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Investigating some irregularities observed during suction measurements using the Hyprop device

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ABSTRACT: The Hyprop is a laboratory device designed to measure the water retention and the hydraulic conductivity characteristics of soils during drying. Various reported Hyprop measurements show irregularities at relatively low suction values. In this study, two series of tests were performed to identify and explain these irregularities. Test results on clean sand showed rapid fluctuations in the measured suction shortly after reaching the air entry value, which are interpreted as Haines jumps. Test results on clayey soils also showed a drop and rise in suction at consistencies ranging between plastic and liquid limit. The change in suction for the clayey soils was much slower and larger than for the clean sand. In some cases the drop in suction initiated when the clayey soils detached from the ring or when cracks occurred in the sample. Consequently, these suction drops are attributed to a combination of unloading and shrinkage. For clayey soils with initial water contents above liquid limit, a correction procedure is suggested to account for the initial negative measured suctions and the loss in hydraulic head. The observations affect the interpretation of Hyprop results at low suction values, particularly regarding the hydraulic conductivity.

1 INTRODUCTION

The Hyprop is a relatively new device used for determining the water retention and hydraulic conductivity characteristics of soils. The system is based on the evaporation method, first introduced by Wind (1966) and later modified by Schindler (1980).

The system consists of a sensor unit with two tensiometers of different lengths and a small temperature probe. The soil sample is placed in a stainless steel ring measuring 80 mm in diameter and 50 mm in height, which is rested on top of the sensor unit. The sample is allowed to evaporate, while suction in both tensiometers, as well as the temperature and weight loss, are continuously measured. From the initial or final water content, the measured weight loss and the specific gravity of the solid fraction, the volumetric water content is calculated and plotted against the mean suction value to obtain the drying branch of the Soil Water Retention Curve (SWRC).

The difference in measured suction values and the difference in height of the tensiometers are used to calculate the hydraulic gradient. Consequently, assuming a linear suction gradient between the two tensiometers, the hydraulic conductivity can be calculated from the measured flow rate (i.e. the rate of weight loss) and the hydraulic gradient according to Darcy's law. Hence, the hydraulic conductivity curve (HCC), which relates the hydraulic conductiv-

ity as a function of matric suction, can be obtained. Schindler & Müller (2006) or Schindler et al. (2010) describe the method in detail.

Various experimental investigations have been reported in which the Hyprop method has been used to determine the SWRC and HCC, including Schindler et al. (2010), Campbell et al. (2012), Maček et al. (2013), Schelle et al. (2013), Dolinar (2015), Eibisch et al. (2015) and Schindler et al. (2015). Typically, the reported suction ranges from 0.1 to 100 kPa. However, much of the reported data in the literature show irregularities in the obtained water retention curve, particularly at relatively low suction values. As these irregularities did not show up in all experiments, they were typically ignored. During an extensive study on the desiccation behavior of clays, Tollenaar (2017) also observed these irregularities and provided some theories regarding their origin. In this paper, some of the results of Tollenaar (2017) are presented together with additional tests on clean sand. Irregularities are identified by using a relatively short time measurement interval to record suction and some theories explaining the observed irregularities and their impact on the interpretation of the Hyprop results are discussed.

2 MATERIALS AND METHODS

2.1 Soil types and index properties

Two soil types were used for this study. Tollenaar (2017) used a commercially available pottery clay (K-10000, Ve-Ka Industrie Keramische Grondstoffen), which according to the USCS is classified as a high plasticity clay. Secondly, tests were performed on a poorly graded clean sand. Index properties of the soils are presented in Table 1 and 2.

Table 1. Summary of measured index properties of the sand.

Index Property	
<i>Grain Size Distribution</i>	
Sand Content (%)	100
D ₅₀ (mm)	0.2
Cu	3.1
Cc	1.1
Unified Soil Classification System (USCS)	Poorly Graded Clean Sand (SP)

Table 2. Summary of measured index properties of the clay.

Index Property	
<i>Specific Gravity</i>	2.74
<i>Grain Size Distribution</i>	
Sand Content (> 63 μm , %)	3
Silt Content ($\leq 63 \mu\text{m}$, %)	55
Clay Content ($\leq 2 \mu\text{m}$, %)	42
<i>Atterberg Limits</i>	
Plastic Limit (%)	24
Liquid Limit (%)	57
Plasticity Index (%)	18
Shrinkage Limit (%)	12
Unified Soil Classification System (USCS)	High Plasticity Clay (CH)

2.2 Test procedures

The sensor unit and tensiometer shafts were filled with de-aired water, using a vacuum pump and re-filling unit (Meter Group AG). The tensiometer shafts were carefully placed on the sensor unit to avoid air entrapment. In case when only the short tensiometer was pressure sensor of the long tensiometer was covered using adhesive tape.

The test on sand was performed at 20 °C ($\pm 2^\circ\text{C}$). The relative humidity was not measured. After saturating the tensiometers with de-aired water, the steel ring was placed on the sensor unit and then it was filled with dry sand. Next, tap water was slowly poured over the sand allowing it to percolate through the material until a thin film of water appeared on top of the sample. Immediately afterwards the test was started and the water in the sample was allowed to evaporate, while the weight and suction in both tensiometers was recorded every minute. At three occasions during the test water was added slowly to the sample to evaluate whether the observed irregularities were reproducible during several wetting and drying cycles. At the end of the ex-

periment the sample was taken out and dried in an oven for 24 hours at 105°C to determine the final moisture content.

The complete test procedures for the tests on the clayey soils are reported by Tollenaar (2017). Based on preliminary tests (see results section) it was decided to use only the short tensiometer for suction measurements in these tests. In one of these preliminary tests the sensor unit was disconnected from the computer and placed inside a Micro-CT Scanner (General Electric, Phoenix, Nanotom S) at regular time intervals. In this test the steel ring was replaced by a PVC ring of similar size, in order to allow the X-rays to penetrate through the ring and soil sample. The CT-scan results were processed using VGStudioMax (Volumegraphics, 2013) and Avizo (FEI, 2013) software.

Clay was provided as blocks with an initial moisture content of about 34%. Using tap water the moisture content of these blocks was increased, to obtain clayey soil samples with five different initial water contents: two samples had a moisture content below and three above liquid limit. One test was also performed using only water (Table 3). The tests were carried out in a climate controlled room with a relative humidity of 34% ($\pm 6\%$) and a temperature of 24 °C ($\pm 1^\circ\text{C}$).

Table 3. Initial values for test on clay: gravimetric water content, w_0 (m_w/m_s), volumetric water content, θ_0 (V_w/V_s) and liquidity index, LI_0 ($((w_0 - w_{LL})/PI)$).

Sample	w_0 (%)	θ_0	LI_0
A	34	0.93	0.3
B	51	1.4	0.82
C	71	1.94	1.42
D	113	3.1	2.7
E	138	3.77	3.45
F	Water		

For test A, the standard sampling procedure was used as described in the manual (UMS, 2015) by pushing the steel ring directly into the clay block. For test B, the metal ring was filled with clay paste using a spatula, while trying to avoid the inclusion of air pockets. In both test A and B, the top and bottom were trimmed, and the holes for the tensiometers were drilled using the small hand auger according to the procedure described in the manual (UMS, 2015). For the tests with water content above the liquid limit slurries were prepared by mixing the clay with water using a Hobart A200N mixer at 200 rpm for 45 minutes, after which the resultant slurry was placed in a sealed plastic container for at least 24 hours to further homogenize. The metal ring was first placed on the prepared sensor unit. Then the clay slurries were poured in the metal ring, after which the measurement was started. At the end of each test, the soil sample and the ring were placed in

an oven for 24 hr at 105°C to determine the final water content.

3 RESULTS

3.1 Tests on sand

The measured water mass and suction for both the long (black) and short (grey) tensiometer and the constructed SWRC are presented in figure 1. The sharp increases in water mass clearly indicate the three moments at which water was added to the sample. Each time water was added, the suction level dropped rapidly. The lowest value of suction obtained after each addition of water depended on the amount of water added (figure 1b). Figure 2 provides a close up of the measured suctions, showing the first two days of measurements.

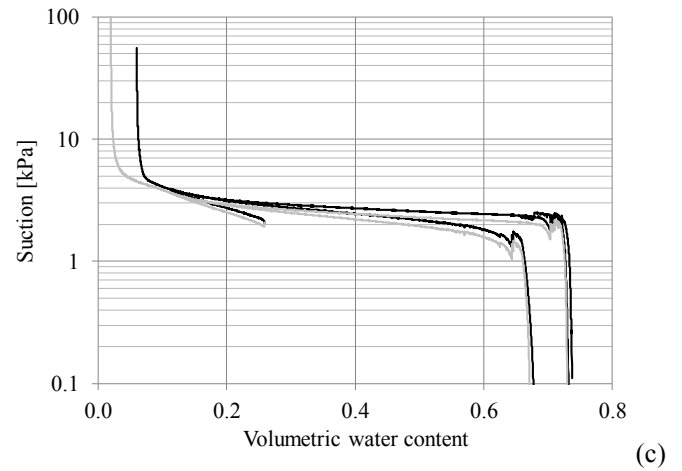
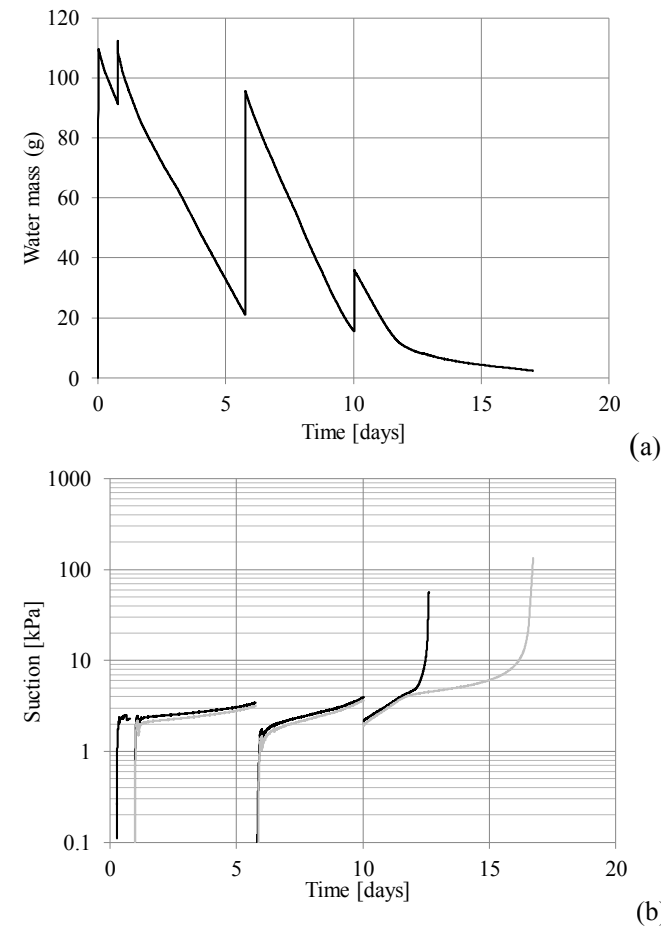


Figure 1. Measured water mass (a) and suction (b) and constructed SWRC (c) for the test on sand

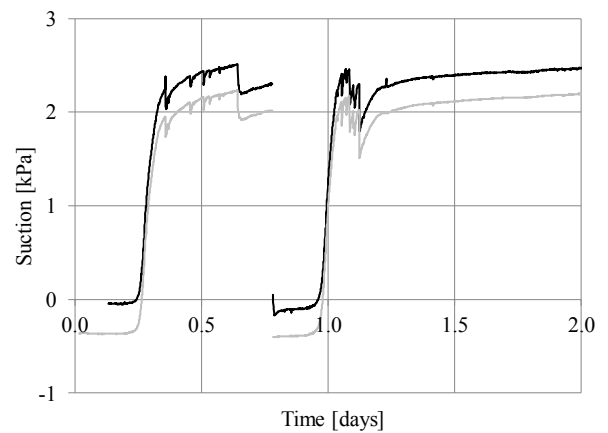


Figure 2. Detail of figure 1b showing the first two days of suction measurements for the test on sand.

Suction initially exhibited negative values, indicating a positive hydrostatic water pressure (displayed as a “negative suction”) above the level of the tensiometer tip. Once sufficient water evaporated, suction levels rapidly increased up to the air entry value of the soil (approximately 2 kPa). Next the rate of increase in suction reduced almost to zero until the water content approached the residual saturation at which the suction started to rise rapidly again. The SWRC is as expected for a poorly graded clean sand (Buckingham, 1907; Black & Croney, 1957, Van Genuchten, 1980). When water was added to the sample suction was rapidly lost, after which it increased gradually back again when it was allowed to evaporate once more.

Close to the air entry value, the measured suction showed irregularities for the first and second drying cycle as displayed in Figure 2. Rapid drops of 0.2 to 0.5 kPa in suction were observed followed by a gradual rise. These irregularities can be expected by regarding the air entry in the soil as a discontinuous process. The air migrates into the pore space through many rapid displacement events, often referred to as Haines jumps (Haines, 1930, Armstrong et al., 2015) In order to move from one pore to another, air needs to squeeze through a pore throat. As a result

the capillary pressure, which is inversely related to the radius of the gas water interface, gradually increases while the gas is drawn into the pore throat. Once the interface passes the narrowest point in the pore throat the gas rapidly floods the next pore, leading to a capillary pressure loss as the radius of the interface increases. Using the bulk modulus of the fluid phase, the drop in capillary pressure can be related to the change in volume by a single gas intrusion. Considering it is a clean sand and that most of the irregularities occur early in the drying process. The Haines jumps may be related to the rapid air entry along the boundaries between the steel ring or sensor unit and the sand. At these smooth interfaces the pore sizes are slightly higher than in the bulk soil, which may result in preferential sidewall flow of the gas phase (e.g. Corwin, 2000).

Besides these irregularities, two other observations may affect the interpretation of the results as suggested by Schindler et al. (2010). Firstly, the difference in suction between the two tensiometers was constant and remained approximately constant during the major part of the experiment (approximately 0.28 kPa). Only after 12 days the pressure difference between the two tensiometers started to increase as the suction in the long tensiometer rapidly ramped up until it cavitated, while the short tensiometer continued to rise gradually. It only reached cavitation five days later at a significantly lower water content. These observations seem to indicate that for most of the drying process, the suction difference between the tensiometers was mainly a function of the pressure offset at the start of the experiment. Hence, for the major part of the experiment the data cannot be used to determine the hydraulic conductivity, either because the suction gradient does not change, or because one of the tensiometers has already cavitated.

3.2 Tests on clayey soils

Preliminary results on the clayey soils showed significant bending of the long tensiometer shaft due to lateral shrinkage of the soil. Also it was found that during the major part of the drying process the hydraulic gradient between the two tensiometers remained constant (close to the hydrostatic gradient) due to the relatively low evaporation rate. In addition, it was found that volumetric water content did not show a linear gradient with depth (Tollenaar et al., 2017a). Hence, the assumption of a linear suction gradient in the vertical direction did not seem to be valid for soils displaying significant amount of shrinkage. Through micro-CT scanning he showed that during the drying process cracks were propagating through the sample, and even touching the ceramic tip of the tensiometer while suction was still being measured (Figure 3). The grey shading in the image is related to the material density. It ranges from black (e.g. air, 1 kg/m³), through different

tones of grey (e.g. water, 1000 kg/m³; soil 1200-1500 kg/m³), to white (porous aluminum oxide tip, ≈ 2500 kg/m³). As the soil could not be considered a continuous phase, the assumption of a linear suction gradient also seemed to be invalid.

During the Hyprop tests on clayey soils several observations affected the interpretation of the test results: 1) At the start of the experiments, suctions were negative. Particularly for clayey samples with an initial moisture content above liquid limit, the period of negative suction could last for several days; 2) During the initial stage of evaporation, the volume changes are mainly vertical. Hence the volumetric shrinkage is approximately equal to the change in height times the surface area; 3) During the initial part of the drying process, particularly for the samples with high liquidity index, the water loss was approximately equal to volumetric shrinkage hence the sample was considered to remain close to full saturation during the initial phase of drying.

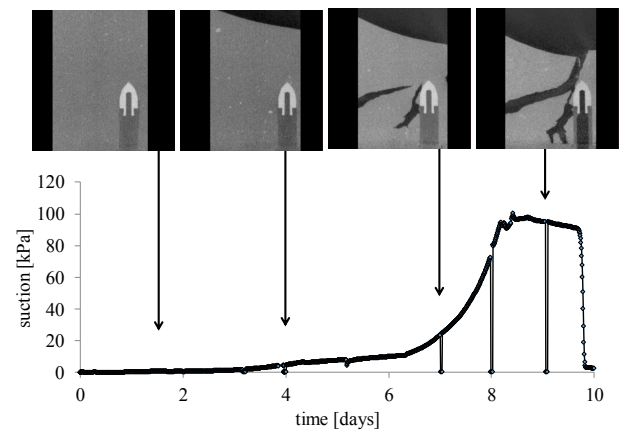


Figure 3. Typical results of micro X-ray computed tomography scanning showing shrinkage and crack propagation in a clayey soil with an initial gravimetric water content of 95% at different stages during a Hyprop test (after Tollenaar, 2017).

At low suction values the measurements showed significant variability. Several processes were considered affecting the suction measurement, including: the hydrostatic pressure in the soil; positive or negative excess pore pressures due to self-weight consolidation, which can occur for very wet soils shortly after filling the ring or installation effects; or an offset in the sensor calibration. One Hyprop test was performed in which the ring was filled with water only. The results are shown in Figure 4. As water does not show excess pressure through self-weight consolidation nor suction, it was expected that suction measurements showed negative values corresponding with the hydrostatic head in the ring as long as the tip was fully submerged under water. At a constant evaporation rate, the increase in the measured suction values should be linear corresponding with the loss in hydrostatic head. Suction should start to develop when the tip of the tensiome-

ter emerges above the water level and when the ceramic tip loses contact with the water level the tensiometer cavitates rapidly when the ceramic tip completely loses contact with the water in the ring. Based on these measurements it was suggested to shift the curve upward, in order to correct for the initial hydrostatic head, so it starts at zero suction. To correct for the change in hydraulic head the head loss was calculated and subtracted from the shifted suction values. As a result of these corrections the suction values (“excess pore pressure”) were equal to zero as long as the tensiometer was submerged below the water level.

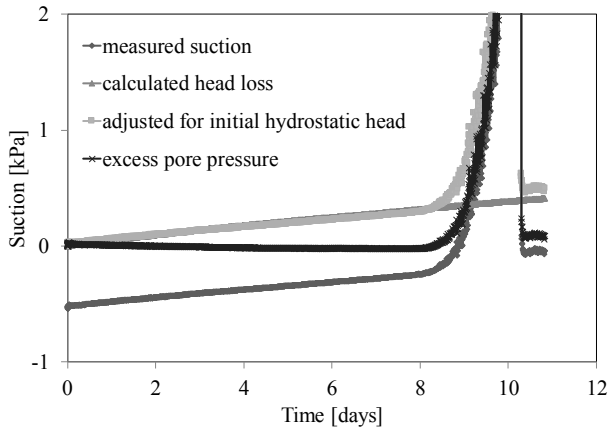


Figure 4. Measured suction, calculated head loss and shifted and corrected suction values for test F using water only (after Tollenaar, 2017)

For slurries it was considered that actual suction or excess pore pressure started to develop as soon as the slope of the measured suction curve started to deviate from the slope of the calculated head loss. To account for this, it is suggested to correct the measured suction values for clayey soils. Similar as shown in Figure 4, the correction involves subtracting the calculated hydrostatic head loss from the measured suction, identifying the value at which the slope of the resulting curve is equal to zero and applying this value as an offset correction. Applying this correction causes the SWRC to shift for samples with an initial moisture content above the liquid limit (C, D and E) and for suction values below 10 kPa as indicated by the arrows in Figure 5c.

For the relatively dry clays A, B and C the measured suction showed a significant drop when reaching a suction between 2 and 4 kPa, similar to the test on sand (Figure 6). In contrast to the test on sand, the suction continued to decrease for several hours before it started to rise again. Similar pressure drops can also be observed in other studies using the Hyprop (Durner et al., 2011; Campbell et al., 2012; Maček et al., 2013; Peters, 2013; Şahin, 2013; Schelle et al., 2013; Dolinar, 2015). However, in these cases these phenomena were not mentioned, nor explained. In some cases the decrease in suction initiated when the soil detached from the ring and

started to shrink laterally. In some other cases the detachment from the ring did not correspond with the start of suction decrease. It is assumed that detachment from other non-visible parts of the equipment, or crack formation through the sample can cause similar pressure drops. Considering that during detachment or crack formation the clay undergoes tensile failure, an increase followed by a decrease in suction can be expected similar to the increase and decrease in stress observed during tensile strength tests such as reported by Tollenaar et al. (2017b). Further investigations are required to fully predict the actual suction development during shrinkage and crack formation and propagation in desiccating clayey soils, e.g. as observed by Tollenaar et al. (2017c)

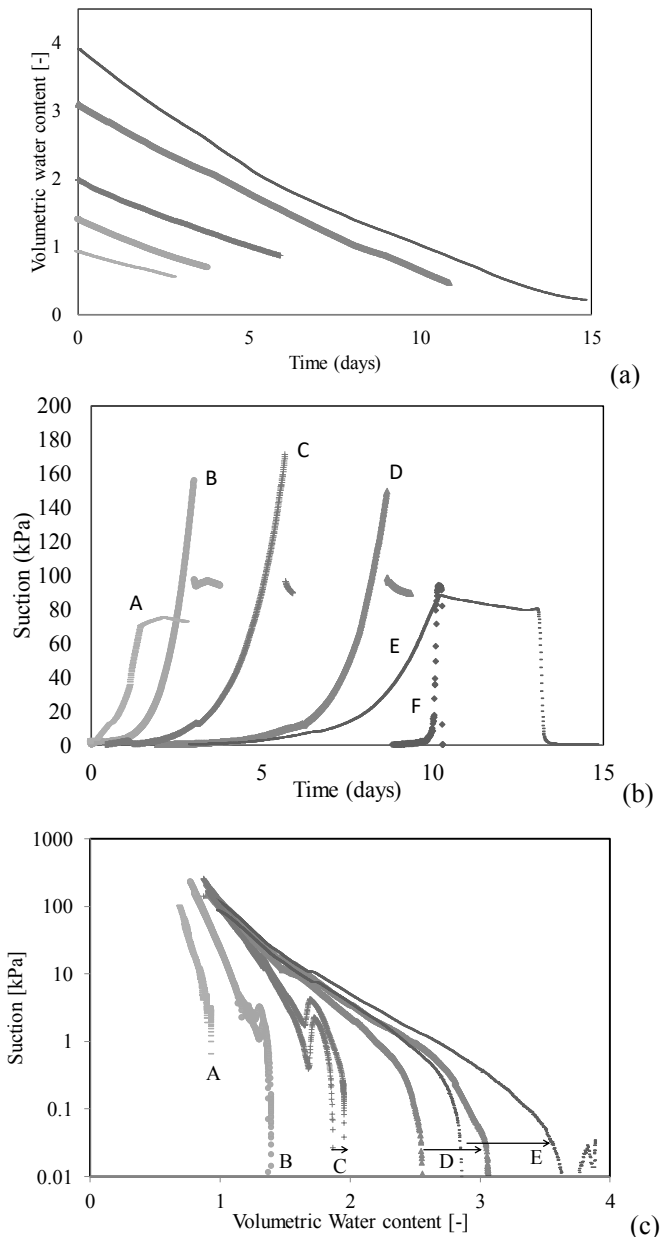


Figure 5 Calculated volumetric water content (a), measured suction (b) and constructed SWRC using measured or corrected suction values (c) from Hyprop tests for clayey soils with different moisture contents (after Tollenaar, 2017).

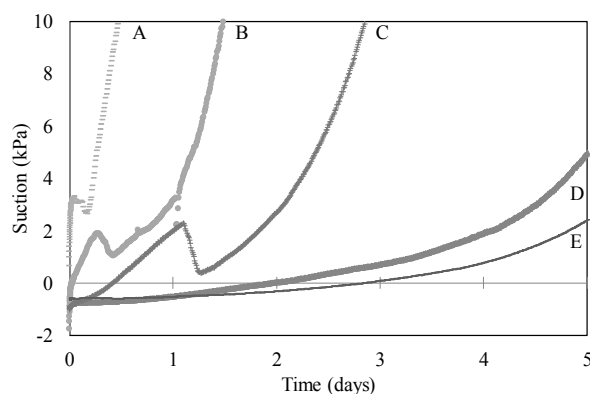


Figure 6 Detail of suction measurements for clayey soils (after Tollenaar, 2017).

4 CONCLUSIONS

The observations presented in this paper show that irregularities in the suction measurements may significantly affect the interpretation of Hyprop tests at relatively low suction values. Rapid drops in suction followed by a more gradual rise may occur during drying of clean sands, which can be interpreted as irregular air entry events, also referred to as Haines jumps. Clayey soils also show fluctuations at relatively low suction values. However, these fluctuations are more gradual and can be related to detachment of the clay from the ring or other parts of the equipment, or to crack formation, which is accompanied by stress release and shrinkage. A correction is suggested for clays with moisture contents above liquid limit to accommodate for the negative suction measurements during the initial drying period and the loss in hydraulic head. The observations also indicate that the use of this test for the determination of the hydraulic conductivity is limited.

5 ACKNOWLEDGEMENTS

This research had the financial support of the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO) and of the Ministry of Economic Affairs through the perspective program BioGeoCivil (grant 11344). It was also partly funded through the CEAMaS project, funded by the European Regional Development Funding INTERREG IV B and Industry-Academia Partnerships and Pathways (IAPP) project, MAGIC, funded from the 7th Framework Programme (FP7-PEOPLE-2012-IAPP) of the EC under grant agreement PIAPP-GA-2012-324426.

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