Monitoring contaminant plume evolution in scaled models

La surveillance de l'évolution de plume de contaminant dans la modèle

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ABSTRACT: This paper describes a miniaturised electrical imaging (resistivity tomography) technique to image contaminant plumes in scaled models of porous media. Generic models of contaminant infiltration into saturated and partially-saturated scaled sand models were designed to explore the potential of using the system for centrifuge modelling at elevated gravities. The imaging technique generated two-dimensional contoured plots of the resistivity distribution within the model before and during contaminant infiltration. The change in resistivity associated with contaminant plume evolution was imaged as a function of time. Experiments were carried out for various different pollutants.

RÉSUMÉ: Cet article décrit une technique électrique miniaturisée de formation image (tomographie de résistivité) aux plumes de contaminant d'image dans les modèles mesurés des medias poreux. Des modèles génériques de l'infiltration de contaminant dans les modèles mesurés saturés et partiel-saturés de sable ont été conçus pour explorer le potentiel d'utiliser le système pour la centrifugeuse modelant aux pesanteurs élevées. La technique de formation image a produit des traçages contournés bidimensionnels de la distribution de résistivité dans le modèle avant et pendant l'infiltration de contaminant. Le changement de la résistivité s'est associé à l'évolution de plume de contaminant était reflètent en fonction du temps. Des expériences ont été effectuées pour différents différents polluants.

1 INTRODUCTION

1.1 *Geophysical site characterisation*

During the last decade, the use of geophysical methods to determine the geotechnical characteristics of brownfield sites has increased rapidly. The potential range of exploratory tools is now extremely varied and many of these developments have been introduced from other disciplines such as mining, hydro-geology and geology. The majority of these methods allow non-invasive determination of the subsurface conditions, reducing the potential disturbance to the soil and improving the accuracy of the measured properties. Geophysical techniques allow the properties of relatively large volumes of soil to be determined relatively quickly. In addition, they can provide information on large subsurface structures such as sink-holes and disused mine workings. Although these methods lack the accuracy of more traditional point sampling and laboratory testing, geophysical techniques are less prone to misinterpretation in highly heterogeneous soils.

One of the most common methods is the electrical survey, where the subsurface properties are determined by measuring the distribution of resistivity. The basis of the technique is to pass a direct current through the soil between a pair of electrodes. This process is observed by monitoring the distortion of the equipotentials (assuming the soil to be a homogeneous half-space) using another pair of potential electrodes located at the ground surface (Barker, 1997). This provides a simple, repeatable technique that can be applied where any contrast in electrical conductivity exists in space (or time). Recent developments have extended the technique to allow computer controlled multi-electrode arrays to provide tomographic two and three dimensional images of the subsurface (Griffiths and Barker, 1993).

1.2 *Earth resistivity methods*

Geoelectrical or electromagnetic methods are the most suitable methods to investigate certain types of contamination plumes because electrical conductivity is the physical parameter most changed by the contamination. The measurements can be carried out either in boreholes, with ground water samples or from the surface.

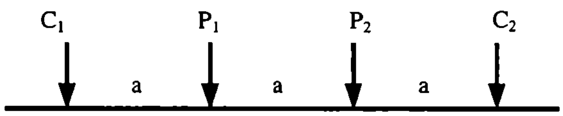

Figure 1(a): Typical resistivity electrode configuration (Wenner)

A typical electrode array for surface resistivity measurements in the field is shown in Figure 1(a). Four equally spaced electrodes are located along a straight line, with distance (a) between them. These consist of two current electrodes (C1 and C2), and two potential electrodes (P1 and P2). A resistivity measurement is made by applying current (I) to the subsurface through the two current electrodes and measuring the voltage difference (ΔV) across the two potential electrodes.

The apparent resistivity of the subsurface (ρ_a) is given by:

$$\rho_a = k.\Delta V/I \qquad (1)$$

where k is a geometric factor dependent upon the electrode arrangement (in this case $2.\pi.a$)

The calculated apparent resistivity is the value of resistivity of homogeneous ground, which would give the same resistance for the same electrode arrangement. The relationship between the apparent resistivity and true resistivity can be determined using a computer inversion algorithm. The ground resistivity has been found to be related to various geotechnical properties, such as mineral content and fluid chemistry, porosity, saturation, etc..

A two-dimensional (or three-dimensional) surveying is conducted with a large number of electrodes connected through a multi-core cable. This is attached to a computer controlled switching unit and relay that selects appropriate sets of electrodes to build up a pseudo-section. The current penetrates deeper with increasing separation of the electrodes (a) and the

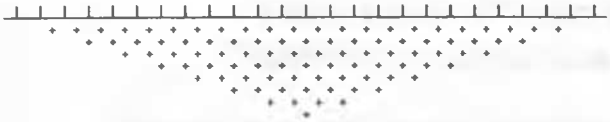

Figure 1(b): Typical pseudo-section and datum points

Wenner configuration shown in Figure 1(a), the array spacing is increased by steps keeping the mid-point of the configuration (the drilling point) fixed. Lateral variations are determined by moving each configuration across the surface through the various sets of electrodes. Figure 1(b) shows a typical Wenner surface electrode array configuration, with the corresponding datum points in the pseudo-section (shown as crosses), used to build up the resistivity image (Barker, 1997).

One of the shortcomings of the technique is that very small contrasts of electrical conductivities of the contamination plume and the surrounding soil can make interpretation extremely difficult and so additional sampling investigations can provide useful information to confirm the findings.

2 METHODOLOGY

2.1 *Centrifuge testing and contaminant transport*

Centrifuge-based physical modelling of contaminant transport problems can offer major time-scaling advantages. Thus, pore fluid seepage at prototype scale over a period of years can be simulated in a model in a matter of hours. Monitoring of plume geometry is generally achieved either by visual observations with a video camera, or by placing electrical instrumentation into the scaled model. Electrical instrumentation requires use of probes and cables, and these may generate preferential flow paths within the model that affect the results of the experiment. Probes may also act as obstacles against contaminant plume migration. Optical measurements assume that the observations along a transparent boundary wall are representative of the interior of the model. This is not always the case, due to boundary effects at the interface between the wall and the model.

In contrast, electrical imaging is non-invasive and, therefore, does not disturb the soil fabric or distort the evolving contaminant flow. Monitoring is achieved by constructing a standard array of electrodes at small scale. This array is used to produce two-dimensional images based on resistivity tomography. The miniaturised electrodes are inserted into the base and the upper surface of the scaled model, so that the instrumentation does not compromise the experiment. The use of a stained contaminant allows the plume geometry at the end of an experiment to be measured directly by excavation of the soil models, and this may be compared with the final electrical image.

2.2 *Miniature resistivity tomography apparatus*

The miniaturised electrical imaging technique used in this study was based on field-scale (prototype) resistivity equipment, which has been widely used in the investigation of field contaminant problems. The main components of the miniaturised electrical imaging equipment consist of a GEOPULSE Earth Resistance Meter, a multicore imager cable and two 25-electrode arrays.

The 25-electrode arrays were placed in the surface and in the base of the scaled model to allow two individual resistivity surveys, one from the surface downwards and the second from the base upwards. The electrode spacing was 30 mm and each array was 720 mm long. The electrodes consisted of 8 mm brass pins connected to individual cores of two screened 25-way cables. The screened cables were connected to a relay box via a connection box located on the top of the centrifuge strongbox. The current sent is about 0.5 mA, the allowable error is set at 0.5% and the geopulse is always carrying 2 cycles (average) for each reading. The time during which current is passed is 0.4 seconds

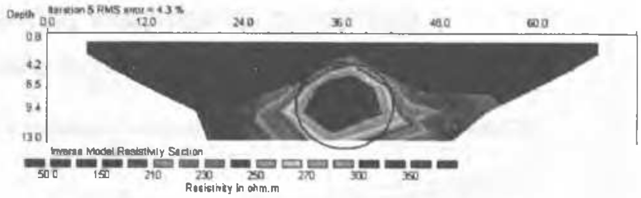

Figure 2(a): Resistivity tomography image of a buried pipe in partially saturated sand (after Depountis et al., 1999)

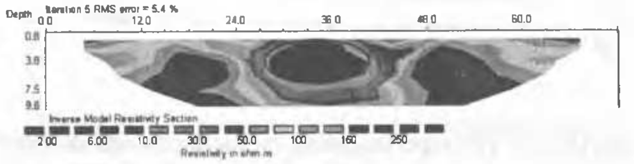

Figure 2(b): Resistivity tomography image of a clay lens in partially saturated sand (after Depountis et al., 1999)

and the time during which current is switched off before current reversal is 0.2 seconds.

The strongbox with the sand model and resistivity array was placed in the centrifuge gondola with the relay box, which was operated from the control room via a 12V DC power supply unit. The relay box allowed switching from one array to the other (Depountis et al., 1999). A multi-core cable connected the relay box with the Geopulse Earth Resistance Meter inside the centrifuge instrumentation unit. The 25 takeout cores of the cable were connected directly to a module (Imager-25) housed in the Geopulse. This allowed automatic addressing of multi-electrode survey systems using any number of electrodes up to a maximum of 25. The Geopulse Earth Resistance Meter was operated in flight from the control room via a P.C. using the control software Image25 (Depountis et al., 1999).

The resistivity survey was saved in a parameter file, which once created could be accessed by the Image25 whenever needed. All the resistance measurements during an experiment were stored in memory for later processing using the RESDINV computer program (Loke and Barker, 1995). The advantage of using this system in scaled models is that two arrays can be used (top and bottom), which is obviously impossible in the field, therefore the potential imaging depth is greater and the whole vertical profile of a model can be monitored. Figures 2(a) and (b) show typical resistivity images (using the top array only) of a buried cylinder and an ellipsoidal body of clay buried in a partially saturated sandy soil and display the effectiveness of the method.

3 CENTRIFUGE TEST PROGRAMME

3.1 *Experimental Setup*

Generic models of contaminant infiltration into saturated and partially-saturated sand were designed to explore the potential of testing pollution plume evolution using the miniaturised resistivity apparatus. Initially tests have been undertaken on the laboratory floor at 1g. Further testing is now being conducted at elevated gravities using the Dundee Geotechnical centrifuge (which is capable of accelerating a model package with a mass of up to 1000 kg at an acceleration of 130 gravities) but these tests will not be shown in this paper. Thus the results shown herein form part of the development and validation of the system.

The apparatus (Fig. 3) used for these experiments were as follows:

- Rectangular strongbox filled with pluviated sand;
- Microresistivity apparatus;
- Perspex cylinder (0.5 m high) acting as the contaminant reservoir;

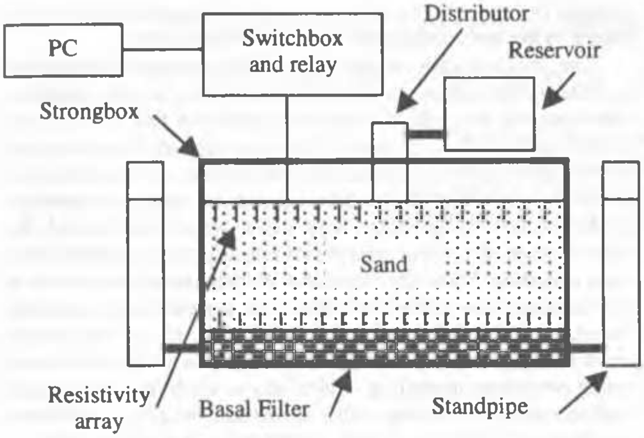

Figure 3: Centrifuge box and resistivity imaging equipment

- Solenoid valve to control the contaminant flow between the reservoir and the sand model;
- Perforated distributor tube to allow uniform distribution of contaminant across the centre line of the model.

The strong box shown in Figure 3 is a parallelepiped, 600 mm wide, 800 mm long and 600 mm high. The front and back walls are made of perspex to allow viewing of the whole soil profile. Standpipes are connected to a basal drainage system to allow control of the water table. Five centimeters depth of gravel covered with a geofabric was used to form the base drainage layer. The sand was pluviated to create a layer 15 cm deep. The two resistivity arrays were set at the base of the sample (above the gravel layer) and at the top of the sand surface. The depth range of each array is about 3 times the chosen spacing. For the tests described the spacing is a = 3 cm, so the depth covered is about 9 cm.

The soil material used for the tests was Congleton Sand, which is a uniform sand with d_{10}=100µm and a coefficient of permeability, k=10^{-2}cm/sec. The contaminants used were NaCl dissolved with tap water and vegetable oil.

3.2 *Testing procedures*

A range of salt concentrations and soil saturations were investigated and only typical results will be shown. An additional test was conducted using an LNAPL (vegatable oil). In each case, the sand was pluviated into the strongbox over the basal resistivity array (positioned prior to pluviation). The sand was wetted from the bottom of the liner until uniform saturation was achieved. When the model saturation stabilised the valve controlling flow of contaminant was opened. The NaCl solution flowed from the contaminant reservoir to the distributor placed between the central surface electrodes allowing infiltration from a 20 mm wide line source, across the model (Fig. 3).

As the infiltration took place the changes in resistivity associated with the contaminant plume evolution were imaged in 2-D perpendicular to the line source as a function of time. The tests shown below were conducted at 1g rather than elevated g on the centrifuge. This is therefore an early part of this study, where proofing of the equipment is still being conducted and elevated g testing is currently being investigated and will not be shown in this paper.

4 EXPERIMENTAL RESULTS

4.1 *Contaminant infiltration into a saturated sand*

Figure 4 shows the resistivity tomography image for a saturated sand sample, with a contaminant with 20 g/l total dissolved solids (NaCl) introduced as a surface line source. The water table has been maintained just below the surface of the sand throughout the test. The figure shows the resistivity image approximately 1 hr from the beginning of the centrifuge test, after opening the valve of the perforated distributor. This test was conducted at 1g and the resistivity image shows a contaminant plume developing rapidly through the sand sample, primarily under the effects of diffusion. The resistivity readings vary from approximately 25 ohm.m at the centre of the plume to 100+ ohm.m at the periphery of the box. Due to the time delay between reading the upper and lower arrays there also appears to be a step in the plume at the mid-height of the box. With improvements to the reading system this artefact will be eliminated.

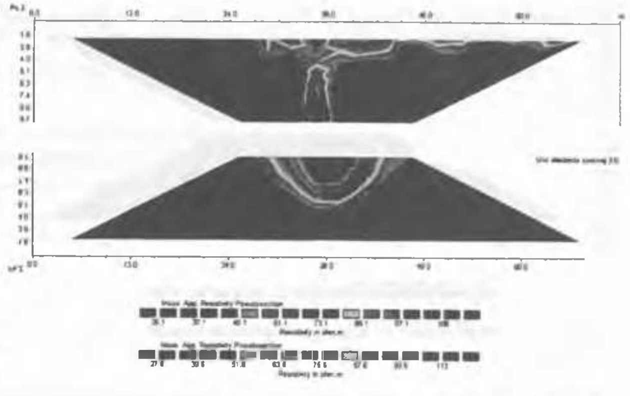

Figure 4: Resistivity tomography image associated with 20 g/l (NaCl) contaminant infiltration into saturated sand at 1g

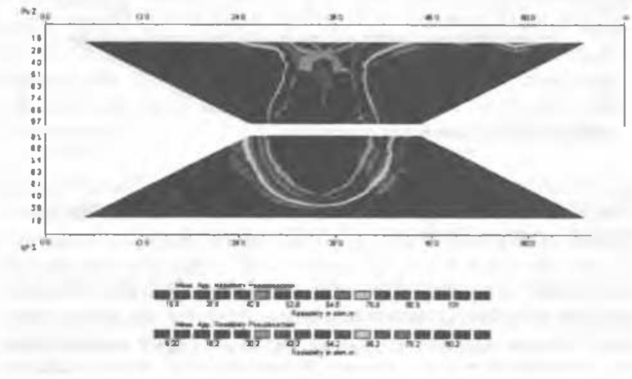

Fig. 5(a): Resistivity tomography image associated with 10 g/l (NaCl) contaminant infiltration into partially-saturated sand at 1g

4.2 *Contaminant infiltration into a partially-saturated sand*

The resistivity distribution for partially-saturated sand sample is shown in Figure 5(a), again approximately 1 hr from the beginning of the test and at 1g. In this case the water table was maintained at the interface of the gravel and the sand layers (5cm from the base of the box. The basal resistivity array was also sat at this level. The contaminant was introduced into the model in the same manner as the saturated sample and a concentration of 10 g/l total dissolved solids (NaCl) was used. This plume has spread more quickly than that for the saturated sample (shown in Figure 4) due to the additional effects of suction acting on the contaminant pulling the fluid into the soil.

For the same test, a further contaminant plume was recorded a number of hours later and this is shown in Figure 5(b). This shows evidence of further downwards movement of the contaminant and sideways spreading. Due to the lower moisture content in the upper layers of the sand model, suction gradients must have occurred between the wet contaminant front and the soil material. The suction gradients in conjunction with gravity forces forced the plume to migrate into the model. Since the moisture content of the model as a whole did not change signifi-

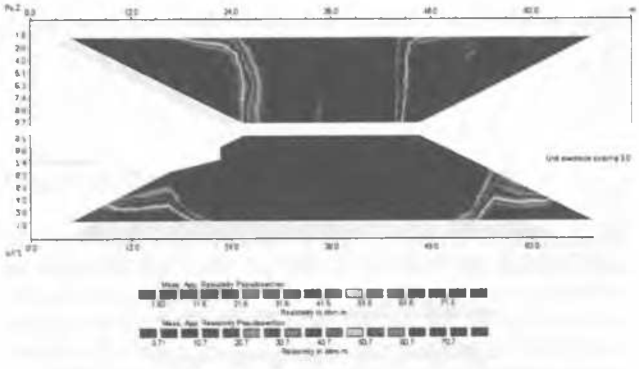

Fig. 5(b) - Tomographies associated with contaminant infiltration experiment at 10g

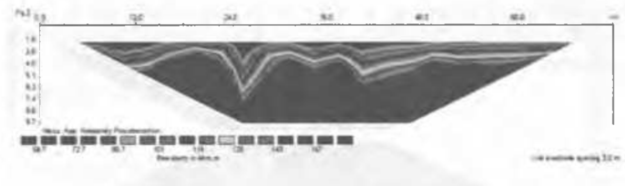

Figure 6 - Tomographies associated with LNAPL contaminant infiltration experiment into a partially saturated sand

cantly after the contaminant release, Figures 5(a) and 5(b) will indicate only the contaminant plume. The lower resistivity contours (below 5 ohm.m), indicate areas of higher contaminant concentration and the contours between 5-20 ohm.m indicate zones of contaminant dispersion.

4.3 *Infiltration of an LNAPL into a partially-saturated sand*

Figure 6 shows the resistivity image resulting from the infiltration of an LNAPL (vegetable oil) into a sand soil. Again this test was conducted at 1g on the laboratory floor. Initially the sand was fully saturated, with the water table very close to the soil surface. The LNAPL was then poured on to the surface to form a 50mm deep layer, right across the box (rather than using the line source) and then the water table was dropped to the top of the gravel layer (basal drainage layer). The resistivity image was then taken one hour after the water table was dropped.
The resistivity image shown is from the top array only and shows decreasing resistivity from the mid-height of the sample towards the surface. As the water table was dropped, an advection front of LNAPL would have formed and proceeded downwards through the model. It appears that the infiltration of the LNAPL front would have pushed water ahead of itself (and out of the base drain). The resistivity values at the mid-height are therefore consistent with an oil-water system. Without the water phase the resisitivity would be much larger. The resistivity values at the surface are closer to those expected for water and it appears that during the infiltration that some mixing occurred leading to higher water/oil ratios near the surface than exist at the mid-height of the sample. It is therefore apparent from the resistivity results that varying concentrations of NAPLs may be measured with the resistivity equipment, however these findings need to be investigated further.

5 DISCUSSION

Much of the emphasis on locating ground contamination during the 1980s focussed on finding inorganic plumes, which are relatively easy to find due to their distinct resistivity differences with the surrounding soil. In the last decade, the emphasis has shifted towards finding organic contaminants, which are more challenging to locate and tend not to conduct electricity (and are thus closer to the surrounding soil in terms of resistivity).

The contamination of soil by NAPLs produces considerable problems with regard to remediation of the site. In particular, conventional methods of treatment have been found to be relatively ineffective at removing DNAPLs from soil bodies and effective alternatives have been slow to develop. This problem has been exacerbated by the prohibitive cost and public acceptability of large-scale contaminant field trails, which has limited this type of research to back analysis of existing sites or simple laboratory studies. Since the fundamental mechanical behaviour of soil is highly non-linear and stress-level dependent, to accurately simulate a field scale process at small scale, the *in situ* stresses must be reproduced correctly in a model. This is can be achieved using centrifuge modelling, which allows relatively cheap, rapid and repeatable modelling with well-defined boundary conditions.

The development of new centrifuge modelling techniques such as resistivity tomography will allow testing of new remediation techniques, provide further understanding of transport of NAPLs in soils and will provide valuable data for calibration of numerical analyses.

6 CONCLUSIONS

This study has investigated the effectiveness of a new miniaturised technique for imaging contaminant plumes in scaled models of sand soils. The miniaturised electrical imaging apparatus is non-invasive and, therefore, does not disturb the soil fabric or compromise the experimental results. Another advantage is that cross analysis can be conducted between the final resistivity contour plots and visual measurements obtained during a test. It is concluded that the miniaturised electrical imaging can be a useful method to monitor contaminant migration and can be applied during scaled tests associated with density-driven or suction driven contaminant transport processes.

7 ACKNOWLEDGEMENTS

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