

Correspondence between electrical resistivity and total suction in compacted kaolin considering the presence of salt

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Abstract. Prospection techniques based on measuring the electrical resistivity of geomaterials are being used mainly for geophysical characterization, for evaluating soil contamination and the extension of contaminated areas, in addition to the compaction control in geotechnical works. This technique is based on the fact that contrasts in electrical resistivity along the profiles analysed help identifying zones of transition, because this property is affected by the presence of water and dissolved salts in the electrolyte, as well as by soil structure. However, *in situ* data interpretation has some difficulties because electrical resistivity is affected by changes in the unsaturated state of the soil, as well as by the presence of salt compounds (natural or from contamination). The correspondence between electrical resistivity and total suction in compacted kaolin considering the presence of salt was investigated in the study presented. The samples tested were compacted for the same voids ratio and water content, however one type was prepared with distilled water and the other with a NaCl solution (0.5 M). This is a relatively small concentration of salt, to which there were no significant changes in the liquid and plasticity limits, neither on zeta potential if pH is equal to 7, however the quantity of ions supplied was enough to affect the electrical resistivity of the compacted material. The water retention curve of the two kinds of samples was determined using a water dewpoint device and through vapour equilibrium. The electrical resistivity was measured in samples to which suction was known, allowing to find a relationship between total suction and electrical conductivity, and therefore between water content and electrical resistivity. The results found are commented considering the electrical transport through the liquid phase and its continuity in the porous media, which depends on the conductivity of the electrolyte and on the degree of saturation.

1 Introduction

Prospection techniques based on measuring the electrical resistivity of geomaterials are being used mainly for geophysical characterization, for evaluating soil contamination and the extension of contaminated areas and for compaction control [1-7].

This technique is based on the fact that contrasts in electrical resistivity along the profiles analysed help identifying zones of transition because this property is affected by the presence of water and dissolved salts in the pore water, as well as by soil structure. However, *in situ* data interpretation has some difficulties because electrical resistivity is affected by changes in the unsaturated state of the soil and by the presence of salt compounds (natural or from contamination). The correspondence between electrical resistivity and total suction in compacted kaolin considering the presence of salt was investigated in the study presented in order to understand how these values would be affected by the presence of salt. Such study has several engineering applications as relations like this may help in better interpretation of *in situ* tests based on measuring

electrical resistivity, as well as in laboratory tests where resistivity sensors may be used.

The samples tested were compacted for the same voids ratio and water content, however one type was prepared with distilled water and the other with a NaCl solution (0.5 M). This salt was chosen because it is well known that its presence affects electrical resistivity and also because it is not harmful and for this reason no special requirements are necessary to ensure safety during the experimental tests. The results were interpreted taking into account soil structure and its changes in the presence of salt, as well as how salt concentration in the electrolyte changes during wetting and drying cycles.

2 Material studied

A commercial white kaolin was used, having 68% of silt-size particles (size between 0.075 mm and 0.002 mm) and 31% of clay-size particles (smaller than 0.002 mm). Solid particles density is 2.61.

The Atterberg limits are presented in Table 1 considering kaolin mixed with distilled water or with the NaCl solution of 0.5 M. It can be seen that salt presence

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reduces the plasticity of the kaolin because classification changes from MH to CL (Unified Soil Classification adopted, USC). This indicates chemical interaction between clay minerals and the ions provided by the salt solution, which reduce dispersive forces between the clay minerals.

Table 1. Atterberg limits for the two fluids studied.

| Fluid | Liquid limit (%) | Plastic limit (%) | Plasticity index (%) | USC |
|----------------------|------------------|-------------------|----------------------|-----|
| Distilled water | 51 | 30 | 21 | MH |
| 0.5 M NaCl (pH= 8.2) | 48 | 25 | 23 | CL |

Dispersive forces are maximum when distilled water is used and are expected to reduce with increasing concentrations of NaCl. This effect can be identified also by comparing the zeta potential of the clay studied when dispersed in distilled water or in a salt solution. Indeed, as shown in Figure 1, for pH= 7 the zeta potential in water is equal to that in 0.5 M NaCl solution, however for this pH the value in water is higher than the values measured for smaller concentrations of NaCl. This indicates the reduction of the thickness of the layer of water adsorbed by the charged surfaces (thickness of the double layer) and a larger tendency for particles to aggregate in the presence of salt, reducing plasticity. This effect prevails when pH is acid (pH< 7), as presented in Figure 1, while for basic solutions the particles will tend to aggregate better in water rather than when salt is present in the fluid [9,10].

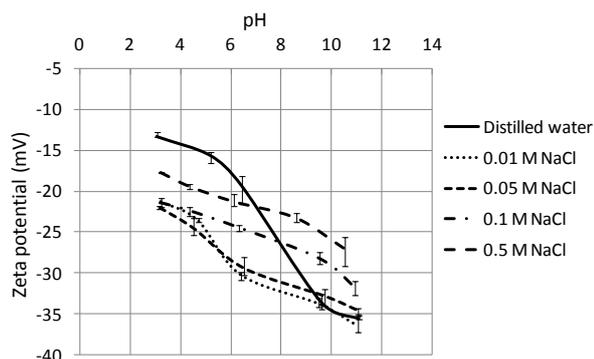


Figure 1. Zeta potential curves and the effect of different concentrations of NaCl [8].

This effect may also be observed when analysing pore size distribution measured in Mercury intrusion porosimetry tests (MIP) presented in Figure 2. The larger peaks identified correspond to the size of micropores (diameters between 40 to 50 nm) and reflect different dispersive forces for the two fluids. In this case dispersion is higher for the NaCl because the pores are slightly larger than those found for the samples prepared with water. Even if pH is 7 for both solutions, for the solution prepared with salt probably its concentration increased during drying for MIP tests and for this reason dispersive forces increased following the tendency identified in Figure 1 for the zeta potential increasing with salt concentration.

The samples used for the MIP plots were compacted with the corresponding fluid in order to have voids ratio of 0.9 and water content of 25%. As shown in the photograph of Figure 3, the compacted material is a double porous material, where the micropores (detected by MIP) are those of the clay aggregates and the macropores are very large (in the order of millimetres, not detected by MIP). These are the voids between the aggregates [11].

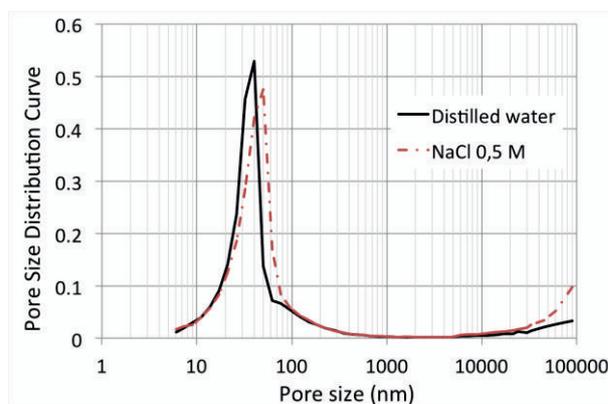


Figure 2. MIP of the samples prepared with distilled water and NaCl 0.5 M solution.



Figure 3. Compacted sample (prepared with water).

The compaction conditions adopted intend to create similar soil structures independently from the fluid used. From the MIP tests it can be seen similar microstructures, and because voids ratio is the same it can be assumed similar macrostructures as well.

3 Experimental setup

The water retention curves were measured for the samples prepared with the distinct fluids using a Dewpoint Potential Meter (WP4C) equipment. The same sample was used for the entire curve, compacted as shown in Figure 3 and subjected to one drying-wetting cycle.

For the electrical resistivity tests, the samples were compacted in a mould (Figure 4), in which four steel electrodes were inserted. These samples were subjected to vapour equilibrium technique (Figure 5) so that each sample have a different water content following a wetting path or a drying path. The samples that followed the wetting path were dried in contact with the air before the use of the vapour equilibrium ($s=87$ MPa). The samples of the drying branch are saturated before vapour equilibrium. Volume changes due to this preliminary treatment were not considered in the analysis because previous studies [12] indicated that the material has low

swelling potential. Partially saturated solutions of NaCl were used to apply different suctions (1, 5, 15 and 39 MPa), prepared as suggested by [13].

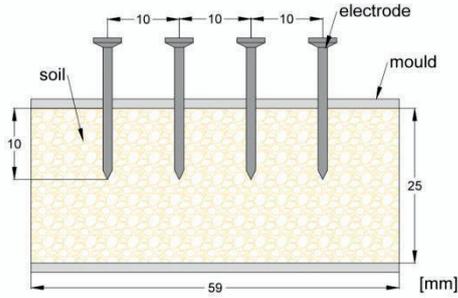


Figure 4. Setup for the electrical resistivity test.



Figure 5. Samples in vapour equilibrium.

Electrical resistivity, suction and water content were measured after reaching vapour equilibrium. Electrical resistivity measurements were done according with Wenner method configuration [14], by applying a DC current in the exterior electrodes and measuring potential in the inner ones. The value of electrical resistivity was computed through Equation 1 (geometric factor from Wenner method [15]), where L_1 and L_2 are the spacing and depth of the electrodes, respectively, and R is the electrical resistance. This parameter corresponds to the slope of a linear trendline determined for several values of applied current and measured potential.

$$\rho = \frac{4\pi L_2 R}{1 + \frac{2L_2}{\sqrt{L_2^2 + 4L_1^2}} - \frac{L_2}{\sqrt{L_2^2 + L_1^2}}} \quad (1)$$

4 Results and discussion

4.1 Water retention curve

The water retention curves are presented in Figure 6.

The curves were adjusted using van Genuchten expression (Equation 2, [16]), where e is voids ratio, G_s is the density of the solid particles, s is total suction, w is water content and P and λ are calibration constants (Table 2). In the absence of data it was assumed constant volume during wetting and drying.

$$S_r = \frac{G_s}{e} w = \left[1 + \left(\frac{s}{P} \right)^{\frac{1}{1-\lambda}} \right]^{-\lambda} \quad (2)$$

The residual state of saturation [17] can be determined. This value marks the discontinuity of the liquid phase. Above this value it can be assumed that the macrostructural water has no longer influence on suction and the consideration of electrons flow through the liquid phase is no longer realistic. The values found are presented in Table 3.

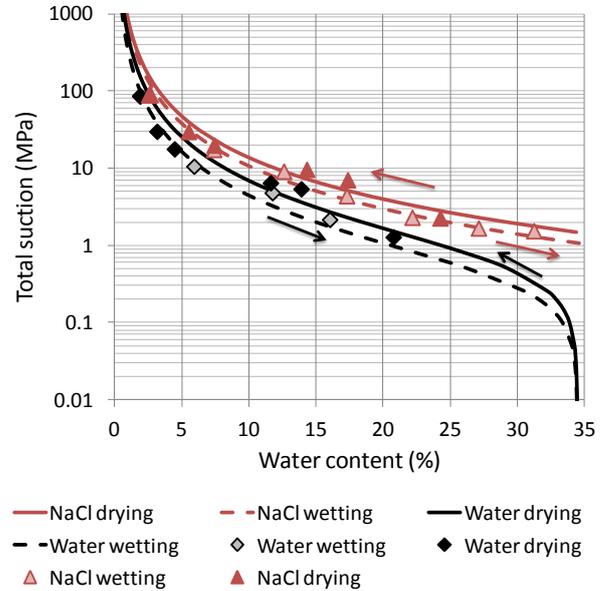


Figure 6. Water retention curves.

Table 2. Calibration parameters of Equation 2.

| Solution | Distilled water | | NaCl 0.5 M | |
|-----------|-----------------|--------|------------|--------|
| | Wetting | Drying | Wetting | Drying |
| P (MPa) | 0.45 | 0.70 | 0.16 | 0.19 |
| λ | 0.350 | 0.350 | 0.353 | 0.360 |

Table 3. Residual state of saturation.

| Solution | Distilled water | | NaCl 0.5 M | |
|-----------|-----------------|--------|------------|--------|
| | Wetting | Drying | Wetting | Drying |
| w (%) | 2.8 | 3.2 | 4.5 | 4.5 |
| S_r (%) | 8.12 | 9.28 | 13.1 | 13.1 |

It can be observed in Figure 6 that the curves measured using water are below those measured using the NaCl solution mainly due to the contribution of the osmotic component. This is because viscosity and surface tension of the solution prepared with NaCl is not that different from the curve found for distilled water.

For the sample prepared with NaCl it was not possible to measure null suction at saturation. This lowest suction was approximately 1.2 MPa. This value is similar to the contribution of the osmotic component, which minimum value occurs to the minimum concentration of NaCl allowed by the maximum amount of water in the pores, assuming no volume change. At preparation, the solution prepared with 0.5 M applies $s=2.2$ MPa (25°C) but the soil was not saturated. Keeping the same mass of NaCl, at saturation its concentration reduces to approximately

0.35 M, corresponding to $s=1.53$ MPa. This last value is closer to the value measured and error can be attributed to some swelling deformation during saturation.

This rule can also be applied for the highest suctions. In this case the maximum suction measured should be 39MPa, the value applied by a full saturated NaCl solution. This suction is verified at the residual state of saturation, confirming that osmotic suction depends on the continuity of the liquid phase, and therefore on the amount of free water. This can be considered to be macrostructural water. Above this suction it can be assumed that water in the microstructure is more important, and therefore osmotic effects due to the presence of dissolved salts are no longer relevant.

To conclude, to calibrate the WRC of the samples with NaCl using Equation 2 an artificial water content at saturation had to be adopted. This value was adjusted to achieve a good fitting [12].

4.2 Electrical resistivity

Table 4 presents the values measured for the electrical resistivity (ρ) for each water content. The electrical resistivity of the samples prepared with NaCl is lower than the values found for the samples prepared with water in the entire suction range, because of the presence of ions in the solution. Both electrical conductivity of distilled water and 0.5M NaCl were measured (6.5 μ S/cm for water and 45.7 mS/cm for the salt solution), however they cannot be directly related with the values of electrical resistivity measured at full saturation because the latter are affected by soil structure (mainly porosity and tortuosity) [1] and by the salts present in the soil.

The values from Table 4 allowed the calibration of Equation 3 [4], where ρ_{sat} is the electrical resistivity measured at saturation and B is a calibration parameter. Both values are presented in Table 5. The values found for parameter B are within the ranges of values expected for clays [4]. The electrical conductivity of the clay minerals was not considered in this equation assuming the validity of the equation only for the cases where liquid phase is continuous. This is a simplification.

$$\frac{\rho}{\rho_{sat}} = S_r^{-B} \quad (3)$$

Table 4. Electrical resistivity and degree of saturation of the samples.

| Fluid | Branch | Readings | Applied suction (MPa) | | | | | |
|-----------------|---------|-----------------------|-----------------------|--------|-------|-------|---------|---------|
| | | | 0 | 1 | 5 | 15 | 39 | 87 |
| Distilled water | Wetting | S_r (%) | 90.6 | 46.6 | 23.9 | 10.7 | 6.2 | 3.4 |
| | | ρ (k Ω m) | 0.079 | 15.106 | 2.357 | 4.621 | 5.492 | 25.544 |
| | Drying | S_r (%) | 86.1 | 58.9 | 41.0 | 12.8 | 6.2 | 3.4 |
| | | ρ (k Ω m) | 0.098 | 1.410 | 0.877 | 0.772 | 328.098 | 879.398 |
| NaCl solution | Wetting | S_r (%) | 87.6 | 74.2 | 42.0 | 19.5 | 10.5 | 4.5 |
| | | ρ (k Ω m) | 0.007 | 0.005 | 0.060 | 0.081 | 0.531 | 5.150 |
| | Drying | S_r (%) | 88.8 | 76.1 | 47.6 | 17.1 | 8.0 | 3.6 |
| | | ρ (k Ω m) | 0.064 | 0.069 | 0.129 | 0.227 | 0.464 | 4.193 |

The curves found for each B are presented in Figure 7. Hysteresis exists, as it is observed in the water retention curve. Electrical resistivity and degree of saturation are related because the electrical current flows preferentially through the liquid phase. It is also observed that, for high degrees of saturation, the electrical resistivity tends to a common value which is dependent on the type of pore fluid.

A considerable decrease in the electrical resistivity is observed when the specimens are dried below the residual state of saturation (Table 3). This is consistent with the assumption that electrical current flows through the liquid phase, because it is expected to become more difficult as soon as this path loses continuity. Such result was observed in other clays [18]. Nevertheless, electrical current in clays can also flow through their electrically charged surfaces, and probably this is the reason why the electrical resistivity could be measured above the residual state of saturation and the values were not very high.

Table 5. Values of B and ρ_{sat} .

| Fluid | B | | ρ_{sat} (k Ω m) |
|-----------------|---------|--------|-----------------------------|
| | Wetting | Drying | |
| Distilled water | 1.70 | 2.76 | 0.079 |
| NaCl 0.5 M | 1.69 | 3.27 | 0.007 |

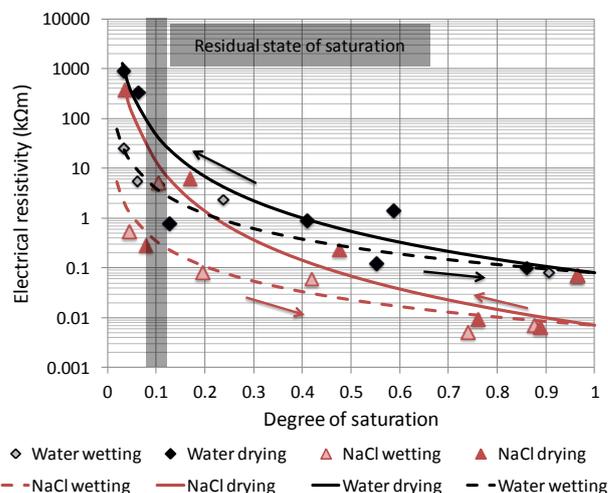


Figure 7. Electrical resistivity relation with degree of saturation and residual state of saturation.

4.3 Electrical resistivity versus suction

A direct relationship between electrical resistivity and suction was found by joining Equations 2 and 3 to obtain Equation 4.

$$\rho = \rho_{sat} \left[1 + \left(\frac{s}{P} \right)^{\frac{1}{1-\lambda}} \right]^{\lambda B} \quad (4)$$

The curves relating electrical resistivity and suction can be defined using the calibration parameters previously presented in Tables 2 and 5. They are presented in Figure 8. This figure includes the experimental points to show the adjustment achieved. It is not very good for the samples prepared with distilled water and measurements done in the drying branch.

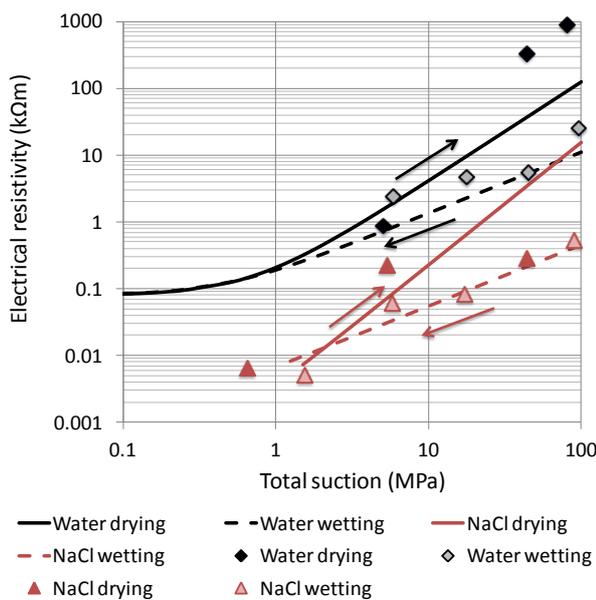


Figure 8. Electrical resistivity versus total suction using Eq. 4.

However Equation 4 is not practical, and for this reason Equation 5 can be proposed as a simpler alternative to Equation 4. In Equation 5, a and b are constants calibrated using the data from Table 4 and ρ and s were already defined. The values of the constants found are in Table 6.

$$\rho = as^b \quad (5)$$

Table 6. Values of a and b .

| Fluid | a | | b | |
|-----------------|---------|--------|---------|--------|
| | Wetting | Drying | Wetting | Drying |
| Distilled water | 0.5197 | 0.0146 | 0.7627 | 2.5643 |
| NaCl 0.5 M | 0.0046 | 0.0164 | 1.0749 | 0.9021 |

It can be seen in Figure 9 that this alternative expression provides a good adjustment for the experimental points as well. The comparison between the quality of curve fitting achieved using the definition of the WRC or the simpler alternative provided by Equation

5 cannot be done such straightforward because it is strongly affected by the equation used for the definition of WRC.

Simpler equations such as Equation 5 can be used to calibrate electrical resistive sensors for soil suction measurement, which may be considered as an alternative to WP4 or other existing equipment.

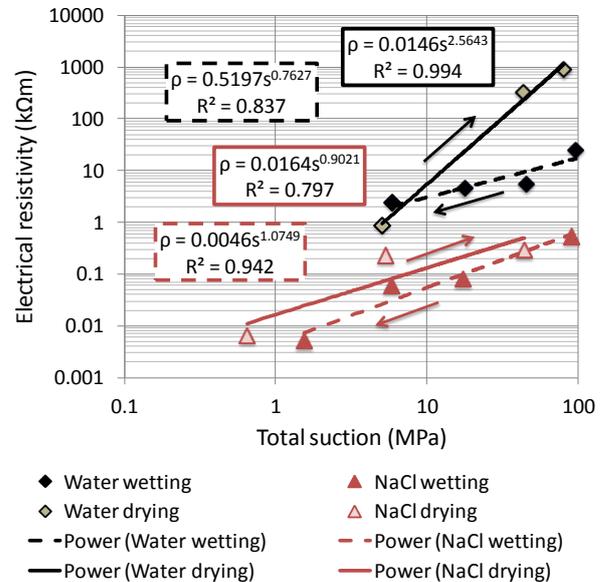


Figure 9. Electrical resistivity versus total suction using Eq. 5.

5 Conclusions

The experimental results show that the presence of NaCl affects the WRC and electrical resistivity.

Concerning the effect of the presence of salt in the WRC, suction value measured at saturation suggest that it corresponds to osmotic suction. It corresponds to the value applied by a solution having the minimum concentration of salt in the pore fluid when the pores are completely saturated. On the other hand, suction measured at residual state of saturation is closer to the value applied by the saturated NaCl solution.

Concerning the effect of the presence of salt in electrical resistivity, it reduces this parameter because of the presence of ions dissolved in the water. Even if electrical current may flow through the electrically charged surfaces, the results show that the liquid phase provides an important path. It can be seen an increase of resistivity when the degree of saturation is lower than the residual degree of saturation, and also hysteresis similar to that observed in the WRC.

Good relationships between total suction and electrical resistivity were found. The quality of the fitting when using the expression for the WRC may be improved by adopting a better definition of this curve. The equation proposed by van Genuchten was adopted in this paper because it is very simple, however it may not be the best for this material.

The relations found between suction and electrical resistivity can be used for soil sensors development and for the interpretation of geophysical prospection tests when the evaluation of soil strength is being investigated. However they require the inclusion of the electrical conductivity of the clay minerals, which is under progress.

Acknowledgments

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References

1. G.E. Archie. *Petroleum Transactions of AIME*, **146** (1), pp. 54-62 (1942).
2. W. Kelly, R. Frohlich. *Ground Water*, **23** (2), pp. 182-189 (1985).
3. Sharma, P. *Environmental and engineering geophysics*. Cambridge University Press, pp. 207-261 (1997).
4. Z. Abu-Hassanein, C. Benson, L. Boltz, *Journal of Geotechnical Engineering*, **122**(5), pp. 397-406 (1996).
5. M. Khalil, F. Santos. *Developments in Hydraulic Conductivity Research*, pp. 49-70. (2011).
6. J. Santamarina, K. Klein, M. Fam. (2001). *Soils and Waves*. John Wiley & Sons, pp. 336-341.
7. D.A. Gunn, J.E. Chambers, S. Uhlemann, P.B. Wilkinson, P.I. Meldrum, T.A. Dijkstra, F. Haslam, M. Kirkham, J. Wragg, S. Holyoake, P.N. Hughes, R. Hen-Jones, S. Glendinning. *Construction and Building Materials*, **92**, pp. 82-94 (2014).
8. V. Gingine, R. Cardoso, *Soil Structure Influence on Electrokinetic Dewatering Process. *Electrokinetics Across Disciplines and Continents**, pp. 19-42, (2015)
9. G.H. Bolt. *Géotechnique*, **6**(2), pp. 86-93 (1956).
10. Y. H. Wang, D. Xu. *J. Geotech. and Geoenv. Eng.*, Vol. **133**(7), (2007). double layer e swelling potential
11. E. Romero, A. Gens, A. Lloret. *Engineering Geology*, **54**, pp. 117-127 (1999).
12. A. S. Dias, *Electrical resistivity of compacted kaolin and its relation with suction*, MSc Thesis, Instituto Superior Técnico, University of Lisbon (2015)
13. E. Romero, 4º Simpósio Brasileiro de Solos Não Saturados, pp. 535-542 (2001).
14. BS 1377-3. *Methods of test for Soils for civil engineering purposes. Chemical and electro-chemical tests* (1990).
15. R. Herman. *Am.J.Phys.*, **69** (9). pp 943-952 (2011).
16. M. van Genuchten. *Soil Sci. Soc. Am. J.*, Vol. 44, No. 5, pp. 892-898 (1980).
17. S. K. Vanapalli, D. G. Fredlund, D. E. Pufahl, *Géotechnique*, **49** (2), pp. 143-159 (1999).
18. M. Fukue, T. Minato, H. Horibe, and N. Taya, *Eng. Geol.*, **54**, pp. 43-53 (1999).