Estimating the Retention Curve of a Compacted Soil through Different Testing and Interpretation Methods

Osvaldo Bottiglieri, Francesco Cafaro, and Federica Cotecchia

Abstract. The paper reports the results of a study about the hydraulic properties of a self-weight compacted medium-grained soil. The investigation was based on both physical modelling and element volume testing, using different suction measurement techniques. The paper shows the efficacy in the assessment of the soil retention properties of the use of the filter paper technique and of low capacity tensiometers to measure the soil suction in different suction ranges.

Keywords: Retention curve, inverse numerical analysis, suction measurement.

1 Introduction

The hydraulic behaviour of partially saturated compacted soils is usually characterized through the assessments of both the retention curve and the conductivity function. An extensive experimental investigation has been recently carried out in order to deduce the hydraulic properties of a partially saturated medium-grained soil (Bottiglieri 2009; Bottiglieri et al. 2008), based upon soil element volume tests and physical modelling of seepage through the soil, under controlled boundary conditions.

The grain size distribution of the soil subjected to testing is shown in Fig.1a (continuous line). The soil is a mixture of two different natural soils. 30% of the soil (soil S1) is an illitic clay, part of the Subappennine Blue Clays, whose grain

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size distribution is shown in Figure 1. 70% of the soil is a quartz sand (S2), also shown in Figure 1 and classified as SP (Unified Soil Classification System - ASTM 2006). The liquid and plastic limits of portion S1 are 55% and 27%, respectively. The specific gravity of the whole soil has been measured to be Gs=2.65.

It is well known that the water retention curve (WRC) of a soil, thus its air entry value and desaturation rate, depend not only on the soil composition (i.e. grain size distribution and index properties; Fredlund 2006), but also on its initial state (Salager et al. 2010). Recent studies are also demonstrating how it depends also on the soil hardening history and achieved structure (Cafaro & Cotecchia 2005). In the present study, the state of the soil subjected to investigation was achieved through a non-routine procedure. The soil was air-dried for several days and set through static *self-weight compaction*, as illustrated in detail later. In order to assess soil states that, being achieved through routine compaction energies, could be of reference for comparison with the *self-weight* compacted states, the mixed soil was subjected to a Standard Proctor Compaction Test (Fig.2). The results in Figure 2 show that the optimum water content of the mixed soil is 10% and corresponds to a dry density of γ_d=19.8 kN/m^3. The *self-weight* compacted state of the soil is also shown in Figure 2. The soil has a quite open fabric (low dry unit weight) on the dry side of optimum; therefore it may be expected to experience a volumetric collapse under wetting (Tadepalli & Fredlund, 1991).

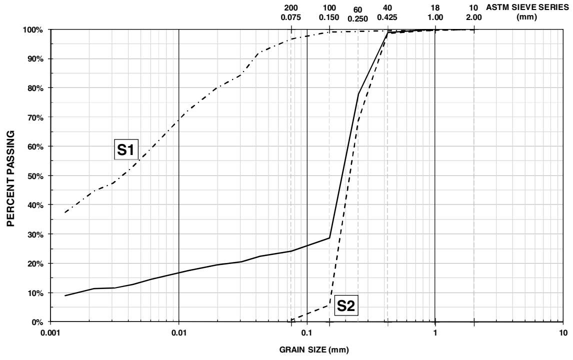

Fig. 1. Grain size distribution of S1, S2 and their mixture.

The experimental programme was designed to derive the WRC and the conductivity function(k(s)) through inverse numerical analysis (Kodesová 2003) of the physical model test data (Cafaro et al. 2008), as well as by means of direct measurements of the soil state during drying and wetting element volume tests. In these latter tests the initial soil state was the same as that of the soil in the physical model, being achieved through static compaction procedure (Bottiglieri et al. 2008).The experimental and numerical procedures employed to derive the soil hydraulic properties are briefly outlined in the following, along with the test results.

Specific aim of the paper is to provide evidence of the usefulness of combining filter paper test suction measurements with measurements achieved by means of standard low capacity tensiometers (suction range of 0-100 kPa) in deriving the soil water retention law even for medium-grained soils.

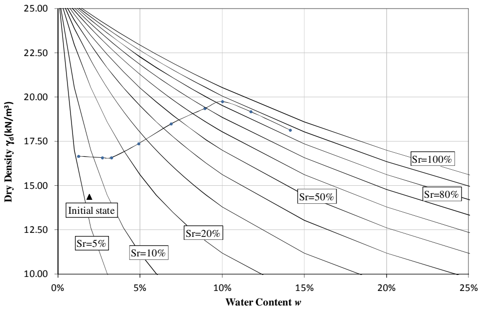

Fig. 2. Standard Proctor compaction curve and soil initial state.

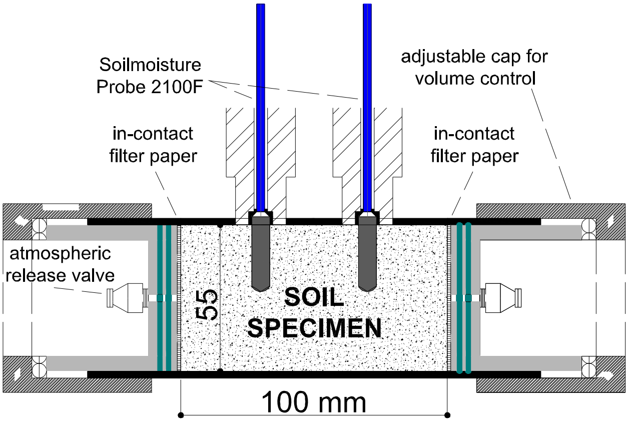

Fig. 3. Scheme of the measurement device: longitudinal section.

2 Testing Procedures

The investigation of the soil hydraulic properties has been carried out through two different strategies. One entails the monitoring of a real-scale seepage domain set through the soil in a built on purpose physical model. Both the soil WRC and k(s) controlling seepage are then derived by means of an inverse numerical analysis of the seepage monitoring data. The second strategy entails the measurement of the evolving soil state during wetting-drying tests on soil specimens set in the device shown in Fig.3 (longitudinal section), and brings to the definition solely of the soil WRC; the *k(s)* can be then deduced according to the relation between *k(s)* and the WRC (Mualem 1976, van Genuchten 1980), once the saturated hydraulic conductivity k_s is known. A detailed description of the device shown in Figure 3 can be found in Bottiglieri (2009).

The used physical model has been shown in Cafaro et al. (2008); it consists of a stainless tank, one longitudinal side of which is made of perspex, hosting a soil layer of one cubic metre volume (base: 1*m* x 2 *m*; height: 0.5 *m*). The tank was inclined of 7% on the horizontal. Thin successive soil layers were pluviated in the tank. After pluviation, each layer was very mildly compacted just to yield a smooth top surface, before being buried and compressed under successive layers. At the end of process specimens were taken at different depths in the model to measure the model void ratio profile. As shown in Cafaro et al. (2008) the measured void ratios, e_0, were found to vary in the range 0.79÷0.83, giving evidence to a uniformity of the soil state across the layer. As a matter of fact, the increase in self-weight loading down the model (0.5 m maximum depth) appears to produce negligible effects. Table 1 reports the dry unit weight γ_d, gravimetric water content, w_0, void ratio, e_0, saturation degree, *Sr*, and volumetric water content, θ_i, characterizing the average soil initial state in the model.

Table 1. Initial soil state.

G_s	γ_d (kN/m^3)	w_0 (%)	e_0	Sr(%)	θ_i
2.649	14.3	1.44	0.81	4.7	0.021

The perspex side of the model tank was equipped with two pairs of 2100F Soilmoisture Probes(each provided with a suction transducer), each pair being mounted along one vertical. The tensiometers could measure matric suction in the range 0 – 100 kPa (Cassel & Klute, 1986; Stannard, 1992). After 24 hour equalization time since installation within the soil model, the tensiometers measured initial matric suctions in the range 60-63 kPa (Fig.4; point I, grey triangle). Thereafter, a controlled water infiltration test was started, through the generation of a controlled rainfall on the model surface (Cafaro et al. 2008), during which the progression of the water front and the soil matric suction at the four measuring points were monitored. Thereby, a two-dimensional finite element inverse analysis of the infiltration process has been developed by means of 2.102 Hydrus-2D (IGWMC, 1999), adopting the Mualem - van Genuchten formulation (Mualem 1976, van Genuchten 1980) of the hydraulic functions:

$$\begin{cases} \Theta = \dfrac{\theta - \theta_r}{\theta_0 - \theta_r} = \left[\dfrac{1}{1+(\alpha s)^n} \right]^m ; \\ k(s) = k_s \Theta^l \left[1 - \left(1 - \Theta^{l/m} \right)^m \right]^2 \end{cases} ; \; s > 0; \; m = 1 - \frac{1}{n} \tag{1}$$

and assigning the soil initial conditions measured across the model as discussed previously: θ_i = 0.021 and s_i = 62 kPa. The analysis has been carried out by calibrating the fitting intervals of the different parameters (eq.1) according to ranges of values expected for the soil class the tested soil belongs to and searching for a solution of high coefficient of determination, R^2=0.976. Table 2 reports the shape factors vector of the primary wetting water retention function, *PW-WRC-i.a.*1, resulting from the inverse analysis, that is also shown in Figure 4. The inverse analysis has also assumed the saturate hydraulic conductivity k_s as unknown; the numerical solution has yielded k_s=1.58E-06 m/s, that is consistent with the k_s measured by means of permeameter testing on a soil sample of the same initial state as that of the soil in the physical model.

During the primary wetting, the soil has experienced an irreversible volumetric collapse of about Δe=0.16. Both this phenomenon and the well known air entrapment taking place upon wetting of sandy soils (Hopmans and Dane, 1986; Stauffer and Kinzelbach, 2001) are the causes of a volumetric water content at zero suction, θ_0 (Table 2), much lower than the initial porosity n_0=0.45 (Table 1).

Table 2. WRC parameters from inverse analysis.

	θ_r	θ_0	α (kPa^{-1})	n
PW-WRC-i.a.1	0.01	0.350	1.590	1.645
PW-WRC-e.v.1	0.01	0.353	0.396	1.622
PW-WRC-e.v.1	0.01	0.353	0.396	1.622
MD-WRC-e.v.1	0.01	0.352	0.104	1.668
PW-WRC-i.a.2	0.01	0.350	0.550	2.050
PW-WRC-e.v.2	0.01	0.353	0.389	1.669
MD-WRC-e.v.2	0.04	0.362	0.136	1.681

The device in Figure 3, used for the direct measurement of the WRC, is a perspex cylinder cell, hosting a specimen of 55 mm diameter and 100 mm length. The device has been implemented with two tensiometers of the same type as those installed in the physical model. As such it allows for measurements of the specimen volume and weight as well as of the suction across the specimen, during drying-wetting tests. Each specimen was made of air dried soil (at the same initial gravimetric water content as the model soil, w_0 Table 1) compacted in the cell at densities very close to that of the model soil (Fig.4, states in the black cross, Y). Following a step by step wetting path using distilled water, retention data were collected (series *e.v.(PW)* in Fig.4). Optimization of these data performed by RETC, a computer program developed by van Genuchten et al. (1991) to analyze the soil water retention and hydraulic conductivity data of unsaturated soils, returns the parameters of the primary wetting retention function, *PW-WRC-e.v.*1*,* reported in Table 2 and Figure 4. Also during the element volume primary wetting, volumetric collapse was observed. After primary wetting, two specimens, *e.v.a(MD)* and *e.v.b(MD)* were subjected to free drying in the device, following a procedure illustrated in Bottiglieri (2009). The experimental data of both tests provide the *MD-WRC-e.v.*1 (Fig.4), whose van Genuchten parameters are reported in Table 2. As expected, the data are indicative of a parallelism between the drying-wetting transition branches and of a hysteretic loop, of magnitude consistent with that observed for similar soils (Fredlund 2006). Nevertheless, the suction data at $\theta_w < 0.1$, circled in Figure 4, are all at about s=60 kPa and plot quite far from the interpolation function (*MD-WRC-e.v.*1). Different explanations may be envisaged for this discrepancy: e.g. inadequacy of the van Genuchten model for the pore size distribution of the tested soil, or fault of the Soilmoisture Probe in the measurement of suctions higher than 60 kPa for the examined medium-grained soil. In order to investigate this discrepancy, assuming the validity of the van-Genuchten model, the residual branch of the soil drying curve has been explored by means of the filter paper technique, as discussed in the following.

3 Use of the Filter Paper Test Data and Conclusions

To overcome the errors rising from the limited measurement range of the tensiometers, the complete WRC has been deduced using a different suction measurement method at high suctions (Evangelista et al., 2006). To this aim, the cap closing both ends of the cell in Figure 2 has been designed to host a filter paper, set in contact with the base of the soil specimen. It was used Whatman N° 42 filter paper, according to the setup and weighing prescriptions from Lu & Likos (2004) and Marinho & Oliveira (2006) and adopting equalization times, calibration curves and data interpretation procedures from recent literature (Chandler 1992, Leong et al., 2002; Marinho & Oliveira, 2006;). It has been assumed that, as demonstrated by Marinho (1994), there is no difference between the calibration curves for total and matric suction and that with in-contact filter paper technique, the measured suction represents the matric suction, if below 1 *MPa*, and the total suction if higher. Since during wetting distilled water was used and considering that, for low clay fraction soils mixed with distilled water, such as the one under study, the osmotic suction may be expected to be negligible for w <0.1 (Sreedep & Singh, 2006), the suction measured by means of filter paper is likely to be the matric one. In Figure 4 for each filter paper measurement the suction values accounting for different calibration curves (Chandler et al. 1986; 1992; Leong et al. 2002) have been plotted.

The data denoted as "*PW-FP-e.v.*" correspond to the initial state of the soil if suction is measured by means of filter paper and corresponds to far higher suctions than that assessed by means of the tensiometers. The data denoted as "*MD-FP-e.v.*", instead, were logged at the end of the main drying test; each being the average of the top and bottom filter paper measurements. The high suctions being measured are consistent with those reported by Salager et al. (2010) for a soil of similar composition and state as the tested one. The van Genuchten curve resulting from the fitting of the tensiometer measurements, up to $s = 60$ kPa, and the filter paper measurements, for 60 kPa $< s <$ 10000 kPa, is denoted as *MD-WRC-e.v.*2 in Figure 4. It is characterized by a much higher correlation than that fitting solely the tensiometer data, *MD-WRC-e.v.*1. Therefore, if the van-Genuchten law applies to the soil, the filter paper technique is more appropriate to assess the medium-grained soil retention properties at suctions higher than 60 kPa.

As shown in Figure 4, the retention function resulting from an inverse analysis that accounts for the suction in the initial state measured by means of the filter paper technique, that is the *PW-WRC-i.a.*2 curve, results in an air entry value upon wetting (relating to α_w) that is far more consistent with that resulting from the element tests. It may be concluded that the hydraulic characterization of the self-weight compacted medium-grained soil under study can be achieved using the van-Genuchten model to regress soil state measurements acquired using different suction measurement techniques in the low and high suction ranges, that correspond to suction values below and above 60 kPa respectively for the type of tensiometer used in the present study.

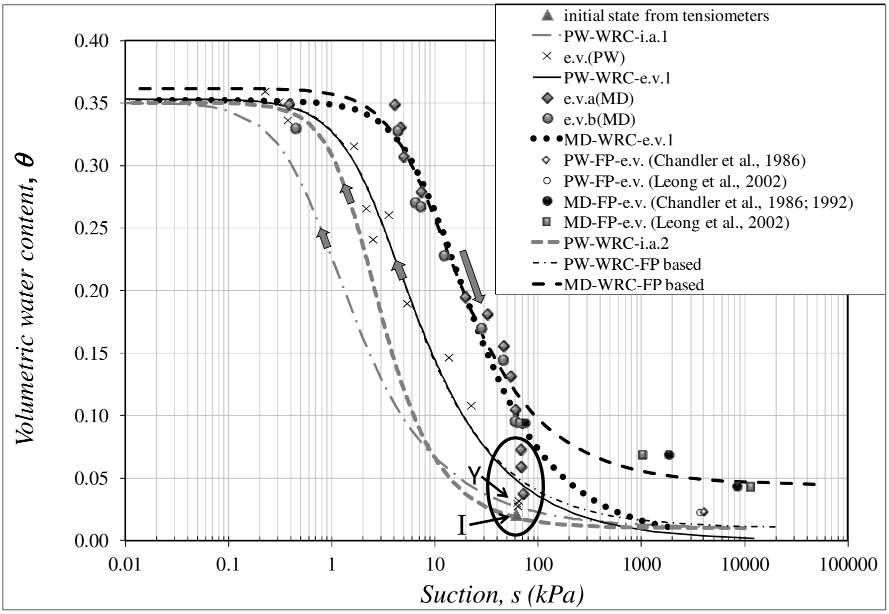

Fig. 4. Experimental data and water retention functions.

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