Extension of measurement range of dew-point potentiometer and evaporation method

Extension de gamme de mesure de potentiomètre de point de rosée et méthode d'évaporation

Maček M., Smolar J., Petkovšek A.
University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia

ABSTRACT: There are numerous methods for measuring soil water retention curve (SWRC). With tensiometer device it is possible to measure suction up to 85 kPa, but above this point measurements are not possible due to cavitation of water. To measure higher suctions other methods should be used. One of very popular devices is dew-point potentiometer WP4-T (Decagon Devices), which enables suction measurements above 1000 kPa. If high capacity tensiometers from HYPROP evaporation method device and dew-point potentiometer are used for suction measurements, the measurements are only possible for low suction range between 0 and approximately 100 kPa and for high suction range between 1000 and 300000 kPa. Between 100 and 1000 kPa suction could be measured by other methods or some extension of these two methods should be used. This paper presents SWRC measurements with HYPROP and WP4-T devices for different soils, the extension of suction range for both devices and comparison between measured suctions in the extended measurement range.

RÉSUMÉ : Il y a de nombreuses méthodes pour mesurer la courbe de rétention d'eau de sol (SWRC). Il est possible de mesurer la succion jusqu'à 85 kPa avec le dispositif de tensiomètre, mais au-dessus de ce point les mesures ne sont pas possibles en raison de cavitation d'eau. Pour mesurer des succions plus élevées d'autres méthodes devraient être utilisées et l'un des dispositifs très connus est le potentiomètre de point de rosée WP4-T (les appareils Décagone), qui permet des mesures de succion au-dessus de 1000 kPa. Si des tensiomètres haute capacité de l'instrument HYPROP, la méthode d'évaporation et le potentiomètre de point de rosée sont utilisés pour des mesures de succion, les mesures sont seulement possibles pour la gamme de succion basse entre 0 et environ 100 kPa et pour la gamme de succion élevée entre 1000-300000 kPa. Entre 100 et 1000 kPa la succion pourrait être mesurée par d'autres méthodes ou une certaine extension de ces deux méthodes devrait être utilisée. Cet article présente des mesures SWRC avec des dispositifs HYPROP et WP4-T pour des sols différents, l'extension d'une gamme de succion pour les deux dispositifs et la comparaison entre des succions mesurées dans la gamme de mesure prolongée.

KEYWORDS: soil suction, dew-point potentiometer, evaporation method, soil water retention curve.

1 INTRODUCTION

Soil suction and the soil water retention curve (SWRC) influence many engineering properties of unsaturated soils and their behaviour. Therefore, accurate measurements of soil suction are important for modelling soil behaviour (Fredlund and Rahardjo, 1993). Due to large differences in soils and their SWRC different measuring techniques were developed and each of them has its own limitations. A good review of measuring techniques can be found in Tarantino et al. (2008).

Tensiometer was developed by Richards (1928) and it measures matrix suction between 0 and 85 kPa. Suction measurements above 85 kPa are not possible due to cavitation of water inside the tensiometer. Special high capacity tensiometer, which enables suction measurements up to 1500 kPa, was developed by Ridley (1993). This is done by using deaired deionised water, small water volume behind porous cap, smooth surfaces, as well as special materials and preconditioning techniques.

In HYPROP evaporation method device (UMS) a continious SWRC is obtained by simultaneously and continuously measuring suction with two high capacity tensiometers installed at different heights of the soil sample and weight change during drying. A typical work range of HYPROP device is from 0 to slightly above 100 kPa.

For soil suction measurements between 1000 and 300000 kPa a potentiometer WP4-T (Decagon Devices) could be used (Operator's manual, 2005). A dew-point potentiometer measures relative humidity of air above soil sample and soil suction is calculated trough Kelvin equation. This measurement technique is an indirect measurement of total suction.

In the range of 100 and 1000 kPa the soil suction could be measured using other methods or some extension of these two methods should be performed. Using the potentiometer WP4-T the accuracy of the measuring method can be increased, if average of data are used instead of a single point measurement. With this approach total suction as low as 300 kPa can also be measured. In case of HYPROP device the suction range can not be extended, but single value of suction could be estimated from air entry value (AEV) of tensiometers porous ceramic caps.

In this paper the HYPROP device and potentiometer WP4-T were used for soil suction measurements and an attempt was made to connect the results within the grey zone, where the limitations of both methods exist.

2 SOIL WATER RETENTION CURVE

Soil water retention curve (SWRC) is defined as relationship between the water content and the soil suction and it can be divided in 3 characteristic zones (Bardner, 1965) (Figure 1):

1. *Capillary saturation zone* where soil is fully saturated. Changes in water contents result in volume deformations without any decrease in the degree of saturation.
2. *Desaturation zone*: When the matrix suction exceeds the air entry value (AEV) of the tested soil, the degree of saturation decreases rapidly. Hysteresis between wetting and drying curve is typical for the desaturation zone.
3. *Zone of residual saturation*: in this zone water content can be changed only by vapour transport (Bishop, 1960). The beginning of this zone is residual suction (s_r), which is

defined as a cross-section of two logarithmic lines as shown in Figure 1 (Fredlund and Xing, 1994).

Shape of SWRC is defined by suction at AEV and at residual suction and is typical for type and density state of the soil. Zapata et al. (2000) showed among others the influence of soil index properties on the shape of SWRC. Kawai et al. (2000) showed the importance of void ratio and Vanapalli et al. (1999) showed the influence of soil structure on SWRC. If good and representable SWRC is to be measured, all these things should be considered.

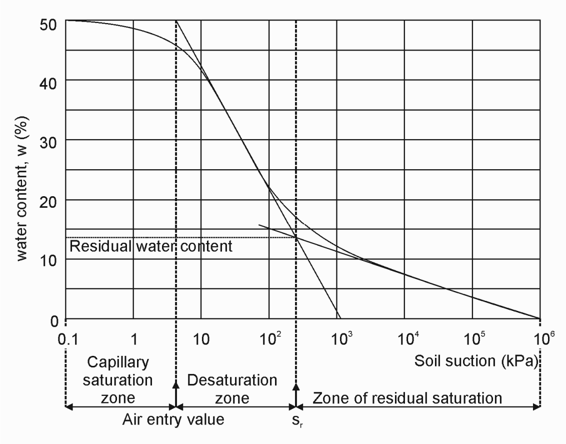

Figure 1. Soil-water retention curve with zones of desaturation (Sillers et al., 2001).

3 SOIL SUCTION MEASUREMENTS

3.1 *HYPROP evaporation method device*

The evaporation method is frequently used method for measuring both the SWRC and the suction permeability curve. The method is based on the measurements of suction using tensiometers installed at different heights inside the soil specimen simultaneously with measuring the specimen weight changes due to the evaporation of water from the specimen. Due to large number of measurements a continuous SWRC is obtained. After the simplified evaporation method (Schindler, 1980) only the average weight and suctions at two points are measured. Due to short time interval the spatial and temporal nonlinearity are negligible. Therefore, two assumptions can be made:

- there exist quasi steady state conditions, which means that flux and hydraulic gradient are constant over the time interval, and
- the linear decreasing of water content and linear decreasing soil suction. This means that soil suction in the middle of the specimen is an average suction measured by tensiometer and that water content in the middle of the specimen is the same as the average water content.

Schindler and Müller (2006) had shown that these two assumptions are valid only if the evaporation rate is constant. If the evaporation rate is decreasing, the suction profile is not linear. Peters and Durner (2008) studied the error made by these two assumptions in the final clearly non linear zone and showed that errors made by linear approximation are negligible.

3.1.1 *HYPROP device preparation*

High capacity tensiometers for the HYPROP device are saturated and preconditioned by cycles of deairing at vacuum (app. 92 kPa) and by the applying normal atmospheric pressure. As the deionised water is used, due to the small water volume and the special preconditioning, suction over 400 kPa can be measured with HYPROP device (Schindler et al., 2010). At the tests described in this paper only suctions up to 150-200 kPa could be reached by same preconditioning.

3.1.2 *Sample preparation*

A sampling steel cylinder of known weight and volume was pushed into the undisturbed or in the laboratory prepared, compacted sample. The overlapping soil along the ring's rim was cut by a sharp knife. Special care should be taken not to smear the pores at the surfaces, as this would increase AEV of the top soil surface. The HYPROP device uses sampling ring with a height of 5 cm and a diameter of 8 cm (Figure 2).

The specimen in the ring is then saturated by immersing it in water. Volume changes are prevented by porous stones on both ends and with the weight of 10 kPa applied on top of the specimen. Better saturation can be achieved when the specimen is saturated under vacuum.

3.1.3 *Measurement*

Into a saturated soil specimen two boreholes are drilled and in these two boreholes the tensiometers from HYPROP device are installed. The saturated specimen with the HYPROP device is put on a balance and the measurements start. The suction on both tensiometers and the weight change of the specimen are recorded simultaneously every 10 minutes. In the first stage when the water tension in tensiometers is increasing, the readings are in good correlation with the soil suction at the location of the tensiometer. In the second stage the cavitation inside the tensiometer appears and the tensiometer readings are more or less constant. Due to upward tensiometer direction only a small amount of water is drowned into the soil specimen. In the 2nd stage the soil suction is higher than the water tension measurements. When the suction in the soil increases over the AEV of the porous cap, air comes into the tensiometer and the water tension inside the tensiometer collapses. When suction in both tensiometers collapses, measurements are finished and the water content and the dry density of the specimen are measured using the standard procedures. The duration of the whole test is between 1 and 2 weeks.

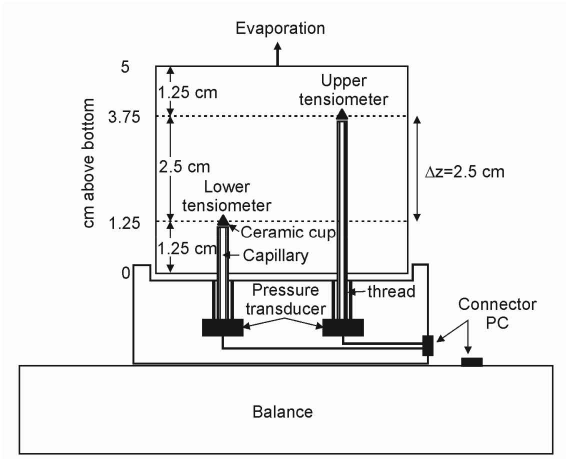

Figure 2. Schematic cross section trough HYPROP evaporation method device (Schindler et al., 2010).

3.1.4 *The extension of measurements*

The basic idea for extending the measurement range is to use the ceramic cap AEV (Schindler et al., 2010). At this point the air comes to tensiometer and the water tension rapidly collapses to 0 kPa. The soil suction should be the same as AEV of the tensiometer's ceramic cap. If this assumption is valid, an interpolation by high order polynomial functions of suction between stage 1 and this point can be performed (Figure 3).

By applying this procedure to both tensiometers the measured data can be extended to higher suctions (up to 800 kPa).

Unlike Schindler et al. (2010) only the average suction of both tensiometers at the point of tension collapse of the top tensiometer is used (Figure 3) and not the whole interpolation function.

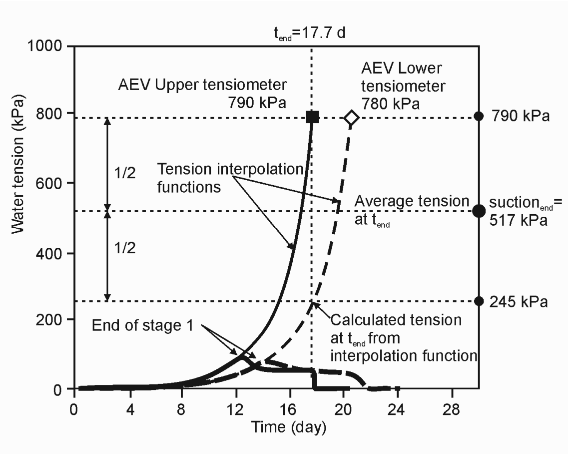

Figure 3. Principle of extending the soil suction range using the AEV of the tensiometer's ceramic porous cap (Schindler et al., 2010).

3.2 *Dew point potentiometer WP4-T*

Vapour pressure methods are ideal for measuring suctions at the dry end of SWRC. The suction is measured when the equilibration of vapour pressure above the soil specimen is achieved. If vapour pressure is measured, the suction can be calculated using the Kelvin equation:

$$\psi = \frac{\rho_w RT}{M_w} \ln\left(p / p_0\right) \qquad (1)$$

where ψ is total suction, R is gas constant (8.314 J/mol), T is temperature (K), M_w is molar mass of water (18 g/mol), ρ_w is water density, p is vapour pressure and p_0 is saturated vapour pressure, p/p_0 is relative humidity.

Potentiometer WP4-T measures vapour pressure through the dew point temperature. This is done by cooling a mirror the reflectance of which is changed when dew appears. From the measured mirror temperature vapour pressure above the sample can be calculated and from the measured air temperature above the sample saturated vapour pressure can be calculated.

Detailed description of the dew point device can be found elsewhere (Leong et al.,2003, Campbell et al., 2007).

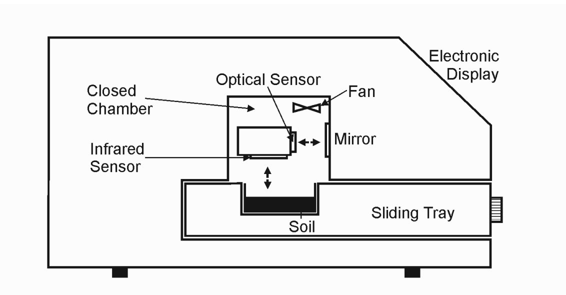

Figure 4. Schematic cross section through dew-point potentiometer WP4-T (Bulut et al., 2002).

3.2.1 *Specimen preparation*

When measuring suction with vapour pressure methods, dry density and structure have little effect on the suction value (Campbell and Gardner, 1971, Thakur et al., 2006, Birle et al., 2008). Therefore, only disturbed specimens were used. All samples were air dried in and then sieved through a 2 mm sieve. A known amount of water was added to the 5-10 g of soil; soil-water mixture was homogenously mixed and then it was compacted in stainless steel cup forming a single specimen. Prepared specimen was sealed and then rested for 24 hour or more to ensure that the water content and the suction equilibrate.

To measure the whole SWRC, specimens with water contents from the air dried soil to the soil in soft consistency were prepared. The procedure is similar to that described by Campbell et al. (2007).

3.2.2 *Measurement*

Before the regular measurements started, potentiometer WP4-T had been calibrated each day by using standard solution of 0.5 M KCl. In case a deviation from the suction of 2.22 MPa for more than 100 kPa was recorded, the device was cleaned and recalibrated. In case of smaller deviations, a deviation was used to correct readings at low suctions.

All measurements were done in continuous mode for about half an hour or longer and the measurements were recorded via Hyperterminal program. When the vapour equilibration was observed, an average of measurements after equilibration was calculated.

The vapour equilibration is more important at low suctions (<1 MPa), as it can be seen from the diagrams in Figures 5 and 6.

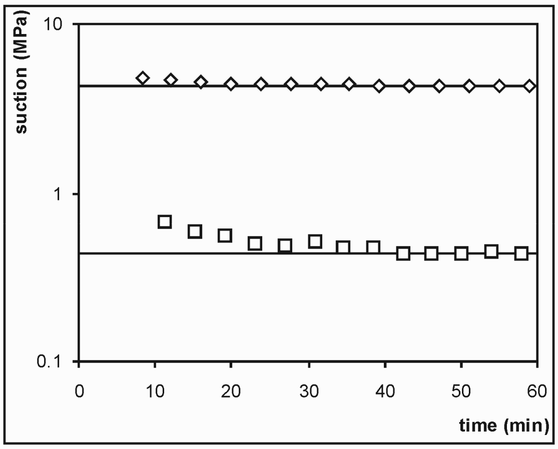

Figure 5. Suction measurements with potentiometer WP4-T in continuous mode. Black horizontal lines are average suction of the last measurements.

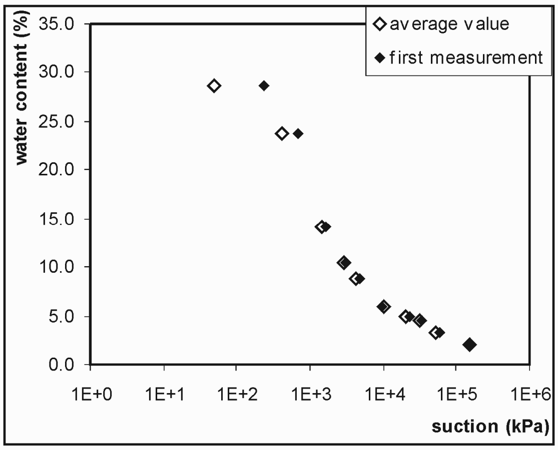

Figure 6. Comparison between SWRC obtained with potentiometer WP4-T from the first measurements and the average value after equilibrium.

The resolution of the measurements is 100 kPa and this should be acknowledged, but with this measurement technique the error due to vapour equilibration is eliminated. With this technique good measurements can be performed at as low as 300 kPa, which is significantly lower than 1000 kPa as reported by Thakur et al. (2006), Campbell et al. (2007) and Agus and Schanz (2007).

4 EXPERIMENTAL RESULTS

SWRC was measured with both methods on 29 soil samples. Three samples belonged to the group of clean sands with less than 5% fines (0.063 <mm), marked by SP-SW symbol, six samples contained 5-12% fines (SP-SM), seven samples were silty sands (SM), eight of them were clays (CH or CL) and five samples were mixed soils with fines content between 40 and 70% (SC/CH). The last mentioned samples were undisturbed, all other were artificially prepared in the laboratory.

Results of some grain size distributions are presented in Figure 7 and the SWRC measurements of these samples are presented in Figure 8. Initial conditions in HYPROP device of specimens shown in Figure 8 are presented in Table 1.

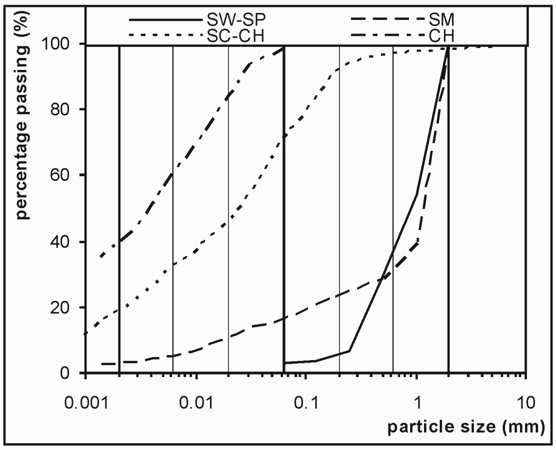

Fig 7. Grain size distributions of samples with the SWRC, presented on Figure 8.

Table 1. Initial conditions in HYPROP device of specimens shown in Figures 7 and 8.

classification	w (%)	ρ_d (t/m^3)	e	Sr (%)
SW-SP	15.5	1.80	0.528	81
SM	15.3	1.91	0.440	96
SC-CH	30.6	1.47	0.876	96
CH	91.0	0.740	2.80	92

At some samples double porosity was observed when measurements with both methods were put together (Figure 9). The first desorption could be correlated to soil structure or capillary drying and the second is due to drying of fine particles. This behaviour could be natural behaviour or it is inherent due to laboratory compaction.

5 RESULTS AND DISCUSION

From Figure 8 it can be observed that both measurements correlate well. It can be also observed that HYPROP device measurements are sufficient only for sands with relatively small amount of silty fines (< 20%). In case of mixed soils, where the behaviour is defined by fines or in case of silts and clays HYPROP device measurements are not sufficient and in this case potentiometer WP4-T should be used as well.

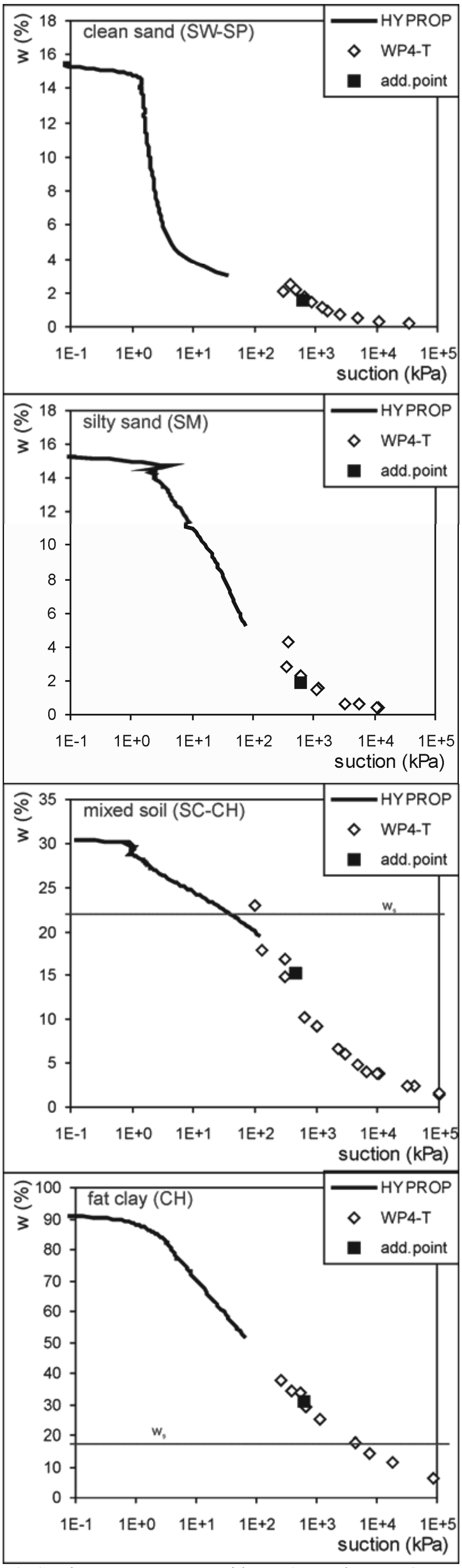

Figure 8. Suction measurements with WP4-T and HYPROP on clean sand, silty sand, mixed soil and fat clay (from the top to the bottom). Add. point – addition point obtained from AEV of ceramic caps.

Due to large volume deformations of such soils the measurement of shrinkage limit is advisable. Shrinkage limit w_s is marked by horizontal line in Figure 8.

From potentiometer WP4-T measurements nothing is known about the behaviour at low suction range, as it could be observed that the shape of SWRC changes at low suctions. This behaviour could be measured by HYPROP device.

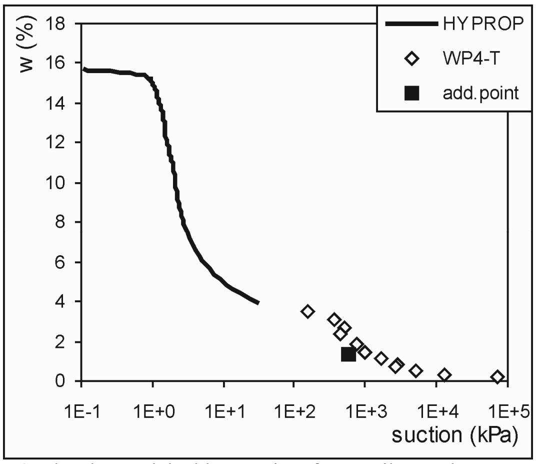

Figure 9. The observed double porosity of some silty sands.

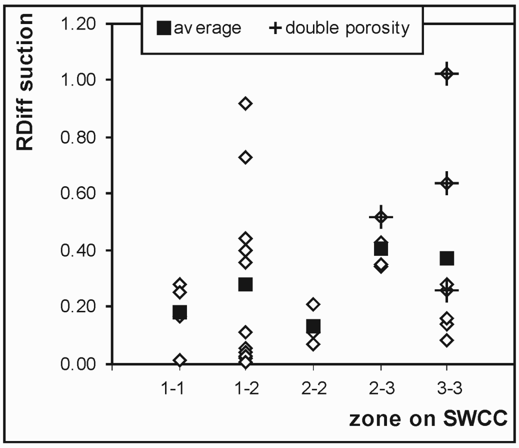

Figure 10. A relative difference between WP4-T device and HYPROP device measurements.

From the HYPROP device measurements an average suction at the tension collapse of the upper tensiometer was determined for all samples. This suction value was compared with the estimated suction from the potentiometer WP4-T measurements at the same water content. A relative difference between both methods was calculated and they were compared to the zone on SWRC (Table 2, Figure 10). An average relative difference is approximately 30%, and is higher if HYPROP measurements in stage 1 are in different zone on SWRC than tension collapse. The highest observed relative difference was 102% and is shown in Figure 10. The observed relative differences of up to 100% are relatively small and higher differences are frequently observed with the same measurement device (Agus and Schanz, 2007, Cardoso et al., 2007). High relative differences in case of zone 3 result from double porosity nature of the tested soil (Table 2, Figures 9 and 10).

The water contents at the same suctions were also compared. The average relative difference was 15% and the highest relative difference was 60%, but it is important to note that the suction is usually drawn in a logarithmic scale and the water content is presented in a normal scale.

6 CONCLUSION

The main purpose of the paper was to demonstrate that the two simple and cheap methods for measuring soil suction in the laboratory are useful when the extensions of their measuring ranges are made and that the comparisons between both measurement methods were found to be good.

However, both methods have their drawbacks. If potentiometer WP4-T is used, the osmotic suction can influence the results. In this case the osmotic suction should be measured.

When the HYPROP device is used, the AEV of the tested soil is important. When the AEV of the soil is higher than the AEV of the ceramic cap, the described assumptions are not necessarily valid. Therefore, good engineering judgment is still needed.

The proposed extensions give good and reliable data. Differences between both methods are small and are in the range of expected differences even for measurements with the same devices.

An extension of the working range of HYPROP device gives less accurate predictions if the zone on SWRC is changed during stage 2 or if the soil has double porosity.

Table 2. Estimated suction and water content at tension collapse and the relative error to the measurements with WP4-T.

classification	zone (from-to)	suction (kPa)	w (%)	RDiff suction (%)	RDiff w (%)
SW-SP	**3-3**	**643**	**1.6**	**16**	**10**
SW-SP	3-3	587	15.7	28	11
SW-SP	2-3	673	15.5	34	14
SP-SM	3-3	614	1.8	14	8
SP-SM	1-2	547	4.6	44	24
SP-SM*	3-3	573	2.5	64	44
*SP-SM**	*3-3*	*587*	*1.3*	*102*	*61*
SP-SM	3-3	587	2.3	9	6
SP-SM*	2-3	700	4.8	52	40
SM	2-3	673	4.7	43	25
SM	2-2	629	2.3	11	6
SM*	3-3	600	3.9	26	14
SM	2-2	658	4.0	7	4
SM	1-2	868	8.5	3	1
SM	**2-3**	**600**	**1.9**	**35**	**20**
SM	1-2	810	4.1	4	2
SC-CH	2-2	692	10.3	21	8
SC-CH	**1-2**	**468**	**15.3**	**40**	**18**
SC-CH	1-2	708	16.1	1	0
SC-CH	1-2	776	13.4	73	27
SC-CH	1-2	631	17.4	36	13
CL	1-2	832	15.2	2	1
CL	1-2	676	12.6	92	27
CL	1-2	851	10.9	6	3
CL	1-2	750	19.0	11	5
CH	1-1	848	31.6	26	34
CH	1-1	646	32.1	28	13
CH	1-1	810	22.4	17	7
CH	**1-1**	**631**	**30.9**	**1**	**0**

RDiff – relative difference, bold – SWRC presented in Figure 8, italic - SWRC presented in Figure 9, * - observed double porosity.

7 REFERENCES

Agus S.S. and Schanz T. 2007. Errors in total suction measurments. in: Schanz, T. (ed.). *Experimental Unsaturated Soil Mechanics*. Springer, Heidelberg ,59-70.

Bardner L. 1965. Consolidation of compacted and unsaturated clays. *Geotehnique* 15 (3), 267-286.

Birle E., Heyer D. and Vogt N. 2008. Influence of the initial water content and dry density on the soil–water retention curve and the shrinkage behavior of a compacted clay. *Acta Geotechnica* 3 (3), 191-200.

Bishop A. W. 1960. Discussion. *Conference on pore pressure and suction in soils.* Buttersworths, London, 63-66.

Bulut R., Hineidi S.M. and Bailey B. 2002. Suction measurements—filter paper and chilled mirror psychrometer. *Proceedings of the Texas Section American Society of Civil Engineers, Fall Meeting, Waco, 2–5 October.*

Campbell G.S. and Gardner W.H. 1971. Psychrometric measurement of soil water potential: temperature and bulk density effects. *Soil Science Society of America, Proceedings* 35, 8–12

Campbell G.S., Smith D.M. and Teare B.T. 2007. Application of a Dew Point Method to Obtain the Soil Water Characteristic. in: Schanz, T. (ed.). *Experimental Unsaturated Soil Mechanics*. Springer, Heidelberg, 71-77.

Cordoso R., Romero E., Lima A. and Ferrari A. 2007. A Comparative Study of Soil Suction Measurement Using Two Different High-Range Psychrometers. in: Schanz, T. (ed.). *Experimental Unsaturated Soil Mechanics*. Springer, Heidelberg, 79-93.

Fredlund D.G. and Rahardjo H. 1993. *Soil mechanics for unsaturated soils.* Wiley. New York.

Fredlund, D.G. and Xing A. 1994. Equations for the Soil–Water Characteristic Curve. *Canadian Geotechnical Journal* 31 (3), 521–532.

Kawai K., Karube D. and Kato S. 2000. The Model of Water Retention Curve Considering Effects of Void Ratio. in: Raharjdo H. (ed.), Toll D.G. (ed.) and Leong E.C. (ed.). *Unsaturated Soils for Asia: Proceedings of the Asian Conference, UNSAT-ASIA 2000, Singapore, 18-19 May 2000*. Balkema, Rotterdam, 329-334.

Leong E.C., Tripathy S. and Rahardjo H. 2003. Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique. *Geotechnique* 53 (2), 173–182.

Peters A. and Durner W. 2008. Simplified evaporation method for determining soil hydraulic properties. *Journal of Hydrology* 356 (1-2), 147–162.

Richards L.A. 1928. The usefulness of capillary potential to soil moisture and plant investigators. *Journal of Agricultural Research* 37 (12), 719-742.

Ridley A.M. 1993. *The measurement of soil moisture suction, PhD thesis.* University of London, London.

Sillers W.S., Fredlund D.G. and Zakerzadeh N. 2001, Mathematical attributes of some soil-water characteristic curve models. *Geotechnical and Geological Engineering* 19 (3-4), 243-283.

Schindler U. 1980. Ein Schnellverfahren zur Messung der Wasserleitfähigkeit im teilgesättigten Boden an Stechzylinderproben. *Archiv für Acker- und Pflanzenbau und Bodenkunde* 24, 1–7.

Schindler U., Durner W., von Unold G., Müller L. and Wieland R. 2010. The evaporation method:Extending the measurement range of soil hydraulic properties using the air entry pressure of the ceramic cup. *Journal of Plant Nutrition and Soil Science* 173 (4), 563–572.

Schindler U. and Müller, L. 2006. Simplifying the evaporation method for quantifying soil hydraulic properties. *Journal of Plant Nutrition and Soil Science* 169 (5), 623-629.

Tarantino A. (ed.), Romero E. (ed.) and Cui Y.J. (ed.), 2008. *Laboratory and field testing of unsaturated soils*. Springer, Heidelberg.

Thakur V.K.S., Sreedeep S. and Singh D.N. 2006. Laboratory investigations on extremely high suction measurements for fine-grained soils. *Geotechnical and Geological Engineering* 24 (3), 565–578.

Vanapalli S.K., Fredlund D.G. and Pufahl, D.E. 1999. The influence of soil structure and stress historyon the soil-water characteristics of a compacted till. *Geotechnique* 49 (2), 143-159.

Zapata C.E., Houston W.N., Houston S.L. and Walsh K.D. 2000. Soil-water characteristic curve variability. *Geotechnical Special Publication* 99, 84–124.

*WP4 Operator's manual version 2.2.*2005. Decagon Devices.