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Mapping landfill gas migration using resistivity monitoring

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Results of geoelectrical resistivity monitoring at two landfill sites, a bioreactor landfill and a conventional municipal solid waste landfill site over a week are reported. The main objective was to investigate if geoelectrical resistivity can be used for localising paths for landfill gas migration. The resistivity results were also related to local pore pressure measurements and to methane emission measurements using a laser-scanning instrument. The results suggest that the use of the interpreted resistivity and of its temporal variation can be suitable for the intended purpose, and confirm the applicability of resistivity imaging at landfills. It is also concluded that better knowledge about the dependence of resistivity variation to temperature, porosity and moisture content variations would improve the interpretation and that measuring or monitoring at least one of these additional parameters together with resistivity would be useful.

1. Introduction

Control and estimation of landfill gas emissions have become a major concern in landfill management, since, apart from the risks of fire and explosion and the odour nuisance, methane is a powerful greenhouse gas. Its effect is more than 20 times that of carbon dioxide, and landfills are regarded as one of the major anthropogenic sources (O'Leary and Walsh, 2002). The concentration of methane in landfill gas varies, often in a range between 40 and 60%, constituting an interesting energy resource as it can be used for heating and power generation. In recent years the development of upgrading techniques for landfill gas to vehicle fuel has further increased the interest for landfill gas utilisation. A large number of landfills, closed or active, are equipped with gas-collecting systems. However, their efficiency is often limited. In many parts of the world legislation requires measures for limiting gas emissions to the atmosphere and often also reporting of the gas emissions (Ljungberg *et al.*, 2008).

Attempts have been made to estimate the total gas emissions at landfills and to identify the areas with higher rates. With this purpose several techniques have been tested, for example infrared cameras, laser scanning and chambers for measuring the methane flux at the surface (see e.g. Ljungberg *et al.*, 2008). It has been pointed out that this is a difficult task even if the techniques have been shown to be useful. None of them can be regarded as entirely satisfactory. Furthermore, no information about what is happening inside the landfill can be

reported in that way. Zones with higher emission rates can be identified on the surface, such as, for example, slopes, where cracks easily open (see e.g. Ljungberg *et al.*, 2008), but the origin and the paths taken by the gas inside a landfill are not obvious.

Owing to the heterogeneous structure of municipal solid waste (MSW) landfills decomposition processes are highly non-uniform, resulting in variable gas generation rates at different locations in a landfill. The decomposition processes are, for example, dependent on the moisture content and the evolution degree of degradable waste.

Because a landfill is often constructed as a succession of horizontally compacted layers, the permeability is generally higher in the horizontal direction. However, other physical heterogeneities such as fissures also cause a non-uniform flow of gas following the path of least resistance. Thus, the processes involved in landfill gas generation and migration are complex, and they are controlled by a number of parameters: the temperature, the concentration of oxygen, the atmospheric pressure and the moisture content at depth, in the topsoil and in the air.

The electrical resistivity of an earth-like material depends on the ratio of the gas and water volume in the pores, as well as on the temperature, the salinity of the pore fluid and on the overall porosity. Generally speaking, the equations to consider depend

on the kind of current conduction involved: through the ions and particles present in the pore water, by way of surface conduction and on their relative importance. Archie's Equation (Archie, 1942) takes only the first kind of processes into account. It can be expressed for the unsaturated medium as

$$1. \quad \rho = a\Phi^{-m}\rho_w S_w^{-n}$$

where ρ is the electrical resistivity, ρ_w the resistivity of the pore water, Φ the porosity, S_w the saturation defined as the ratio of the volume of pore water to the total pore volume. The constant a lies generally between 0.6 and 1, the cementation exponent m generally lies between 1.4 and 2.2 in common rocks and the saturation exponent is close to 2 (e.g. Ward, 1990). This equation has been used for MSW material (Grellier, 2005), where the conductivity of the pore water is generally high. Its relative simplicity makes it attractive. Nevertheless, it might not be entirely satisfactory for waste materials where the surface conduction can be expected to be relatively important. An indication for that is the high induced polarisation usually measured on municipal landfills (see e.g. Carlson *et al.*, 1999; Dahlin *et al.*, 2002; Leroux *et al.*, 2007). Other models such as the equation proposed by Waxman and Smits (1968) might then better describe the electrical resistivity in such materials. However, this kind of empirical model requires calibration with laboratory data to assign values to the different parameters (see e.g. Mavko *et al.*, 2009). Very little data is available at present that concerns waste materials, and the heterogeneity in waste will probably render predictions difficult.

The resistivity furthermore depends on the temperature, following an equation given by Keller and Frischknecht (1966)

$$2. \quad \rho_t = \frac{\rho_{18}}{1 + \alpha(t - 18)}$$

where t is the temperature in °C, ρ_{18} is the resistivity at 18°C, ρ_t the resistivity at the temperature t and α is a constant depending on the material considered and on the pore water composition. It is classically given as $\alpha = 0.025$ per °C (Ward, 1990). Grellier *et al.* (2006) have shown that this equation is applicable for the leachate found in MSW, with comparable values for α , slightly depending on the type of ions present in the leachate, their concentration as well as the concentration in solid particles in suspension.

The conduction of electricity in MSW is a complex phenomenon, depending on several parameters. A more precise description of their influence requires laboratory measurements and experimentations, as reported for example in Moreau *et al.* (2008). Consequently, the resistivity alone cannot be directly translated into a gas or methane concentration of the material.

But the presence of a certain amount of gas is likely to influence the material's resistivity, because of the change in temperature, humidity and possibly porosity induced. Especially gas emissions have been observed to be intermittent, showing that the changes vary considerably with time (Ljungberg *et al.*, 2008). The paths taken by the migrating gas could then be detected by monitoring resistivity; that is by mapping its variations with time. The time scale to consider lies probably in the range from a few hours to a few days.

Electrical resistivity imaging is a relatively well-known method and has been used for a number of landfill applications. Its principles are described in, for example, Zonge *et al.* (2005). In short, a number of electrical potentials are measured between pairs of electrodes while transmitting current between two other electrodes. A large number of electrodes positions are used so as to provide an adequate coverage of the volume. In practice it is, however, often only possible to place the electrodes on the ground surface. Since landfills are very heterogeneous media it is appropriate to try to create a three-dimensional (3D) image by placing the electrodes on a grid and measuring along parallel lines. The measurements are processed by inversion to produce the image, which generally consists in iterative computations aiming at finding a realistic resistivity model with a numerical response sufficiently close to the one measured.

In a field experiment conducted in 2007 at the Filborna landfill in Sweden, resistivity was measured at several locations with stationary electrodes placed on 11 parallel lines. Simultaneously, the methane concentration at the surface was measured using a laser-scanning unit, and methane flux at discrete locations was measured by the static chamber method. The measurement showed zones where large resistivity variations were clearly correlated with zones of high gas emissions (Dahlin *et al.*, 2008). Prior to that, growing resistive anomalies had been observed under experiments of leachate recirculation at bioreactors, and they had been interpreted as gas accumulation and migration (e.g. Rosqvist *et al.*, 2005; 2007).

These considerations led the present authors to conduct two large-scale monitoring experiments at two different landfill sites producing landfill gas. Two experiments of resistivity monitoring were conducted at two sites: a bioreactor landfill and a conventional MSW landfill. 3D models of resistivity and resistivity variability were compared with gas pressure at depth and with methane concentration at the surface using a laser-scanning technique.

2. Material and method

2.1 Resistivity monitoring

In the two field experiments geophysical resistivity monitoring was carried out with the ABEM Lund imaging system. Nine parallel lines of electrodes were set up. Each line was 20 m

long with 21 electrodes placed regularly every 1 m. The lines were equally spaced with 2 m between them. The array used for the measurements was the pole–dipole, in both forward and reverse configurations. Each site was monitored successively during one week with a remote-controlled system, with automatic data transfer to a server at Lund University for data processing and inverse modelling. The time for the 50% duty injection cycle was 1 s, which is sufficiently short to make it possible to measure all the lines (3888 measurements) within about 1 h and 45 min, and also sufficiently long to allow for the potential to stabilise. Charge-up and polarisation effects are notoriously important at landfills (Carlson *et al.* 1999; Dahlin *et al.* 2002; Leroux *et al.* 2007) and measuring too hastily can result in underestimating the resistivity. The data have to be processed by inversion before a resistivity image of the studied area can be produced. All data for each complete set of measurements were inverted together using Res3Dinv (Loke and Barker, 1996; Loke, 2008). A true 3D model was computed independently for each time-step, using the same parameters and the same grid geometry. The L1-norm or robust inversion method was used, which implies the minimisation of the absolute discrepancy between the measured and the computed data. This method is less sensitive to noise and is able to reconstruct models with sharp boundaries (Loke *et al.*, 2003).

A single resistivity image accounts for the overall structure at the landfill, but resistive anomalies cannot be directly interpreted as mainly due to landfill gas, since higher resistivity can be attributed to other causes, as discussed above. It is not clear whether the presence of landfill gas should always result in higher resistivity either. Therefore, the present authors have chosen to interpret a single resistivity image in terms of the structure of the landfill, and to interpret the variation of resistivity with time as an indicator of the presence and migration of landfill gas. In some cases the variation of resistivity might confirm what can be suspected from the landfill structure, but new features might also be detected. To estimate the variations of resistivity during

the monitored period, the variation coefficient (C_v) has simply been computed for all the inverted models and calculated as

$$3. \quad C_v = \frac{\sigma}{\bar{\rho}}$$

where $\bar{\rho}$ is the mean resistivity value for one cell and σ is the standard deviation given by

$$4. \quad \sigma = \frac{1}{N} \sqrt{\sum_{i=1}^N (\rho_i - \bar{\rho})^2}$$

In the latter equation ρ_i is the interpreted resistivity value for one cell for the i th measurement, and N is the number of interpreted measurements for the considered cell over the studied time period.

The variations of resistivity were visualised in different ways, including 3D representations and depth slices. These have been plotted together with depth slices of the resistivity in order to facilitate comparison. The results were then interpreted using other kinds of available information.

2.2 The investigated landfills

One experiment comprised measurements on a bioreactor landfill in May 2008. Its dimensions are 120 × 60 m with an initial depth of about 16 m and it is covered with a plastic liner (see Figure 1). It was filled during 2000–2001 with moulded and mixed MSW that was irrigated before it was put in place.

In the other experiment, measurements were made on the conventional MSW Filborna landfill site in August 2008. It stands as a topographic height built in horizontal layers of MSW. Each layer is about 2 m thick and is subdivided into smaller cells by a number of compost walls (see Figure 2). The uppermost layer was completed in 2007. It was then covered by inert material, locally removed for this purpose.

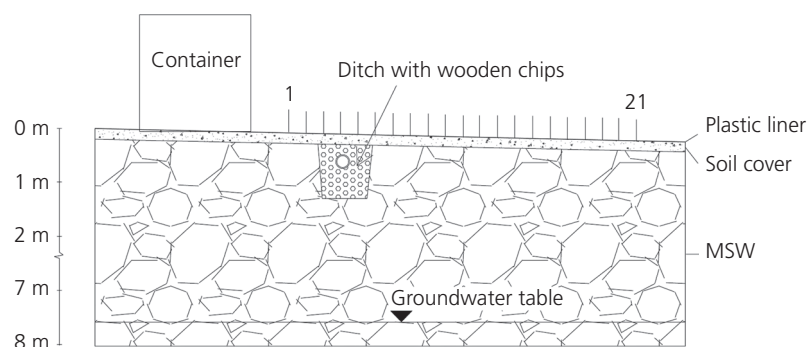


Figure 1. General cross-section of the bioreactor landfill for the investigated area in the direction parallel to the lines

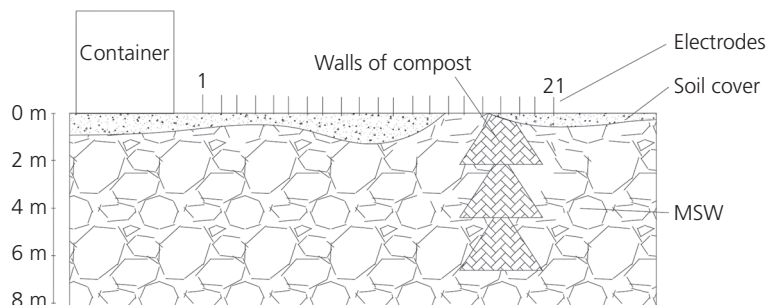


Figure 2. General cross-section of the Filborna landfill for the investigated area in the direction parallel to the lines

Both sites produce gas in significant amounts, collected by way of a network of horizontal pipes at the bioreactor landfill, and by way of both vertical and horizontal pipes at the Filborna landfill. At each of the landfills, the size of the monitored area is 20×16 m. Both landfills are situated at a waste management site managed by NSR in Helsingborg in southern Sweden. During the monitored weeks nothing specific happened at the sites and the passive gas extraction took place as usual.

On each site the climatic data (i.e. precipitation, atmospheric pressure, air and upper soil temperature) were recorded locally. The geophysical measurements reported here were taken during a warm and sunny week on the bioreactor, and during a rainy week on the Filborna landfill. The groundwater level is found at about 7 m depth at the bioreactor landfill and at much greater depth at the Filborna landfill.

Moreover, at the Filborna landfill site local flux of methane emissions was measured using the static chamber method and soil moisture using the time domain reflectometry (TDR) technique. These results are presented in Johansson (2009).

2.3 Laser scanning

On the Filborna landfill site, the methane concentration in the air was measured by scanning the area with a hand-held Siemens AG, CT PS 8 laser system instrument, specifically developed for field-based remote detection of natural gas. It measures the backscattering of an infrared laser beam at a frequency specifically absorbed by methane molecules. This way it yields a concentration expressed in parts per million (ppm/m) and even signals the presence of methane by a sound, making its use convenient in the field. In the current study the instrument was moved about 1 m above the ground surface over the monitored area. One drawback with this technique is that it yields rather qualitative estimations of the emissions, owing to the fact that methane molecules are very light and quickly rise in the air. Furthermore, the values that can be obtained are strongly dependent on the wind, which

can cause rapid gas displacements that are difficult to predict (Ljungberg *et al.*, 2008). The measurements were obtained by scanning the area on several occasions under calm conditions during the monitoring period.

2.4 Pore pressure measurement

With the purpose of correlating the variation in resistivity with a variation in pore pressure, which it was assumed would be caused only by gas pressure variation, the subsurface pore pressure was measured on two locations at the bioreactor using a BAT MKIII Vadose sensor, designed for measurements in unsaturated soils (Torstensson, 1984). Plastic pipes were used to connect the cable to the sensors in order not to disturb the resistivity measurements. The sensors were installed about 1 m below the ground surface, at the locations indicated in Figures 7(a) and 8(a) (see later) and continuous monitoring was carried out for one month at each site. Early results from the resistivity measurements were used for choosing the positions of the sensors. On both sites one sensor was placed on a high resistive area, and the other one on a low resistive area.

3. Results

3.1 Resistivity

Figure 3 shows a 3D model of the resistivity for one measurement conducted on 20 May 2008 at the bioreactor landfill. The inverted resistivity was relatively low, below $10 \Omega\text{m}$ in large parts over the area. These low values are probably attributable to the high organic content in the waste, and to the expected high moisture and high ionic content (salinity). A ditch filled with wooden chips where a gas-collecting pipe (see Figure 1) was installed is clearly visible as an elongated resistive structure, perpendicular to the resistivity lines. The same ditch was also clearly indicated in previous investigations at the bioreactor landfill (Rosqvist *et al.*, 2003; 2005; 2007). The wooden chips around the gas pipe in the ditch have a high porosity and subsequently high gas permeability. These considerations result in expectation that the ditch would be an important path for gas migration, which to some extent could explain the high resistivity observed.

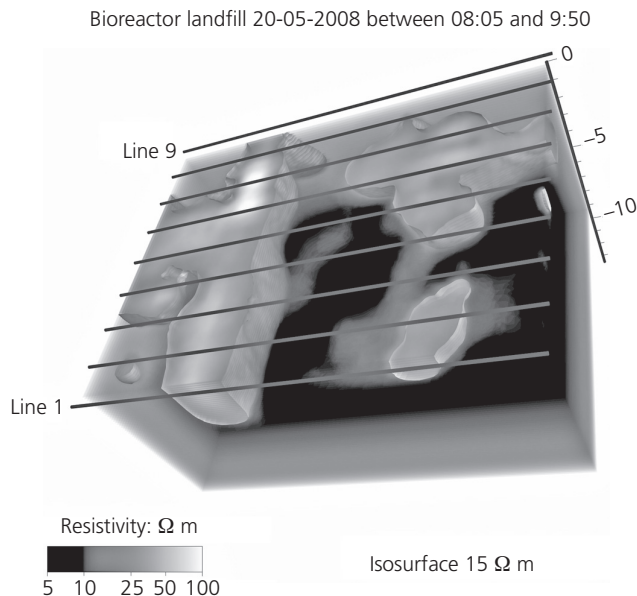


Figure 3. 3D resistivity model at the bioreactor landfill from the measurements made on 20 May 2008

Other highly resistive bodies are visible to the right of the ditch on Figure 3 between about 10 cm and 2 m depth. There are no known internal structures explaining these superficial bodies. It is suggested that the highly non-uniform structure in the waste, for example owing to different stages of decomposition in the waste and possibly in combination with gas migration, contributes to these anomalies.

Figure 4 shows a 3D model of the resistivity for one measurement made on 18 August 2008 at the Filborna landfill. The inverted resistivity varies from very low (under $3 \Omega \text{m}$) to relatively high (over $500 \Omega \text{m}$) values. However, most of the resistivity values lie in the range usually shown by investigations on MSW, that is between very low resistivity and up to approximately $50 \Omega \text{m}$.

An elongated, asymmetrical prismatic structure with low resistivity (below $10 \Omega \text{m}$) and whose size increases at depth can be observed on the right part of Figure 4. This feature corresponds well to the subsurface compost wall present in the area (see Figure 2). Inside it runs a plastic pipe transporting gas from a nearby vertical collecting well. Although the pipe is not perforated, it is possible that gas also circulates around it. Generally compost is relatively loose and porous, facilitating gas migration. The low resistivity shown is possibly due to its high organic and moisture content.

A large superficial high resistivity area is observed above and around the compost wall, where values above $500 \Omega \text{m}$ are reached. This area is particularly interesting because landfill gas migration from the landfill to the atmosphere is likely to take place there.

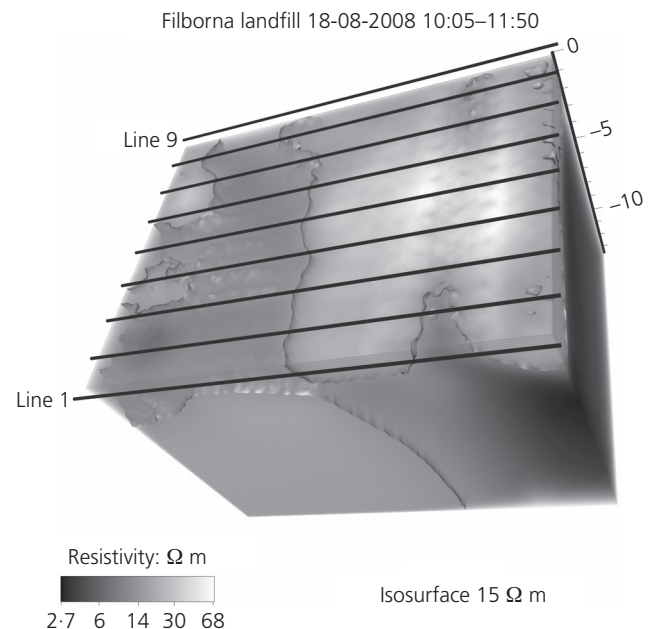


Figure 4. 3D resistivity model obtained from the measurements conducted at the Filborna landfill on 18 August 2008

At the surface several lines can be observed with visible electrode positions marked as dots. This is an artefact arising during the inverse modelling procedure, which could most likely be reduced by optimising the software settings or the code. But, regardless of the dots, a superficial high resistivity zone above and around the compost wall can be attested.

3.2 Resistivity variation

Figure 5 shows a 3D plot of the coefficient of variation of the inverted resistivity for 72 measurements taken between 20 May and 25 May 2008 at the bioreactor landfill. The coefficient of variation is relatively low, below 0.02 in large parts of the landfill and especially at depth. A few superficial zones appear clearly with larger values, larger than 0.1 and in some cases up to 2.7. Many of these zones are found in the area where the ditch filled with wooden chips is located. A few others are located to the right of the ditch, in the area exhibiting large resistivity visible in Figure 3.

Figure 6 shows a 3D plot of the coefficient of variation of the inverted resistivity for 59 measurements taken between 18 August and 22 August 2008 at the Filborna landfill. Here too, the coefficient of variation is low, below 0.01, over most parts of the landfill, and especially at depth. But superficial volumes with larger coefficients of variation can be identified, with values over 0.07. The largest and most apparent of these volumes is situated over and around the compost wall, in the area where large resistivity values are found in Figure 4.

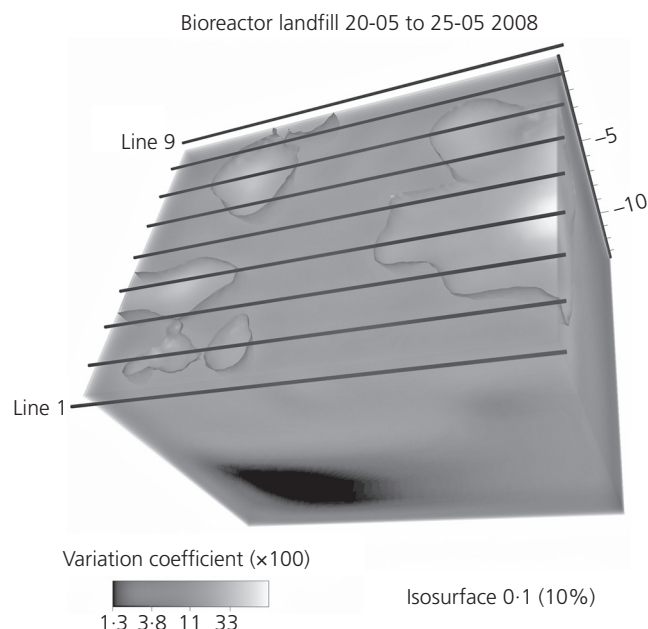


Figure 5. Coefficient of variation of the inverted resistivity on the bioreactor landfill for measurements made between 20 May and 25 May 2008

3.3 Location of resistivity variation relatively to the resistivity structure

In order to investigate if spatial correlation was indicated in the results between the inverted resistivity value and its variability,

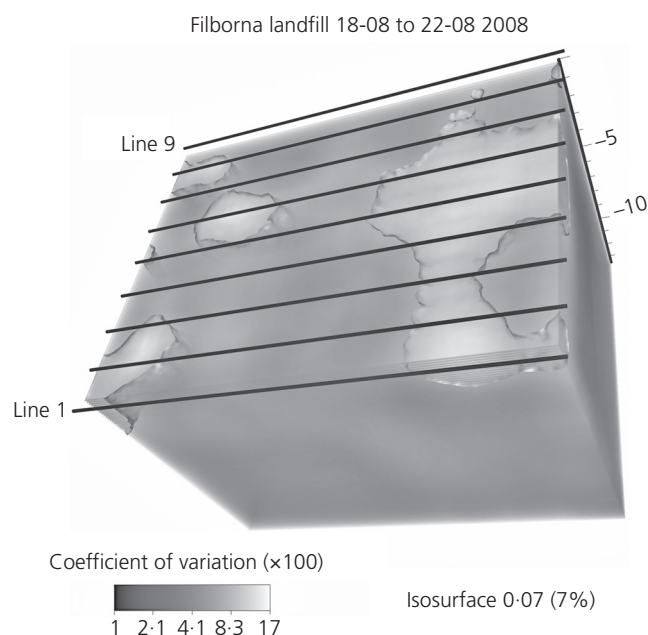


Figure 6. Coefficient of variation of the inverted resistivity on the Filborna landfill for the measurements made between 18 August and 22 August 2008

the inverted resistivity for the first considered measurement and the coefficient of variation for the whole time period analysed here were plotted together on six horizontal surfaces with increasing depths. This was done for the two sites, on respectively Figure 7 for the bioreactor landfill and Figure 8 for the Filborna landfill.

At the bioreactor landfill, in the area where the ditch is located and in the area at the edge of the field plot, a gradient between high and low resistivity and high coefficient of variation overlap. This clearly indicates zones with variable resistivity near the zones with relatively high resistivity. However, there are also areas where a high variability in the inverted resistivity was not correlated with a gradient between low and high values.

At the Filborna landfill, high superficial resistivity as well as high variability are observed over and around the subsurface compost wall. Another area with large coefficients of variations was found at a location at $x = 2$ to 8 m and $y = 8$ to 12 m. In this zone, both high and low resistivity can be observed. This shows that causes other than a resistivity gradient or high resistivity need to be considered to explain the high variability of the data.

3.4 Variability of resistivity with depth

In Figure 9 the mean inverted resistivity and its coefficient of variation for the one week measurements, both calculated for whole horizontal layers at the bioreactor landfill and at the Filborna landfill are shown in 17 layers, representing depths from 0.1 to 13.6 m.

In general, the mean inverted resistivity values at the bioreactor landfill are low, with the highest values close to the surface and showing approximately $20 \Omega\text{m}$. From 1 m depth down to approximately 7 m depth the inverted resistivity decreases to values below $5 \Omega\text{m}$. At greater depths the mean resistivity is almost constant. The groundwater measurements showed the groundwater table at approximately 7 m, which partly could explain the relatively low values below this depth. It could also contribute to the low coefficient of variation under the groundwater table, where the resistivity is probably essentially dominated by the leachate. In addition the distances between the electrodes are relatively small, and the total layout length is only 20 m, which results in low resolution in resistivity data already below a few metres in such a conductive environment, and consequently less variable data.

At the Filborna landfill the mean inverted resistivity is relatively high close to the surface ($50 \Omega\text{m}$) and decreases rapidly down to approximately $20 \Omega\text{m}$ at 1 m depth. Below 2 m depth the mean resistivity stabilises at $25 \Omega\text{m}$. The remains of the partly removed inert soil cover are probably caused by the relatively high resistivity of the most superficial layers.

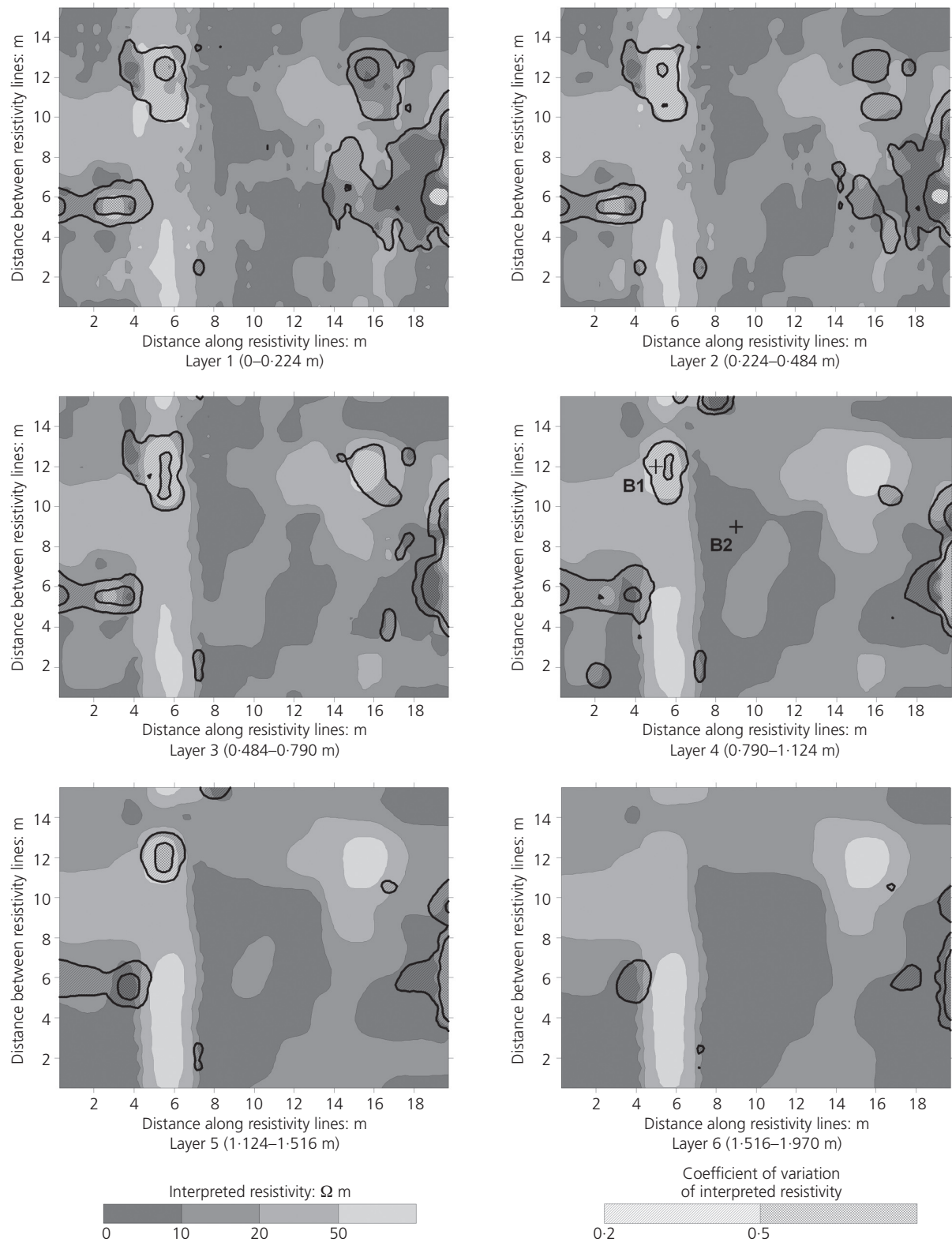


Figure 7. Bioreactor landfill, six horizontal plans where the inverted resistivity and its variability have been plotted

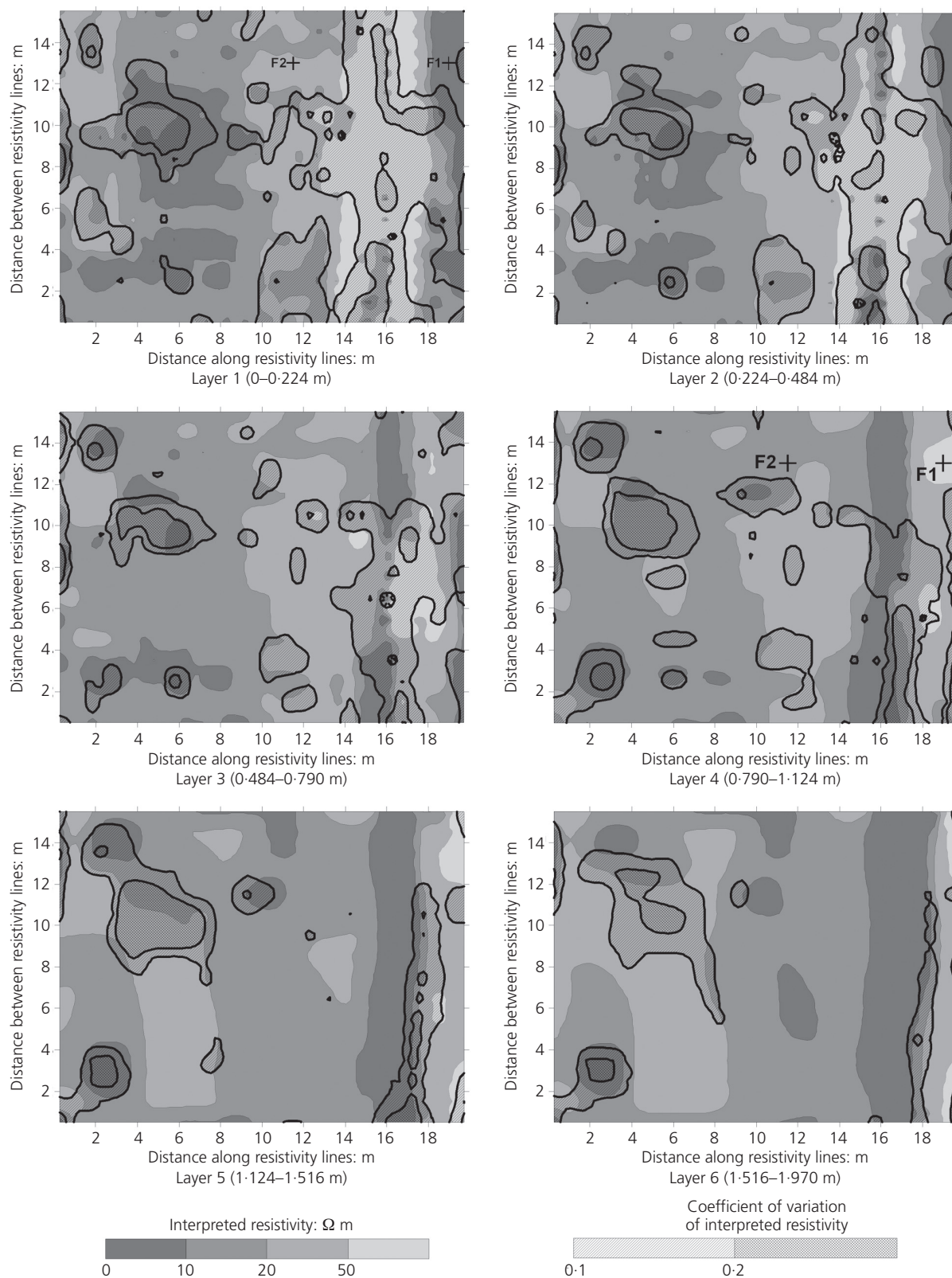


Figure 8. Filborna landfill: six horizontal plans where the inverted resistivity and its variability have been plotted

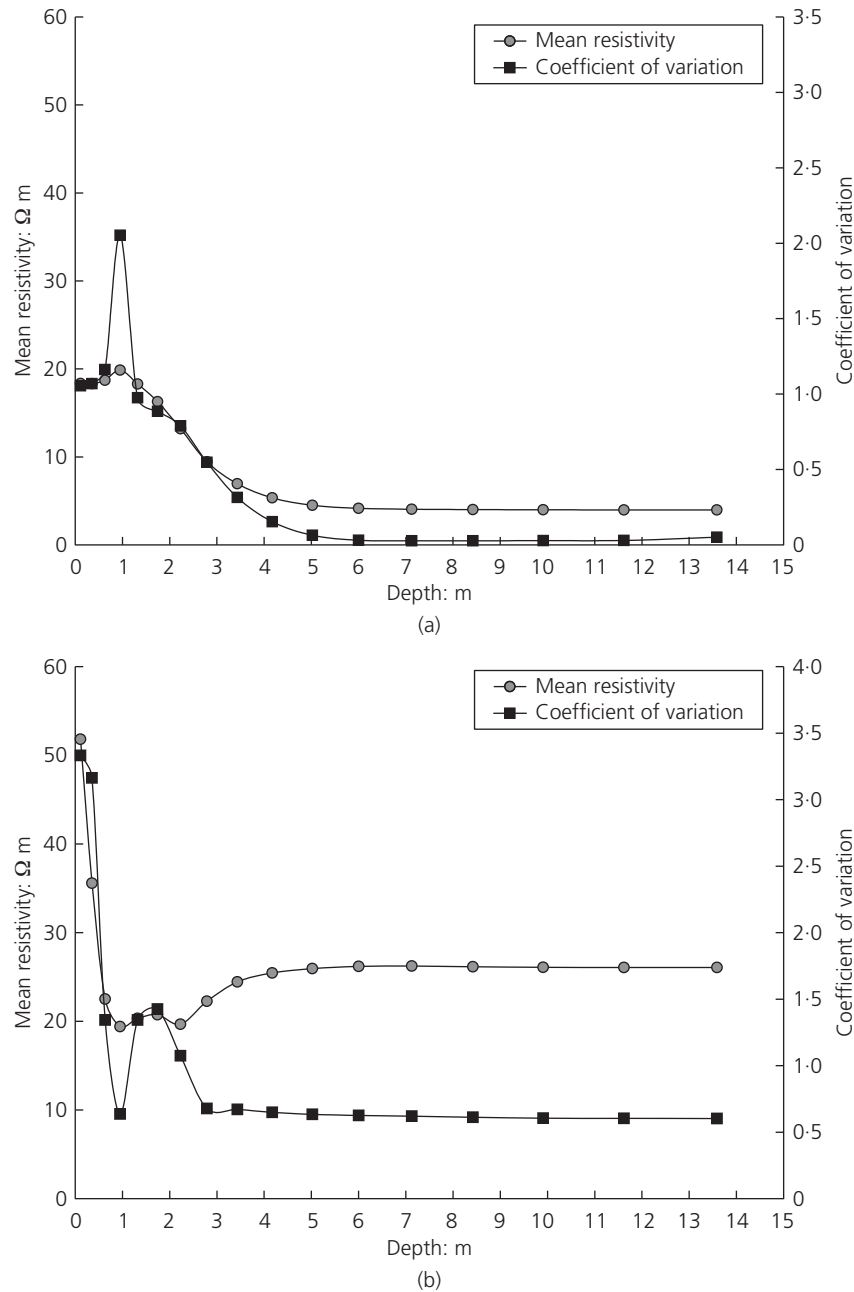


Figure 9. Mean resistivity and coefficient of variation at different depths at the (a) bioreactor and (b) Filborna landfills (calculated for all cells in a layer)

At the bioreactor landfill the uppermost layers show relatively high coefficients of variation with a peak at layer 4, which is found at approximately 1 m depth. Under this depth the coefficient of variation decreases down to approximately 0.2 at about 5 m depth. At greater depths the coefficient of variation remains low, about 0.2, and constant.

The coefficient of variation at the Filborna landfill shows a similar pattern with large values (over 3) in the most superficial layers and much lower and relatively stable values at depths below 2 m (0.7 to 0.6). A peak appears here also between 1 and 2 m depth with values rising to approximately 1 to 1.5.

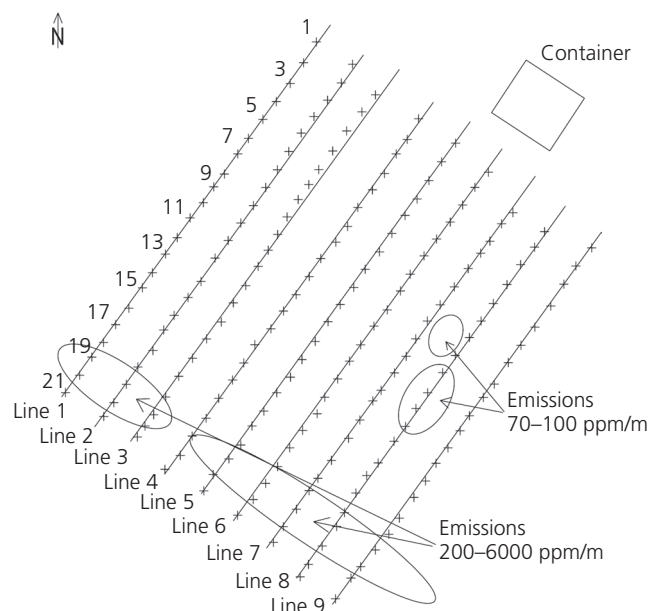


Figure 10. Methane concentration at the surface above Filborna landfill obtained with laser scanning between 18 August and 22 August 2008

3.5 Methane emissions at the surface

On Figure 10 laser-scanning results at the Filborna landfill show high levels of methane emissions (between 200 and 600 ppm/m) at the surface along the subsurface compost wall. An area with emissions at lower levels (between 70 and 100 ppm/m) is also found over the monitored area. This figure summarises the outcome of several measurements over a few days. The locations of higher methane concentrations were stable, but the concentrations were variable. Their range is therefore given, instead of mean values, in order to express this variability. The high levels of methane emissions along the compost wall are particularly interesting since they coincide well with the high inverted resistivity values and their high variability found in this zone (Figures 4, 6 and 8). The localisation of methane emissions correlates well with the localisation of inverted

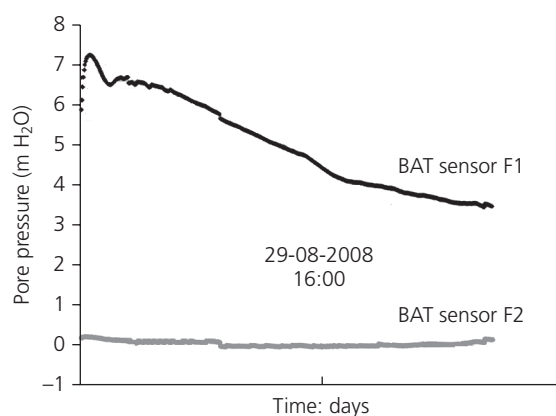


Figure 12. Pore pressure measurements on the Filborna landfill between 22 August and 3 September 2008

resistivity variations, showing that the latter can be interpreted as an indication of methane leakage along the compost wall.

3.6 Pore pressure monitoring

Figure 11 shows a negative pore pressure of approximately 1 m H₂O for sensor B1 in the bioreactor landfill, possibly explained by the gas uptake by way of the closely situated gas collection pipe. Initially the sensor B2 registered a pressure of 3 m H₂O, but then gradually decreased to a rather stable value of 1.5 m H₂O after a month. The decreasing pore pressure could be explained by a gas leakage through the bentonite sealing surrounding the Bat sensor pipe or a generally decreasing gas pressure at this location.

In Figure 12 the sensor F1 placed in a high resistive area at Filborna landfill shows a high pore pressure, initially at a maximum value of 7 m H₂O. During the monitored period the recorded value decreases gradually, similarly to what happens for sensor B2 on the bioreactor. After 12 days the pore pressure was 3.5 m H₂O on this location. This decrease could, as for the sensor B2, be explained either by a gas leakage through the bentonite sealing surrounding the Bat sensor or by a generally

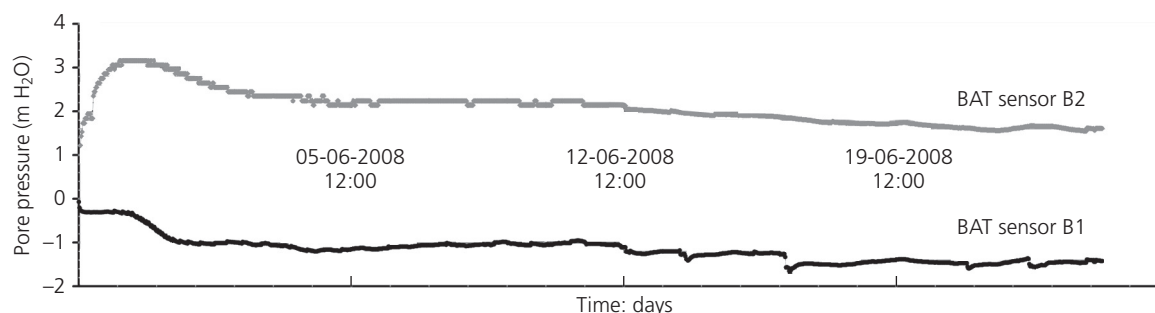


Figure 11. Pore pressure measurements on the bioreactor landfill between 19 May and 24 July 2008

decreasing pore pressure in the area. The sensor F2 was placed in a low resistive area. The measured pore pressure stayed stable and close to 0 m H₂O under the whole monitored period. This correlates well with the low resistivity and low variability assumed as indicating low gas activity.

At both sites the groundwater level was below the depth of the sensors and, therefore, the most plausible explanation of the large positive pore pressure values on sensors B2 and F1 particularly is the presence of landfill gas.

4. Discussion and conclusions

In this study the main focus was on the temporal and spatial variation of the inverted resistivity, since it was assumed that variability, in particular temporal variability, could indicate gas migration.

The results of the resistivity measurements were regarded as consistent since the resistivity values found lie in the same range as in previous investigations at MSW landfills, some of them also made on the bioreactor landfill. Large variations in the interpreted resistivity coinciding with large interpreted resistivity values have been found at several areas on the two monitored sites, a bioreactor landfill and an ordinary MSW landfill. A large range of materials with very different resistivity can be assumed in the landfills. Yet the resistivity structure was consistent with the known existing structures inside both sites, that is, a trench filled with wooden chips in the bioreactor landfill and a compost wall in the Filborna landfill. These structures can also be expected to constitute important migration paths for the landfill gas, since they have a relatively high porosity and in the bioreactor landfill the ditch contains a pipe for landfill gas collection. Thus, the results of the study confirm that resistivity remains a powerful tool for detecting internal features in landfills.

At the Filborna landfill the resistivity values were most variable in delimited superficial areas over the subsurface compost wall. In this area also high methane concentration was measured in the air using the laser-scanning instrument. This strengthens the interpretation of the high variability in the interpreted resistivity being an indicator of landfill gas migration. In fact, the clear correlation between subsurface measurements by means of resistivity and the laser-scanning results above the surface is regarded as the most interesting result in this study.

The successive time steps were inverted separately without any constraints between successive models that could focus the inversion on the changes. This could possibly result in artefacts, but this effect was minimised by the use of the same geometry and parameters all along, as well as a low number of iterations. Time-lapse procedures are generally preferable, but the choice of the reference model can be difficult. In the study presented here, the amplitude of the observed variations and the

consistency of their pattern support the interpretation of them being caused by actual physical changes inside the landfill.

The resistivity variations were found to be more pronounced at the superficial zones and they decreased generally with depth, to reach small values below a few metres. One explanation is the limited depth of investigation owing to the experimental set-up; that is, with relatively small distances, over an overall conductive landfill mass. Consequently, only limited information could be achieved about the resistivity at depth. An illustration of this general limitation is given in Jolly *et al.* (2007), with computed examples. A complementary explanation is the expected large temporal variations close to the ground surface, most sensitive to variable atmospheric influence. As a result of gas migration from greater depths, it can be assumed that the landfill gas content is higher close to the surface. However, it should be pointed out that deeper structures containing large amounts of landfill gas most likely exist.

It has been shown that it is possible to detect gas accumulation and leakage at the surface but it would also be desirable to localise where the gas forms as well as its migration paths. Since the results demonstrate that superficial areas with higher gas pressure and/or migration can be localised, zones at greater depths containing significant amounts of gas may be found, provided that appropriate geometrical configuration is used in the resistivity monitoring. It is therefore suggested that future investigations should aim at detailed measurements at greater depth using this technique.

The use of geophysical resistivity monitoring for imaging paths of gas migration at landfills is promising, even if the internal process in the waste mass is complicated and the variation of resistivity is attributable to several intricate factors. The resistivity technique has reached such a state that it is possible to use in real-case applications to reasonable costs. When monitoring, the only part of the equipment that must stay in place is the electrodes, and they constitute the cheapest and least vulnerable part. Since the gas emissions and the resistivity variations happen relatively quickly and irregularly in time, it is important to measure resistivity over time. Simple field procedures, involving less measurement, could give good results in practice at lower costs. An example of such a field survey is given in Dahlin *et al.* (2008).

More accurate knowledge about the dependence of resistivity variation to temperature, porosity, organic content and moisture content in MSW materials would contribute to a safer interpretation of the results. It has been noted in studies concerning the dependence of resistivity to the salinity of the pore water (e.g. Taylor and Barker, 2002 in sandstones) and in studies concerning its dependence to the temperature (e.g. Aaltonen, 2001 in soils) as well as in studies concerning its dependence to moisture (e.g.

Moreau *et al.*, 2008 in waste) that it could vary depending on the nature of material considered and on its internal structure. Therefore general laws based on extensive laboratory measurements on different samples of MSW materials could be extremely useful. The dependence of resistivity to the above-named parameters in MSW has still only been partially investigated.

Since the resistivity in waste depends on several interacting parameters, it would be useful to measure at least one of them when monitoring, for instance the temperature. It is relatively easy to do this on the ground surface, but installing sensors at depth can be complicated and costly.

Furthermore, for future investigations it is essential to collect all available information about the landfill in question, such as: its construction, its age, the deposited waste, properties of the leachate, possible watering pipes, the gas extraction system and information about gas leakages. This kind of information is important to ensure high quality in the interpretation of the resistivity results.

With the aim of a better understanding of the gas processes in MSW landfills, it is concluded that the techniques described here can be used and improved by future research and development focused on studies at different scales, and on the interaction between different processes.

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