A Local Monitoring of Water Content in Unsaturated Soil Triaxial Testing

José Muñoz-Castelblanco, Pierre Delage, Jean-Michel Pereira, and Yu-Jun Cui

Abstract. Advanced triaxial testing in unsaturated soils includes local strain and suction measurements. However, in unsaturated soils, the complete local determination of the state of the specimen also requires the monitoring of local changes in water content. To this aim, a new electrical resistivity probe, composed of two pairs of electrodes was developed. Some experimental data on the changes in resistivity with the degree of saturation were obtained by carrying out calibration tests in specimens of natural unsaturated loess from Northern France. Two resistivity models were also used to analyze the obtained data. Results are finally discussed with respect to the loess's water retention properties.

Keywords: resistivity, water content, loess, triaxial, new probe.

1 Introduction

To investigate in the laboratory the relationship between water content and electrical resistivity, Gupta & Hanks (1972) and Rhoades et al. (1976) tested compacted specimens by using circular four-probe resistivity cells, a device also utilized by

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Kalinski and Kelly (1993). Other resistivity measurements were made by Fowles (1980) on compacted specimens, McCarter (1984) on remoulded clays, Fukue et al. (1999) on remoulded and natural clays and Chen et al. (2007) on expansive soils. As quoted by Kalinski and Kelly (1993), the resistivity of saturated soils depends on the particle size distribution, mineralogy, specific clay surface, porosity, pore size distribution, connectivity of pores, water content, salt concentration and temperature.

In unsaturated soils, the changes in degree of saturation are derived from the changes in both sample volume and water content. Local strain measurements in unsaturated triaxial soil testing should hence preferably be coupled with local measurements of the changes in water content. In this paper, a new resistivity probe to measure the local water content variation in a triaxial system was tested on an unsaturated natural loess from Northern France. Results are analyzed by means of two theoretical models.

2 Basic Concepts

In unsaturated soils, the electrical resistance depends on the resistance of the solid phase R_s, of air R_a and of water R_w. Since the air phase is an electrical insulator, and since water has a significantly higher electrical conductivity than solids, the electrical current mainly flows through water. In saturated soils, Archie (1942) proposed a simple empirical model (equation 1) relating the soil electrical resistivity ρ, that of the pore water ρ_w to the porosity n. This law was adapted for unsaturated soils (Archie 1942) by introducing the degree of saturation S_r as presented in equation 2, where a and b are experimental parameters.

$$\rho / \rho_w = (n)^{-a} \tag{1}$$

$$\rho / \rho_w = (n)^{-a} (S_r)^{-b} \tag{2}$$

Fukue et al. (1999) proposed a more sophisticated model accounting for the combined effects of the serial and parallel transmission of the electric current in the three phases (air, water and solids). They defined a structural coefficient F to separate the parallel flux (related to 1 – F and mainly occurring in water) and the serial one (related to F and influenced by the insulating properties of solids and air) giving the following expression of the electric resistivity ρ through a cylinder of radius r:

$$\rho = \frac{\pi r}{w G_s n} \Gamma ; \quad \Gamma = \frac{\rho_w}{(1-F)} \tag{3}$$

where w is the gravimetric water content, G_s is the specific solid density and n the soil porosity. F has a dimension of length and depends on the structure of the soil. The value of parameter Γ is related to the soil state.

3 Resistivity Probe

A small sized electric resistivity probe (11 mm in diameter) was developed to measure the water content at the mid-height of the triaxial specimen. It was inspired from the concept of concentric and surface probe developed by Maryniak et al. (2003). The probe is composed of four circular electrodes of diameter 1.5 mm disposed in a squared-grid (inter electrodes distance of 6 mm) as presented in Fig. 1.

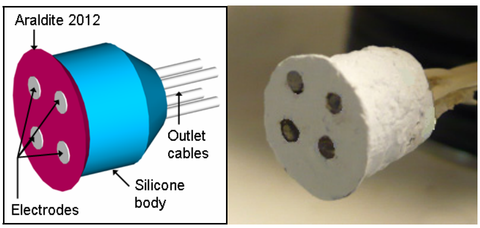

Fig. 1. Cermes resistivity probe.

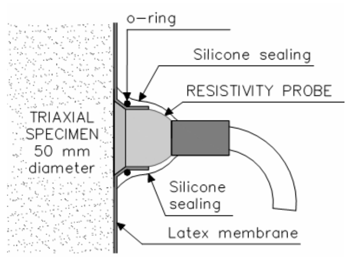

Fig. 2. Holding system

A hydrophobic dielectric matrix (Araldite 2012 epoxy resin) was used to accommodate the electrodes with proper electric isolation. Fig. 2 shows how the resistivity probe is fixed on the lateral side of the triaxial sample. Two input electrodes are supplied by a voltage source of 10 V and the output signal is received by two output electrodes.

4 Experimental Results

Tests were carried out on samples of a natural unsaturated loess of low plasticity, high porosity with an open structure that result in a significant collapse susceptibility (Cui et al. 2004, Delage et al. 2005, Yang et al. 2008, Karam et al. 2009, Munoz-Castelblanco et al. 2011a). To investigate the relationship between water content and the soil resistivity, five triaxial specimens (three from 1m deep and two from 3.3 m deep) of height 100 mm and diameter 50 mm were used. Samples were submitted to controlled wetting and drying processes while measuring their electrical resistivity at mid-height with the new gauge.

Fig. 3 shows the data obtained on the samples from 1m and 3.3 m depth along both the wetting and drying paths (whole range in a semi log plot in Fig. 3a and a zoom in linear plot between 0 and 100 Ωm in Fig. 3b). A fairly good compatibility between the data from the different samples is observed along both the wetting and drying paths.

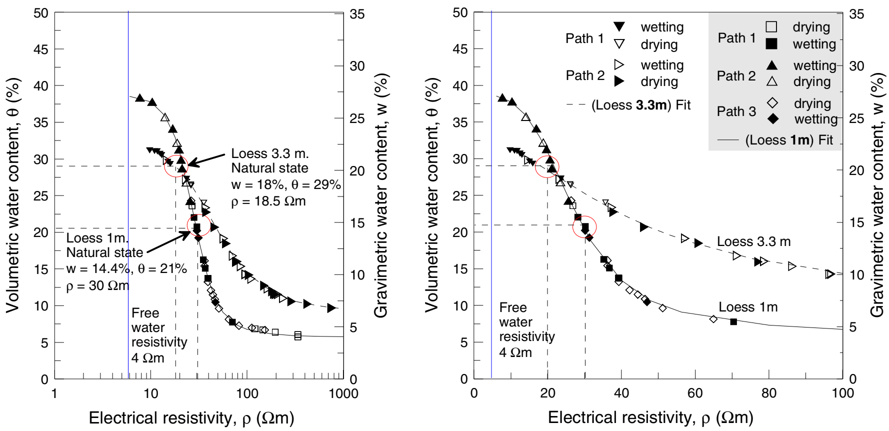

Fig. 3. Calibration curves of the resistivity probe for samples from 1m and 3.3 m depth. (a) Resistivity values in log-scale. (b) Zoom in true scale

At 1 m depth, the slope of the curve indicates that a reasonable estimation can be made for gravimetric water contents between *w* = 24 and 5%. For a drier sample with *w* < 5%, the resistivity rapidly reaches values higher than 100 Ωm and the changes become too tiny. The curve of the 3.3 m sample appears to be less steep than that of the 1 m sample, allowing better determination of the water content between θ = 13% and 31% (*w* between 8% and 22%).

5 Analysis

The data from both soils are also presented in a ρ/ρ_w versus S_r plot in Fig. 4 and compared to the modified Archie's law and to the model proposed by Fukue et al. (1999). Archie's curves agree reasonably well at degrees of saturation between 15 and 70% for the 1m deep specimen and between 30 and 70% for the 3.3 m deep specimen. Thanks to their concave shape, Fukue's curves appear to better agree with the data than Archie's model. This shape is due to the non-linear variation of the (1 – *F*) value with respect to the degree of saturation. The coefficient (1 – *F*) / (1 - F_{sat}) of the 1m deep sample is almost equal to 1 for degrees of saturation higher than 20% (*w* = 10%) and it sharply increases below this value. This large resistivity increase is suspected to be due to discontinuities into the water phase at low water contents, specifically in soils containing some clay (Fukue et al. 1999).

F_{sat} values are 0.94 m and 0.97 m for the 1m and 3.3 m deep specimens, respectively. They correspond to Γ_{sat} values of 297 Ω and 366 Ω respectively. Whereas there is no particular physical meaning of the *F* parameter, Fukue et al. (1999) stated that parameter Γ was an indicator of the soil state, Γ values close to or higher than 300 Ω indicating undisturbed specimens. The values obtained here confirm the good quality of the extraction and sampling procedures followed.

Fig. 5 represents in the same graph the changes in relative resistivity with respect to the degree of saturation together with the water retention curve of the 1m depth sample, taken from Muñoz-Castelblanco et al. (2011b).

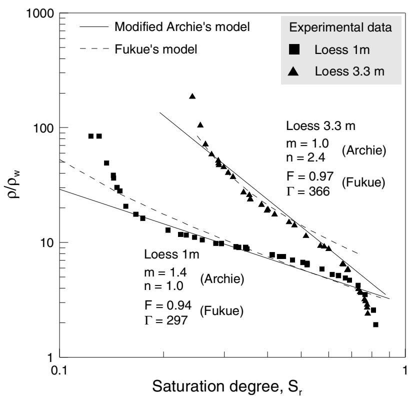

Fig. 4. Comparison of experimental data with both the modified Archie's law expression and Fukue's model.

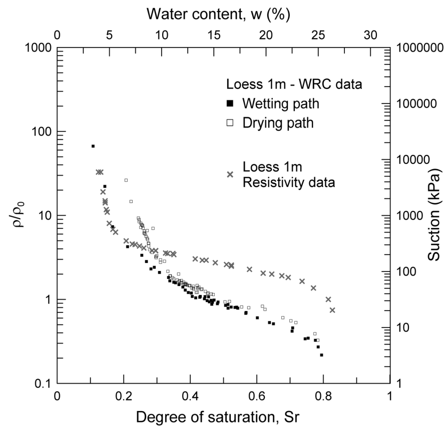

Fig. 5. Comparison between resistivity changes and the water retention properties.

The water retention curve exhibits, in a standard fashion, a hysteresis whereas the resistivity curve doesn't. Both curves are comparable, confirming the predominant role of water in the electrical transfer. The absence of hysteresis is due to the fact that resistivity is mainly related to the amount of water and not to its energetic potential. It is favourable for water content measurements, since they are independent of the hydraulic path previously followed by the sample.

6 Conclusions

The measurement of the electrical resistivity of a natural unsaturated loess from Northern France under various water contents showed a deviation from Archie's law at low degrees of saturation, related to the clay fraction and to possible changes in microstructure during drying. Fukue's model appeared to better fit at low degrees of saturation thanks to the structural factor *F* that depends on the degree of saturation. It is suspected that the electrical conduction through the soil can be divided into two regimes: one related to a continuous water phase in the range of high water contents and the other to a discontinuous water phase within the clay fraction, in the range of lower water contents. Compared to the water retention curve, the changes in resistivity with respect to the degree of saturation do not exhibit any hysteresis, making easier the determination of the water content.

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