Measuring in-situ dry density using dynamic penetrometer.

M. Morvan & P. Breul
Institut Pascal, Polytech Clermont-Ferrand, Université Blaise Pascal, Clermont-Ferrand, France

ABSTRACT: Panda penetrometer (Gourvès et al 1997) is a light dynamic penetrometer, designed for soil characterization of the first meters below the surface. It provides the cone resistance variation with depth. For homogeneous soils, three parameters can be determined: the critical depth zc, the initial cone resistance qd0, and the cone resistance in depth qd1. Some researchers showed a relationship, between cone resistance and dry density of the studied soil, which is unique for a given soil at a given saturation state. If this relationship is extended to every saturation state, then it is possible to use this device for control of compaction without estimating the soil hydraulic state. The present study establishes, for a silt, a unique relationship between cone resistance in depth and dry density to every saturation state. Saturation degree and suction appear to be important variables in this relationship. Finally, the relation is extended and validated for 3 different soils and different saturation state.

1 INTRODUCTION

Evaluating the *in-situ* dry density of a soil is a necessity when controlling its compaction. Previous works showed that a relationship between dry density of tested materials and cone resistance measured from penetrometric test exists. However, obtaining this characteristic by using penetrometric technique means knowing the soil classification and its hydraulic state. For Panda penetrometer (Gourvès and Richard, 1995, Gourvès et al., 1997, Breul et al., 2009)), this unique relationship was enlightened for a given soil and a given water content. Three water contents were studied depending on proctor optimum: dry, medium, wet.

The aim of this paper is to propose a new relationship valid for any water content in order to reduce uncertainty of the *in-situ* dry density evaluation. Moreover, in a context of climatic changes, this relationship could be interesting in evaluating soil bearing capacity variation due to drying-wetting cycles. In the future, this evaluation could give us a mean to compute suction *in-situ* using other parameters that can be easily obtained in laboratory, e.g.: grain size distribution, proctor results, Atterberg limits.

2 PANDA AND EXISTING RELATIONSHIP

2.1 *Panda*

Panda penetrometer is a light dynamic penetrometer that allows to obtain soil cone resistance for first meters below the soil surface using variable energy. Due to its small size (cone of 4 cm2 and rods diameter of 15,4 mm) and its lightness, it gives the opportunity to examine first meters of most soft soils even when it is hard to get to.

The dynamic beating is realized manually by the mean of a standardized hammer. The beating energy and the cone displacement are recorded for each blow. Thanks to this simultaneous measurement, the device provides a penetrogram (cone resistance variation versus depth) with a cone resistance measurement every each 5 mm of cone displacement on average (Fig.1).

From the recorded penetrogram, several parameters are deduced for homogenous soil (Gourvès and Richard, 1995):

- Critical depth zc, depth from which cone resistance stays constant
- Initial cone resistance qd0
- Average cone resistance below zc , qd1.

Like all penetrometers, Panda device has been developed in order to obtain the *in-situ* mechanical soil properties during geotechnical soil investigations. However, as considering that the dynamic resistance of a soil is strongly connected to the state of density of the tested materials, it can also be used for the control of compaction (Chaigneau et al., 2000), as for example in the control of tailing deposits in Chile (Villavicencio, 2009).

2.2 *Existing relationship (Panda data base)*

Relations linking the cone resistance in depth (qd1) measured with the Panda to the material dry density were established in order to obtain an indirect evaluation of the dry density of the studied soil. For that purpose, a base of "model soils" (containing 1 to 3 materials for each class of soils defined in the French classification GTR) was built (Chaigneau, 2001). The objective of this base of "model soils" is to be able to characterize any soil studied *in-situ* by referring to "model soils" of similar properties. For each material, Panda tests have been carried out in a calibration chamber (80.6 cm height and diameter of 37.5 cm), for five levels of density, varying from the bulk density to about 110% of the standard Proctor density and for three different water contents corresponding to a wet, medium, and dry state.

In (Chaigneau et al., 2000), authors showed that for one material class at given water content, the relation between the cone resistance and the dry density is:

$$\gamma_d = \alpha \ln(q_{d1}) + \beta \qquad (1)$$

This relation being valid for one water content, it would be interesting to be able to generalize it for all ranges of water content of a soil in order to estimate the *in-situ* dry density of a material only from the knowledge of the geotechnical soil classification and from a penetrometric test.

3 NEW RELATIONSHIP: PRELEMINARY STUDY ON CNR SILT

The establishment of the new relationship linking dry density to cone resistance has been carried out on a silt named CNR silt.

3.1 *CNR silt results*

CNR silt is classified in A1 for the French GTR classification and its characteristics are:

- D max=2.6mm
- Passing at 80microns: 77.76%
- Grain volumetric weight: 26.62 kN/m3.
- Liquidity limit: 25.8%
- Plasticity limit: 22.5%
- Normal proctor results: wopt=14.2% and optimum dry volumetric weight 17.98kN/m3.

This database also gives us results of Dynamic penetrometer Panda tests were carried out for each soil at different saturation state and density. For each test, the average dry density, the cone resistance in depth, and the average water content were measured. Each test is repeated three times and results are the average over these three tests. Figure 1 presents an example of the obtained penetrogram for wet CNR silt. Thanks to this penetrogram, we obtained zc=0.26m, qd1=4.05MPa, qd0=2.33MPa. In this study, only qd1, the cone resistance in depth, is used.

The objective of the presented study was to characterize the influence of pore water on cone resistance.

In order to verify water content effects on cone resistance, we present results in (qd1, γd) plane without taking water content variations into account (Fig. 2). We can notice that the obtained relationship is not accurate enough and the dependency to water content is to be studied.

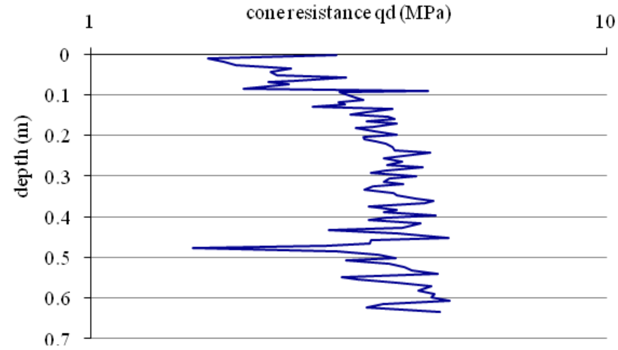

Figure 1: example of CNR silt penetrogram.

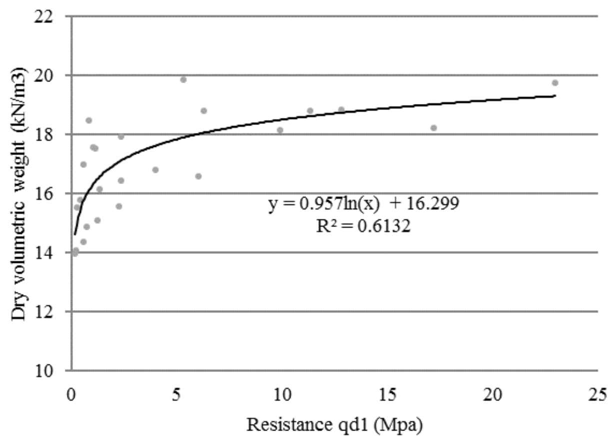

Figure 2: Calibration points (qd1 v/s γd) plotted together without water content distinction.

Calibration curves for each water content tested are presented in Fig. 3. With these calibration curves, knowing water content of a soil, we can approximate a $\gamma_d = f(q_{d1})$ law.

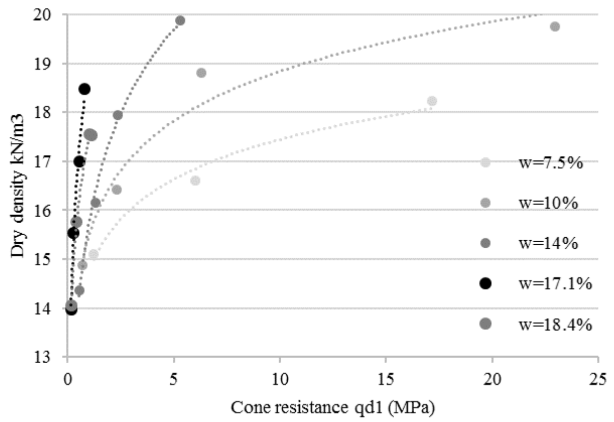

Figure 3: Calibration curves (qd1 v/s γd) for different water contents.

These curves lead to the following relationship for each water contents:

$$\gamma_d = \alpha(w)\ln(q_{d1}) + \beta(w) \qquad (2)$$

Figure 4 shows values of α and β parameters versus water content. It is difficult to conclude on the dependency of these parameters on water content. Any correlation cannot be found. To choose a variable mechanically acceptable and that is in accordance to experimental data, we performed a preliminary study.

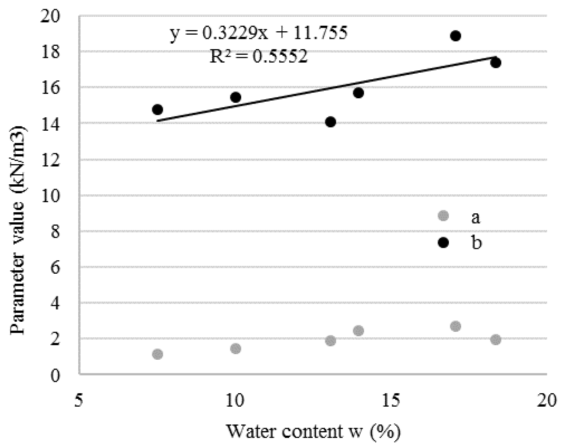

Figure 4: Variation of α and β parameters with water content.

3.2 *New relationship: Previous study.*

Among previous studies on cone resistance (Pournaghiazar et al., 2011, 2013) formulated a relationship for CPT as follows: This relation is given in eq.3.

$$q_c = Ap'^B e^{CD_r} \qquad (3)$$

With *A, B, C* and *D* being parameters, p' confining effective stress and D_r, relative density ($D_r = \frac{e_{max} - e}{e_{max} - e_{min}}$).

We can rewrite this equation to get closed to Chaigneau relationship (Chaigneau et al., 2000):

$$\gamma_d = A''\ln(q_{d1}) + B'' + C''\ln(p') \qquad (4)$$

If we consider the simplified form of effective stress given by Bishop:

$$\sigma' = \sigma - u_a + sS_r \text{ so } p' = p - u_a + sS_r \qquad (5)$$

With σ' Bishop effective stress for unsaturated soils, σ total stress, u_a air pressure, s suction and S_r saturation degree.

We made the assumption that calibration curves were realized with no confining pressure and that air pore pressure is zero. So eq.5 can be simplified to:

$$\gamma_d = A''\ln(q_{d1}) + B'' + C''\ln(sS_r) \qquad (6)$$

3.3 *New relationship: application to CNR silt*

To verify this equation, we measured the retention curve of CNR silt. This curve gives suction for each saturation degree. To obtain this curve, we used the Normalized Whatman 42 filter papers (ASTM, 2003, Bicalho et al., 2007, Muñoz-Castelblanco et al., 2010). For each point, water content and void ratio of the soil were measured as well as the water content of the filter paper. This method is based on the suction equilibrium between the sample and the filter paper with a well-known retention curve. Suction of the filter paper can be obtained using these equations:

For w<45.3% $\log(s) = 5.327 - 0.0779w$ (7)

For w>45.3% $\log(s) = 2.412 - 0.0135w$ (8)

Samples where realized at a constant void ratio of 0.80. Figure 5 shows the experimental points obtained and the simulation results using a Brooks and Corey law (eq. 9) (Brooks and Corey, 1964).

$$S_r = \left(\frac{s_e}{s}\right)^k \qquad (9)$$

Where s_e, air entry suction and *k* are material parameters linked to particle size distribution and particle chemistry.

For CNR silt, we obtained se=5kPa and k=0.25.

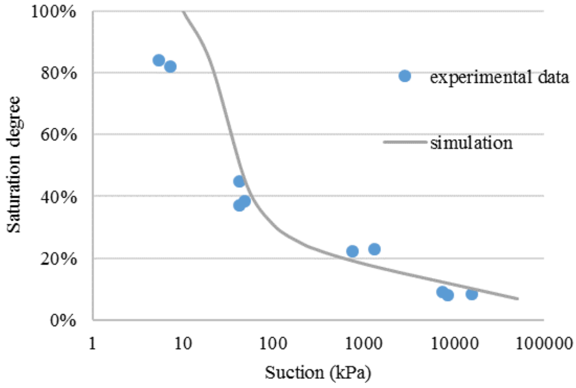

Figure 5: Water retention curve of CNR silt (Brooks and Corey equation and experiment).

Figure 6 shows the dependency of *B* parameter toward *sSr*.

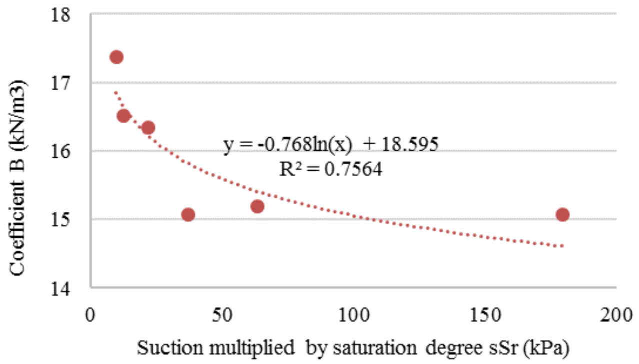

Figure 6: Variation of and B with sSr for CNR silt.

The obtained curve global equation is:

$$\gamma_d = 0.82\ln(q_{d1}) + 18.595 - 0.768\ln(sS_r) \qquad (10)$$

Figure 7 shows the good agreement between measured and calculated dry densities. Mean difference between measured and calculated dry densities is about 2.5%.

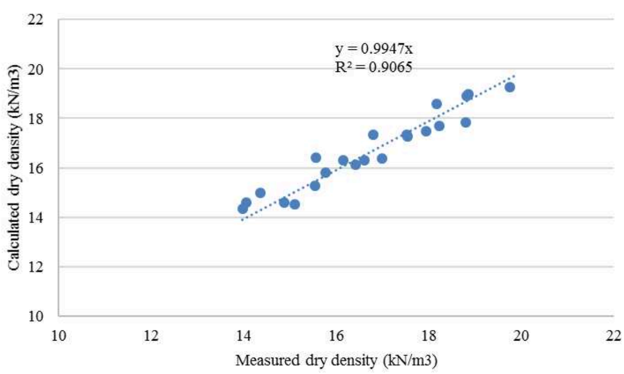

Figure 7: Comparison of measured dry density with calculated dry density for CNR silt.

Equation (10) has the same form as equation (6). The proposed equation is in agreement with bibliography.

4 VALIDATION FO THE RELATIONSHIP

In order to verify this methodology on other kind of soils, we performed a global study on Lachamps clay and Allier clay.

4.1 *Material properties*

Lachamps clay is classified in A2 for the French GTR classification. Its characteristics are regular values for clays:

- D max=0.08mm
- Passing at 80microns: 96.73%
- Grain volumetric weight: 24.04kN/m3.
- Liquidity limit: 42.7%
- Plasticity limit: 27.6%
- Normal proctor results: wopt=15.8% and optimum dry volumetric weight 18.08kN/m3

We measured the retention curve of Lachamps clay to obtain the relationship linking *s* and S_r.

Allier clay is classified in A2-2 for the French GTR classification. Its characteristics are regular values for clays:

- D max=0.71mm
- Passing at 80microns: 67.88%
- Grain volumetric weight: 24.04kN/m3.
- Liquidity limit: 36.1%
- Plasticity limit: 23.2%
- Normal proctor results: wopt=14.9% and optimum dry volumetric weight 17.60kN/m3.

4.2 *Water retention curves*

Measuring water retention curve is a long laboratory test. So we propose to use the model developed by Aubertin et al. (2003) to obtain this relationship. This simulation is mainly based on grain size distribution a classical and simple laboratory test.

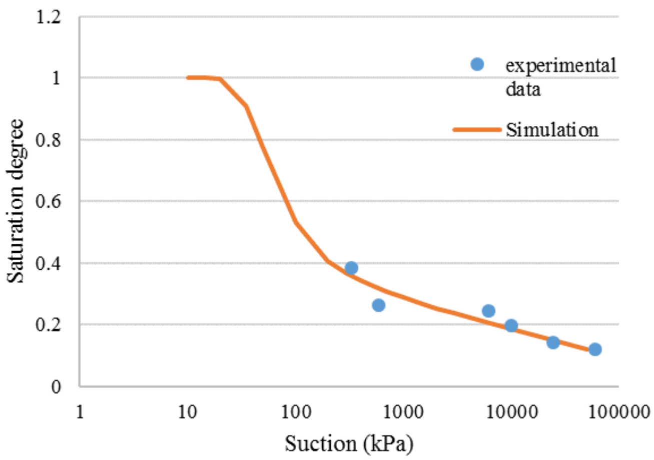

Figure 8: Water retention curve of Lachamps clay (Aubertin et al. simulation and experiment).

Figure 8 shows the good agreement between simulation and experimental data. So we decided to use this model to simplify the methodology to obtain the parameters of $\gamma_d = f(q_{d1}, sS_r)$. We made the assumption that for typical fine soils the retention curve given by the model (Aubertin et al., 2003) is accurate enough. We choose to validate this hypothesis using Allier clay results.

Figure 9 shows the Brooks and Corey curve obtained with parameters se=15kPa and k=0.28.

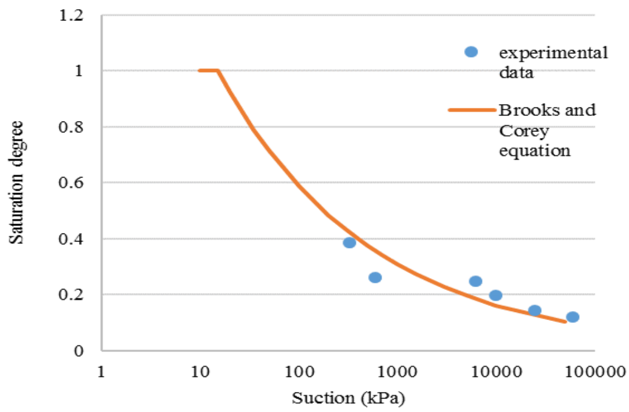

Figure 9: Water retention curve of Lachamps clay (Brooks and Corey equation).

Figure 10 shows the estimated water retention curve and obtained Brooks and Corey curve for Allier sand with parameters se=20kPa and k=0.32.

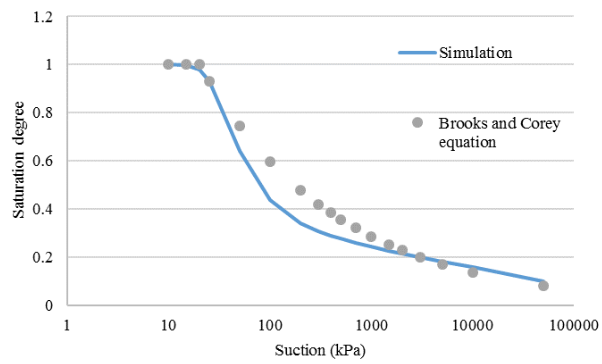

Figure 10: Water retention curve of Allier clay (simulation and Brooks and Corey equation).

4.3 *Validation of the relationship*

Using Books and Corey parameters, variation of coefficient B can be plot toward *sSr*. The accuracy of the relationship is quite good.

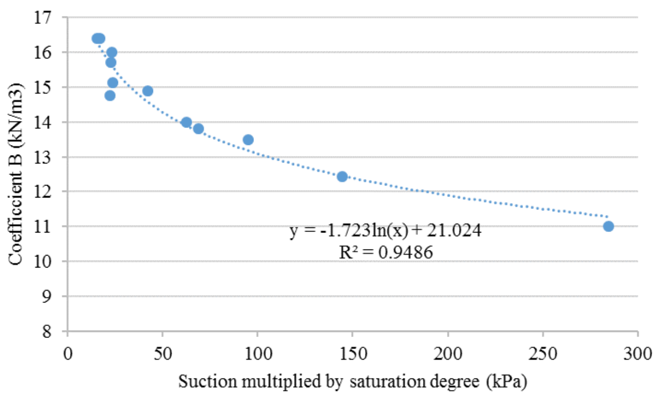

Figure 11: Variation of and B with sSr for Lachamps clay

Figure 11 presents results for Lachamps clay. So we obtain a relationship with three parameters:

$$\gamma_d = 1.06\ln(q_{d1}) + 21.024 - 1.7\ln(sS_r) \quad (11)$$

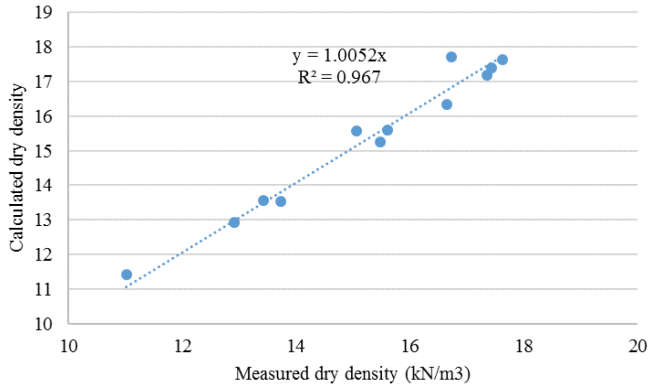

Figure 12: Comparison of measured dry density with calculated dry density for Lachamps clay

Figure 12 presents the comparison of measured dry density with calculated dry density using equation 11. The relationship is quite accurate and the mean difference between calculated and measured dry densities is about 1.7%

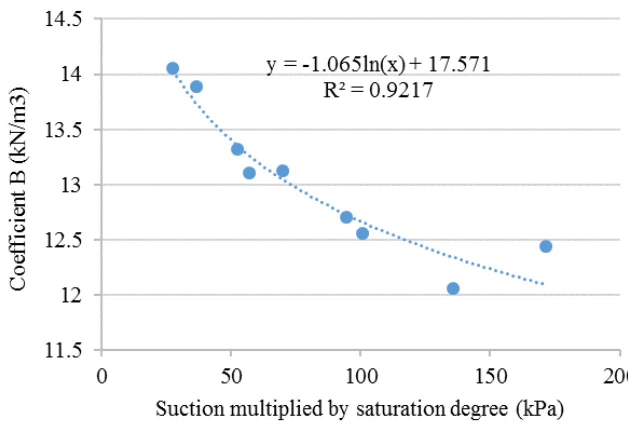

Figure 13: Variation of and B with sSr for Allier clay.

Using Allier clay Brooks and Corey parameters, we calculated sSr for each test. Figure 13 shows the dependency of B toward sSr. Thanks to this curve, we determined the parameters of the proposed equation giving dry density:

$$\gamma_d = 1.29\ln(q_{d1}) + 17.571 - 1.07\ln(sS_r) \quad (12)$$

Figure 14 shows the comparison between calculated dry density and measured dry density. The results are quite accurate. The maximum difference between measured dry density and calculated dry density is 2.5% and the mean difference is 1%. So this equation can be used to predict dry density.

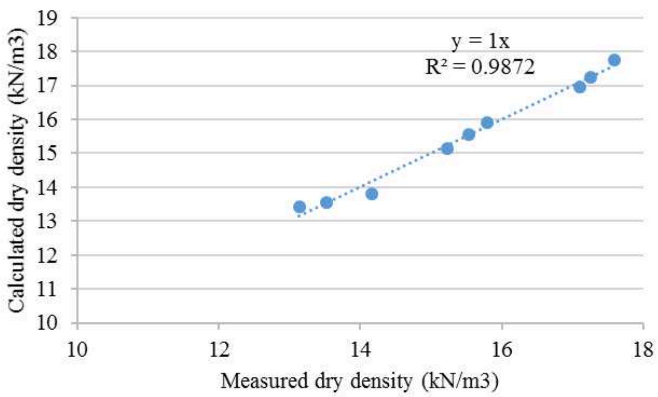

Figure 14: Comparison of measured dry density with calculated dry density for Allier clay.

5 CONCLUSIONS

In this work we proposed a methodology to measure *in-situ* dry density without estimating the soil hydraulic state. Tests using PANDA penetrometer were performed using a calibration chamber that permits the measurements of three parameters: water content, dry density, and cone resistance in depth. It was shown that these three parameters were linked and we proposed a new relationship based on the hydric state using *sSr*. To obtain this relationship we proposed a simple methodology based on few laboratory tests to complete the calibration chamber results. This methodology has been verified for fine soils. It might be discussed for sands and soils with large particle size distribution. With the established equation, it is possible to calculate saturation degree using dry density and cone resistance or to calculate dry density using saturation degree and cone resistance.

6 REFERENCES

ASTM, 2003, Standart Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. D5298-03 ©ASTM International.

Aubertin M., Mbonimpa M., Buissière B. and Chapuis R. P. 2003, A model to predict the water retention curve from basic geotechnical properties, *Canadian Geotechnical Journal*, 40(6): 1104-1122.

Bicalho, K. V., Gomes Correia, A., Reis Ferreira, S., Fleureau, J.-M. & Marinho, F. 2007. Filter paper method of soil suction measurement. In*: 13th Panamerican Conference on Soil Mechanics and Geotechnical Engineering,* Isla de Margarita, Venezuela.

Breul, P., Benz, M., Gourvès, R., & Saussine, G. 2009. Penetration test modelling in a coarse granular medium. *International conference on micromechanics of granular media*, *Powder and Grain*, AIP Conference Proceedings 1145(1): 173-176.

Brooks, R. H. & Corey, A. T. (1964). *Hydraulic properties of porous media*. Fort Collins, CO: Colorado State University, hydrology paper no. 3.

Chaigneau, L., Gourvès, R., Bacconnet, C. 2000. Penetration test coupled with a geotechnical classification for compaction control, *GeoEng2000, An international conference on geotechnical & geological Engineering*, Melbourne, Austraia.

Chaigneau, L. 2001. Caractérisation des milieux granulaires de surface à l'aide d'un pénétromètre. *Thèse de l'Université Blaise Pascal*, Clermont-Ferrand.

Gourvès R., Richard B. 1995. Le pénétromètre dynamique léger PANDA, *Proceeding of ECSMFE*, Copenhagen, Denmark, 83 – 88.

Gourvès R., Oudjehane F. and Zhou S. 1997. The in-situ characterization of mechanical properties of granular media with the help of penetrometers, *proceeding of Powders and Grains*, Durham, USA, 57-60.

Muñoz-Castelblanco, J. A., Pereira, J.-M., Delage, P. & Cui, Y.J. 2010. Suction measurements on a natural unsaturated soil: A reappraisal of the filter paper method. In: Unsaturated Soils - *Proceedings Fifth International Conference on Unsaturated Soils,* Barcelona, Spain. CRC Press 1: 707-712.

Pournaghiazar, M., Russell, A. R. & Khalili, N. 2011. Development of a new calibration chamber for conducting cone penetration tests in unsaturated soils. *Canadian Geotechnical Journal* 48(2): 314-321.

Pournaghiazar, M., Russell, A. R. & Khalili, N. 2013. The cone penetration test in unsaturated sands. *Géotechnique*, 63(14): 1209-1220.

Villavicencio G. 2009. Méthodologie pour évaluer la stabilité des barrages de résidus miniers, *Thèse de l'Université Blaise Pascal*, Clermont-Ferrand.