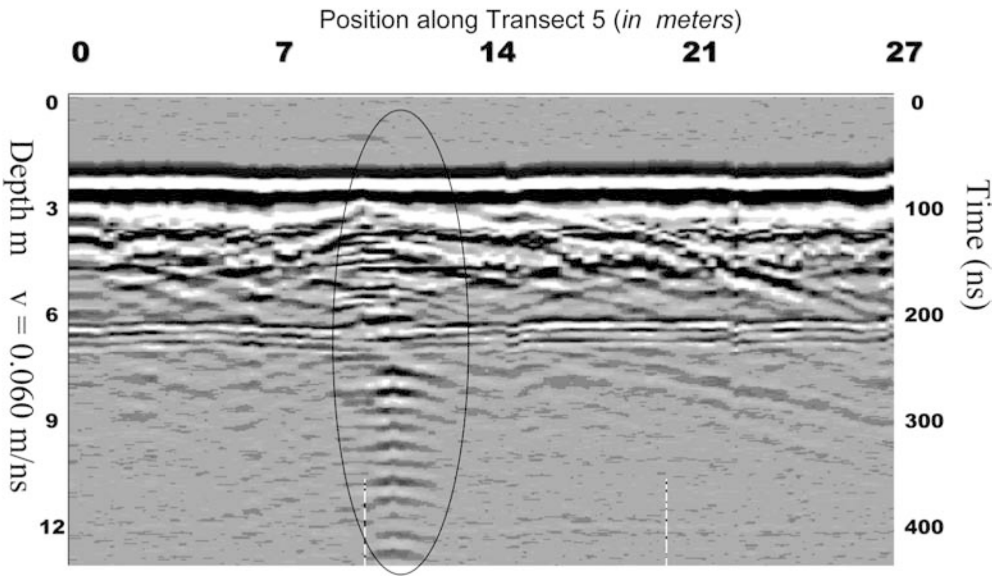

Fig. 7
GPR image (100 MHz) from transect 5. The anomalous feature is *circled* (locations shown in Fig. 1)

that the range of depths and dielectric contrasts found between the different underground features in and around landfill sites requires the use of an integrated, multi-frequency GPR data set. The capabilities of integrated, multi-frequency GPR surveys could therefore provide landfill operators, environmental agencies and commercial companies with a rapid, cost-effective methodology for assisting in the monitoring of leachate breakout points and enhancing contaminant migration modelling.

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