Electrical resistivity tomography: monitoring of hydro-chemical processes and parameter estimation

G. Della Vecchia1 and R. M. Cosentini

Department of Structural Engineering and Geotechnics, Politecnico di Torino, Italy

ABSTRACT

Electrical resistivity tomography (ERT) is a useful tool for site characterization and monitoring. This paper describes some 3D laboratory applications of ERT, used to monitor wetting processes in unsaturated soils and the transport of contaminants in water-saturated samples. ERT was used to create maps of electrical conductivity of the monitored domain at different time intervals. Electrical conductivity changes were used to infer degree of saturation or concentration variations within the pore space. Test results confirm the applicability of the technique for problems involving movement of water in unsaturated soils, salt transport and oil migration. The observations in laboratory under controlled conditions proved very useful for validation and calibration of models to be used for full-scale analyses. As a further application, ERT was used for the hydraulic characterization of unsaturated soil samples, in terms of hydraulic conductivity and retention curve. The results are compared to the retention curve as obtained with the classical approach of axis translation technique and provide an encouraging agreement.

Keywords: tomography, monitoring, inversion, transport, infiltration, parameter, sand

1 INTRODUCTION

The range of problems which geotechnical engineers face is increasing in complexity and scope [1], highlighting the need to incorporate the effects of geo-environmental phenomena and variables on soil behaviour. These variables include suction, temperature and the concentration of chemical species. New experimental techniques have now become necessary, which measure both classical soil mechanics and physicochemical variables, such as water salinity and water content.

Methods based on electrical properties seem particularly promising [2]. The flux of electrical charges through materials permits conductor materials, like metals or electrolytes, to be distinguished from insulating materials, like air, ice or plastics. Soils exhibit intermediate electrical properties, depending on their physical and chemical characteristics, i.e. fabric, porosity, water content, composition of interstitial fluids. Electrical resistivity can be considered as a proxy for the variability of soil properties.

The electrical resistivity tomography (ERT) technique aims to reconstruct the spatial distribution of electrical conductivity. During ERT measurements, electrical current is applied at two electrodes, while other pairs of electrodes measure the induced electrical potentials. Finally, the electrical conductivity field is obtained by a suitable inversion procedure.

1 Dep of Structural and Geotechnical Eng, Politecnico di Torino, Corso Duca degli Abruzzi, 24 - 10129 Torino, Italy.
gabriele.dellavecchia@polito.it
Common applications of ERT in geophysical site investigation include reconstruction of geological horizons, imaging of hydro-geological structures and monitoring of soil water and contaminants flow. Compared to other techniques, ERT is relatively cost effective and it is also easy to interpret, since the electrical conductivity can be related to hydro-geological variables (porosity, degree of saturation, solute concentration of the pore fluid) in a straightforward way on the basis of both empirical and theoretical relationships. However, a quantitative interpretation of ERT results is limited by a number of factors [3]. Sources of uncertainty include the non-uniqueness of the ERT inverse problem, ambiguity of the imaged bulk electrical conductivity in terms of water content and chemical concentration and unknown boundary conditions of the domain investigated.

ERT performed on laboratory samples reduces the number of unknowns, due to the controlled conditions of the test both in terms of materials involved and in terms of imposed initial and boundary conditions. The advantage of ERT compared to standard electric laboratory measurements consists in the possibility to estimate the spatial variability of the electrical conductivity distribution inside the specimen, using non-destructive measurements performed at the external boundaries.

This paper begins by investigating the use of 3D ERT to quantify local changes in water content within an unsaturated soil sample that is subjected to wetting. The study goes on to explore the feasibility of back analysis of these results to derive the water retention curve and the unsaturated permeability function of the soil sample. Finally, attention is given to the capability of 3D ERT in imaging transport processes of contaminants in saturated porous media.

2 EXPERIMENTAL SET UP

The tests presented were run in the EIT oedometer cell presented by Comina et al. [4], equipped for spatial and temporal monitoring of electrical and seismic properties, under controlled mechanical conditions. The cell has an internal diameter of 130 mm and can accommodate samples with heights of up to 60 mm. The equipment was modified to allow hydraulic control via the top and base plates (Figure 1). The cell has 42 electrodes located on its internal boundary: 16 are equally spaced on the sidewall, and 13 are on both the base and top plates. About 800 electrical measurements were performed for each tomography.

These measurements are used to reconstruct the electrical conductivity field within the sample, using an inversion technique based on a least-squares algorithm with a Tikhonov regularization [5]. Acquisition of a single set of measurements can be performed in a few tens of seconds. Different sets of measurements can be used to visualise transient processes.

![Figure 1. Base of the ERT oedometer cell: drainage lines and electrodes.](image)

3 HYDRO-MECHANICAL PROCESSES

The application of ERT in monitoring local water content changes during transient wetting processes on laboratory samples is presented.

3.1 Material characterisation

Experimental tests were run on silty sand coming from the Trecate site, in the Ticino river alluvial plain. Sand cylindrical laboratory samples (height 4 cm, diameter 13 cm) were prepared by moist tamping at a degree saturation $S_r = 0.2$ and a porosity $\phi = 0.45$. The hydraulic and electrical behaviour of the material was firstly characterized in the laboratory at constant porosity.
Saturated hydraulic conductivity was measured through a constant head permeameter, obtaining a value of $k_w = 1.45 \cdot 10^{-5}$ m/s. The water retention curve was determined by means of suction-controlled oedometer cell, through the axis-translation technique. The electrical conductivity degree of saturation relationship was determined in the ERT oedometer by preparing homogeneous samples at increasing water contents. Experimental data (Figure 2) was fitted with Archie’s law [6], which holds for porous media with non-conductive solid grains. Under conditions of constant porosity and water salinity, Archie’s law can be written as:

$$\frac{\sigma}{\sigma_{sat}} = S^q$$

where $\sigma$ and $\sigma_{sat}$ are the current and the saturated electrical conductivities and $S$ is the degree of saturation. The exponent $q$ is a fitting parameter that takes into account the geometry of the interconnected porosity. For the material used in this investigation a value $q = 2.0$ was estimated.

![Figure 2. Relationship between electrical conductivity and degree of saturation at $\phi = 0.45$ for the Trecate sand.](image)

3.2 Imbibition tests

After preparation, the samples were left in the cell at least 12 hours, to ensure a uniform distribution of water content. Two imbibition tests were performed, by applying different water fluxes from the bottom drains. In the first test, 90 cm$^3$ of water entered the sand sample in 40 s; in the second test, a water inflow of 50 cm$^3$ in 41 min was imposed. In the first test, electrical measurements were performed after closing the bottom drains, documenting homogenization at constant global water content. In the second tests, electrical acquisitions were performed during the wetting and the homogenisation stage. During the tests, a vertical stress of 2.54 kPa was applied and displacements of the top of the sample were measured by a LVDT transducer. In both tests, the volumetric strain was negligible.

Figure 3 shows different images of the reconstructed electrical conductivity fields belonging to the inflow stage of the second test. The progressive increase of the high-conductivity zone evidences the detection by ERT of the water inflow process. In fact, according to Eq. 1, the higher the electrical conductivity, the higher the degree of saturation. Satisfactory reconstruction of homogenisation stages on the same material were presented in [7]

![Figure 3. Different images of the reconstructed electrical conductivity field during the wetting process on Trecate sand.](image)

3.3 Parameter estimation

3D tomographic monitoring was then used to solve an inverse problem aimed at estimating the parameters of the water retention curve and of the relative permeability function. Wetting and homogenisation taking place within the oedometer were simulated considering the processes as small-scale tests. Being known the initial conditions and the boundary conditions in terms of fluxes, continuity equations for water and air were numerically integrated using the finite element method. Isotropy in terms of hydraulic behaviour was assumed.

The link between degree of saturation and suction $s$ (defined as the difference between air
and water pressure) was modeled with the van Genuchten relationship:

\[
S_e = \frac{S_e^{RES}}{1 - S_e^{RES}} = \left( \frac{1}{1 + (\alpha S_e)^n} \right) ^{1/n} \tag{2}
\]

where \( S_e \) and \( S_e^{RES} \) are the effective and residual degree of saturation, respectively, and \( n \) and \( \alpha \) are two experimental parameters. The dependence of the hydraulic conductivity \( k_w \) on degree of saturation has been modelled as:

\[
k_w(S_e) = k_w^{sat} (S_e)^\beta \tag{3}
\]

where \( \beta \) is an experimental parameter and \( k_w^{sat} \) is the saturated hydraulic conductivity. Once calculated the solution of the direct problem in terms of degree of saturation, electrical conductivity was obtained by Eq. 1.

The inverse problem was formulated as a non-linear optimisation process, aimed at the determination of the parameters \( \alpha, n, e, \) and \( \beta \). An objective function was defined to minimize the distance between the solution of the numerical simulation and the tomographic reconstruction. Parameters were estimated for both the imbibition test performed. The water retention curves obtained from the inversion procedure are in good agreement with the ones obtained with the axis translation technique on duplicated samples, as shown in Figure 4.

![Figure 4. Comparison between estimated water retention curves and experimental data.](image)

As for relative permeability parameter \( \beta \), values slightly lower than 3 were found, in agreement with literature data on similar materials. The values of the estimated parameters are reported in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \alpha ) (1/kPa)</th>
<th>( n ) (%)</th>
<th>( \beta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.75 \times 10^{-2}</td>
<td>4.5</td>
<td>2.75</td>
</tr>
<tr>
<td>2</td>
<td>1 \times 10^{-1}</td>
<td>2.4</td>
<td>2.25</td>
</tr>
</tbody>
</table>

4 TRANSPORT PROCESSES

Monitoring of transport of dissolved species in the pore water of soils and geological media is particularly relevant when safety risk may occur. The change of chemical composition of pore fluids may affect hydraulic and mechanical behaviour of rocks and soils in a number of engineering and natural environmental problems. Typical cases of subsurface contamination can be the migration of a contaminant leached from a landfill or LNAPL (Light Non-Aqueous Phase Liquid) leakage from a underground storage tanks. The issue of contaminant transport is of increasing interest in the context of clay containment barriers and in situ containment of contaminated groundwater [8].

This chapter introduces the capabilities of 3D ERT in monitoring contaminant transport, describing salt diffusion tests on homogeneous and layered samples and oil injection tests on homogeneous samples.

4.1 Salt diffusion tests

Salt diffusion tests on both homogeneous and heterogeneous samples were conducted in the instrumented oedometer cell. Electrical conductivity changes were used to calculate concentration variations within the interstitial fluid. The first test was performed on a homogeneous saturated specimen of Ticino Sand, mono-granular siliceous sand with well-rounded particles having an average size of 0.5 mm. The sample was prepared by moist-tamping at porosity \( \phi = 0.40 \). The height of the sample was 4 cm.

Few grams of NaCl were placed in a point on the top of the specimen. Salt grains were then submerged with distilled water to induce
dissolution and diffusion of the contaminant within the specimen. The evolution of the electrical resistivity was monitored for three days. In Figure 5, the electrical conductivity maps corresponding to 20 and 60 minutes from the beginning of the diffusion are shown.

The layered sample was prepared by placing in the center of the Ticino sand specimen a clay layer with a thickness of 1 cm. The clay was remoulded Spes White China Clay Kaolinite, consolidated under a vertical stress of 100 kPa. Figure 6 shows the reconstructed electrical conductivity field for the layered sample at 20 and 60 minutes after beginning of diffusion.

Comparison of Figures 5 and 6 suggests that ERT reconstructions correctly locate the position of the salt source for both the homogeneous and the layered sample. Moreover, in the test performed on the layered sample, salt appears to spread more in the horizontal direction than in the vertical direction. The conductivity increase on the left flank of the specimen suggests that leakage occurred at the interface between the kaolin and the cell. Leakage was probably due to a weak contact between the soil and the cell wall and caused the saline solute to enter the bottom sand layer firstly laterally. The detection of these features of the transport process shows the ability of 3D ERT in reconstructing complicated diffusive flows in the specimens and in monitor preferential flow paths.

4.2 Oil injection test

Another test was performed in order to evaluate the capability of ERT to deal with contaminant transport problems. A saturated Trecate sand sample was prepared by moist tamping at a porosity \( \phi = 0.45 \). A saline NaCl solution at a concentration 0.75 M was used as interstitial fluid.

The sample was then contaminated with a non-miscible fluid, by injecting in the center of sample known quantities of polydimethylsiloxane oil (Rhodorsil® Oils 47, kinematic viscosity 350 mm²/s, electrical resistivity 1015 Ohm·cm). Each injection consisted in 10 cm³ of oil. After each injection, electrical conductivity evolution was monitored.

During the test, the drains at the bottom plate were kept closed, while the drains on the top cap were left open to allow the flow of the water displaced by the injected oil. Figure 7 shows two tomographic reconstructions performed after the first and the second injection of oil.

The ability of ERT in performing a correct reconstruction of the quantity of oil injected is evidenced in Figure 8, which shows a comparison between the water degree saturation calculated from the volume of the oil injected and that obtained by the interpretation of the reconstructed electrical conductivity field (through Eq. 1). The error in the reconstructed degree of saturation is lower than 5%.
5 DISCUSSION AND CONCLUSION

Since the initial and the boundary conditions are known, the use of ERT on samples in the laboratory makes it possible to evaluate the accuracy of the tomographic reconstructions. Another advantage is that the use of tomography on laboratory samples helps significantly in the analysis of laboratory tests as small-scale tests.

In this paper, some laboratory tests performed on different sand specimens, both in saturated and unsaturated conditions, are presented. Oil and air were both used as non-wetting fluid.

The authors propose a new technique for the determination of hydraulic parameters in unsaturated conditions. The temporal evolution of the reconstructed electrical conductivity field is used as a basis for the inverse analysis of the wetting process. The results obtained are very encouraging, in fact only limited preliminary characterisation is necessary, i.e. the determination of the saturated hydraulic conductivity and of the relationship between electrical conductivity and the degree of saturation. For this procedure, other experimental tools, such as tensiometers or techniques to control suction, are no longer necessary. Considering the typical difficulties found in measuring relative permeability and the time needed to obtain water retention curves with conventional techniques, these results encourage further research efforts in this field.

On the subject of transport processes involving contaminants, the authors used ERT to monitor the diffusion of a saline tracer and the flux of non-miscible oil in an initially water-saturated sample. In this way, the global quantity of the contaminant present in the sample was correctly reconstructed.

The results presented in this paper are evidence that electrical tomography is a useful tool for monitoring processes involving the flux of non-aqueous fluids, like air or oil. The methodology, herein applied on sand samples, can be extended also to undisturbed samples of cohesive materials, once performed the electrical characterisation of the interstitial fluid.

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