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Editorial

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The role of geophysical methods in obtaining information on sub-surface soils has become increasingly accepted in conventional geotechnical engineering practice. However, the need for careful interpretation remains because in most cases, parameters are measured by proxy (e.g. shear wave velocity for stiffness, electrical resistivity for moisture content) rather than directly. This means that what is actually being measured may often be affected by parameters other than that which it is desired to assess. In a waste landfill, the potential for confusion is likely to be magnified by the highly heterogeneous nature of the material being investigated, the presence of gas and the chemical complexity of both the solid and the liquid phase. For example, while it has been attempted for some time to use measurements of electrical resistivity as a proxy for water content, the usefulness of the results has been highly variable.

The papers in this issue of *Waste and Resource Management* originated from a two-day workshop held in Malmö, Sweden, in November 2008, which brought together landfill engineers and specialists in geophysics to discuss the current strengths and limitations of geophysical methods applied to landfill planning, engineering and management. Discussion of the presentations made at the Malmö workshop led to the following observations and recommendations for future work.

The most common application of geophysics in landfills at present involves the measurement of electrical resistivity, usually to try and detect leachate plumes or liquid movement/water content within landfills. However, water content is just one of a number of factors affecting the electrical resistivity; others include the porosity, the conductivity of pore fluid and the composition/clay content/mineralogy of the solid phase. The probability of interference from other influences should be taken into account in interpreting the data. Combining measurements of electrical resistivity with another measurement, for example the induced polarity or chargeability of the ground, can enhance the usefulness of the geophysical data obtained. In particular, the use of the normalised chargeability (defined as the induced polarity divided by the electrical resistivity) looks promising, perhaps eliminating the effect of the pore fluid electrical conductivity. It is possible to capture potentially useful information from the decay curve of electrical charge – something that is not often attempted at present.

In interpretation some artifacts and loss of definition with depth are inevitable, especially with surface measurements. The choice of inversion technique can help reduce this, for example 'robust' inversion in the standard program Res2D (Loke *et al*., 2003). It is still necessary however to try to establish 'ground truth', for example by coordinating geotechnical and geophysical investigations to obtain supporting information (e.g. on density/porosity and pore fluid/solid phase chemistry) and using prior knowledge to constrain inversion to reduce the occurrence of artifacts. It is not clear whether it is better to carry out a full 3D investigation, or to interpolate between 2D survey lines to obtain a 3D picture. Standard inversion software may be applicable in layered systems but is less likely to be suitable in systems containing vertically-oriented inhomogeneities. Generally, geotechnical engineers should become more closely involved with the development of inversion algorithms for use in realistic ground conditions.

Considering future work, parameters are perhaps not investigated as fully in the laboratory as they should be. The main application of geophysics seems to be to detect leachate plumes or liquid movements within landfills, but do we or should we look at the expected changes in resistivity and relate these to the actual site data? Continuous monitoring, with electrodes left permanently in place, may be beneficial in identifying changes in conditions leading to changes in electrical resistivity. What is the effect of waste degradation on the geophysical measurements made?

The papers published in this issue of *Waste and Resource Management* illustrate and amplify some of these issues. The paper by Rosqvist *et al*. (2011) describes the application of electrical resistivity measurements at two landfill sites in an attempt to identify landfill gas migration pathways. One of the landfills was operated as a bioreactor at an enhanced moisture content with leachate recirculation to encourage degradation and gassing, the other was operated conventionally. Continuous geophysical measurements were made over a period of time together with pore pressure and methane emission monitoring, the latter using a laser scanner. The results were promising, but the need for further knowledge of the dependence of electrical resistivity on temperature, porosity and moisture content was identified together with the desirability of measuring at least one of these parameters in addition to the resistivity.

Moreau *et al*. (2011) describe a study of the relationship between the water content of a waste and its electrical resistivity, carried out in a laboratory on specimens of waste recovered from the field. The key conclusion is perhaps that the electrical resistivity depends as much on the state of biodegradation and the leachate as on the water content, a finding that must be taken into account in attempting to determine water content from measurements of electrical resistivity in the field.

The paper by Paap *et al.* (2011) reports the results of using geophysical techniques in conjunction with more traditional methods to characterise two landfills – one coastal and one inland – in the Netherlands. The geophysical methods used included electromagnetic measurements and continuous vertical electrical sounding (CVES) for electrical conductivity, multichannel analysis of surface waves (MASW) for assessing stiffness in the shallow subsurface, and ground penetrating radar. The focus of the measurements was on identifying the site boundaries, and assessing heterogeneity within the landfills.

Martínez (2011) presents case studies describing the use of geophysical and conventional ground investigation techniques, first to evaluate the suitability of a clay (primarily the detection of sand pockets) to provide a natural basal sealing layer to a landfill; and secondly to identify the upper surface of a limestone aquifer to determine safe excavation depths (against uplift due to unrelieved pore water pressures) into the overlying clay in connection with the construction of new waste disposal cells.

The final paper in this issue (Richards and Powrie, 2011) is not part of the geophysical testing suite but does relate to landfill engineering. It describes a series of geotechnical centrifuge model tests carried out to investigate the response of landfill capping systems to step- and ramp-subsidence of the underlying waste. It discusses the relevant scaling rules for physical models and concludes that failure of the low permeability layer within the cap could cause the fate of incident rainfall to change from almost 100% runoff to almost 100% infiltration. Further conclusions relate to the influence of cap and subsidence geometry on the integrity of the resistive layer as the waste degrades and are of importance to long-term assessments of landfill performance.

A further paper by Jolly *et al.* (currently under review) is an important contribution in demonstrating the applicability and limitations of electrical resistivity measurement. It shows very clearly, with reference to a controlled laboratory experiment, the inevitability, effect and potential for erroneous interpretation of artifacts arising from the inversion process used to interpret the raw data. It then describes the application of time-lapse electrical imaging using surface electrodes to track the movement of leachate within a waste mass in response to pumping from a horizontal collector well described by Cox *et al.* (2006) during an 18-month drainage experiment reported by Beaven *et al.* (2007). It is shown that, for the conditions in this field study, the differences in resistivity recorded are explained by waste degradation and leachate resistivity, rather than by variations in the gravimetric moisture content of the waste. In this it mirrors the conclusion of Moreau *et al.* (2011), and provides a salutary and cautionary lesson for the interpretation of geophysical measurements in landfills.

The featured papers provide a useful and archival illustration of the current state of knowledge, understanding and practice in the use and interpretation of geophysical methods in landfill engineering. The technique is at a stage at which it can be useful, but the limitations and potentially confounding factors need to be considered. There is ample scope to develop the techniques, for example by combining different types of geophysical measurement, supplementing geophysical measurements with more traditional methods and developing new inversion algorithms. A further workshop is planned to discuss these and other developments in Malmö, June 2011. If you would like more details, please email hakan@rosqvist-resurs.se.

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