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Water retention properties of stiff silt

Retencijske lastnosti trdnih meljev

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Dedicated to Professor Mihael Ribičič on the occasion of his 70th birthday

Key words: stiff sandy silt, suction, Bishop - Wesley triaxial cell, water retention curve, potentiometer WP4C
Ključne besede: Trden peščeni melj, sukcija Bishop – Wesley triaksialna celica, retencijska krivulja, potenciometer WP4C

Abstract

Recent research into the behaviour of soils has shown that it is in fact much more complex than can be described by the mechanics of saturated soils. Nowadays the trend of investigations has shifted towards the unsaturated state. Despite the significant progress that has been made so far, there are still a lot of unanswered questions related to the behaviour of unsaturated soils. For this reason, in the field of geotechnics some new concepts are developed, which include the study of soil suction.

Most research into soil suction has involved clayey and silty material, whereas up until recently no data have been available about measurements in very stiff preconsolidated sandy silt. Very stiff preconsolidated sandy silt is typical of the Krško Basin, where it is planned that some very important geotechnical structures will be built, so that knowledge about the behaviour of such soils at increased or decreased water content is essential.

Several different methods can be used for soil suction measurements. In the paper the results of measurements carried out on very stiff preconsolidated sandy silt in a Bishop - Wesley double-walled triaxial cell are presented and compared with the results of soil suction measurements performed by means of a potentiometer (WP4C). All the measurement results were evaluated taking into account already known results given in the literature, using the three most commonly used mathematical models. Until now a lot of papers dealing with suction measurements in normal consolidated and preconsolidated clay have been published. Measurements on very stiff preconsolidated sandy silt, as presented in this paper were not supported before.

Izvleček

Zadnje geomehanske raziskave zemljin kažejo na to, da je njihovo obnašanje veliko bolj kompleksno, kot se to lahko opiše z modeli za saturirane zemljine. Danes se trend raziskav nagiba v področje nesaturiranih materialov. Kljub velikim premikom na tem področju ostaja še vedno veliko vprašanj povezanih z obnašanjem materialov v nesaturiranem območju, zato so se v geotehniki uveljavili novi koncepti modelov, ki vključujejo študij sukcije.

Večina preiskav sukcije je osredotočenih na normalno konsolidirani glineni ali meljni material, medtem ko rezultatov preiskav v trdnem, prekonsolidiranem peščenem melju, po dosedaj znanih podatkih, ni objavljenih. Trdni, prekonsolidirani peščeni melj je tipičen za Krško kotlino, kjer se bodo gradili večji geotehnični objekti, in je poznavanje sukcije materiala ob povišanju vlage v njem bistvenega pomena.

Za meritev sukcije je bilo uporabljenih več različnih metod. V članku so predstavljeni rezultati meritve sukcije trdnega peščenega melja v Bishop - Wesley dvostenski triosni celici in primerjava z rezultati meritev sukcije v potenciometru (WPC4). Rezultati so potrjeni z matematičnimi modeli, ki so v tovrstni literaturi najbolj poznani. Rezultati raziskav predstavljajo prispevek k poznavanju obnašanja prekonsolidiranega trdnega peščenega melja v nesaturiranih pogojih.

Introduction

Recent research into the behaviour of soils has shown that it is in fact much more complex than can be described by the mechanics of saturated soils. The general field of soil mechanics can be sub-divided into that part which deals with saturated soils and that part which deals with unsaturated soils. Nowadays the trend of investigations has shifted towards the unsaturated state. Despite the significant progress that has been made so far, there are still a lot of unanswered questions related to the behaviour of unsaturated soils. This refers in particular to the changes in volume and strength which occur in the soil. Under certain conditions soils may behave very unpredictably, either through a rapid increase in their volume (swelling) or by (structural) collapse. For this reason, in the field of geotechnics some new concepts, which include the study of soil suction, are now being introduced.

Several methods for measuring soil suction are known, i.e. measurements with a stick tensiometer, with a potentiometer, with a pressure plate extractor and filter paper. These methods can provide reliable information at both high and very low suctions, whereas in the intermediate zone measurements can be unreliable.

This deficiency can be remedied by using of the Bishop - Wesley double-walled triaxial cell, which can provide very precise measurements of changes which occur in the volume of water and air in the pores.

In geotechnical engineering, soil suction is an important parameter which is used in the design and construction of buildings, roads, tunnels, hydropower dams, and deep excavations, as well as for the construction of sealing layers and covers for surface waste deposits, and elsewhere. Suction also needs to be studied in the case of landslides. Numerous research projects have been performed, including geotechnical and environmental aspects, in connection with waste disposal and ground pollution. Special attention has been focused on the question of the swelling of soils after compaction into sealed layers for the covering of radioactive waste deposits (Umedera et al., 1996; Delage, 2002).

Numerous authors have also studied the impact of soil suction on the triggering of landslides in unsaturated soils (Tofani et al., 2006; Lu & Godt, 2008; Godt et al., 2009), some of them (Ng et al., 2003; Springman, 2011) with the help of artificially caused precipitation.

In recent years quite a lot of research has been performed in Slovenia, too, in connection with various geotechnical structures (Maček et al., 2006; Petkovšek, 2006, Maček, 2006). Based on the results of the laboratory investigations (Petkovšek, 2006), the favourable impact of soil suction on the strength characteristics of bentonite, very stiff clay (i.e. „Sivica“), and flysch material was determined. Apart from laboratory tests, in situ soil suction measurements have been performed in Slovenia, since 2004, on the Lenart - Cogetinci - Vučja vas motorway section, where an embankment of swelling clay was stabilized by lime (Petkovšek, 2008) and the effect of soil suction on the stability of the large Slano blato landslide was examined by Maček (2012).

Until now lot of papers dealing with suction measurements in normal consolidated and preconsolidated clay have been published, but no such measurements on very stiff preconsolidated silt, as it is found in the Krško Basin, are mentioned. Since several important geotechnical structures will be built in this area, it was necessary to carry out more detailed measurement of the soil suction occurring in this material.

Background

The soil suction has been defined as the energy level of the pore water in soils (Suescun Florez, 2010). It is the result of the adsorption of water onto mineral grains, together with a capillary phenomenon and the osmotic effects of the salt in the pore water. It can also be labelled as a measure of the energy that attracts water into the structure of the soil, or keeps it there. It is perceived as a tensile stress of the water in the soil, or as a negative pore water pressure (Marshall & Holmes, 1988).

Three types of soil suction are known: matrix suction, osmotic suction, and total suction. Total soil suction is defined as the sum of the matrix suction and the osmotic suction, and is written as:

$$\psi = (u_a - u_w) + \pi \quad (1)$$

Where: ψ is the total suction, $(u_a - u_w)$ is the matrix suction, and π is the osmotic suction.

From Equation (1) it can be seen that the matrix suction is defined as the difference between the pore pressure of air (u_a) and the pore pressure of water (u_w). It is in fact defined as the energy which is needed to remove water from the soil matrix or from its structure, without any changes to the physical state of the water. Matrix suction occurs as a result of the capillary phenomenon, the soil structure, and the adsorption of water onto the mineral grains (Bulut et al., 2001). Osmotic suction (π) is a consequence of the concentration of salt dissolved in the water, and is independent of the pressure.

If it is assumed that the osmotic suction is zero, then the change in total suction equals to the change in the matrix suction.

$$\psi = (u_a - u_w) \qquad (2)$$

Suction can be expressed per unit volume, mass or weight. The unit expressed per unit volume is given in pascals (Pa), bars (bar), or atmospheres (atm).

The soil-water characteristic curve (SWCC)

The soil-water characteristic curve, sometimes referred to as a „water retention curve“, is a curve which describes the relationship between the suction and the water content, so that it predicts the behaviour of soil in the drying phase (i.e. desaturation) and the wetting phase (i.e. saturation). The shape of the water retention curve depends on many factors, from the density of the soil, its adsorption capacity, the size of the pores in the soil, whether the soil is in a drying or wetting phase, and also on the mathematical model used for the calculation of the retention curve. In most cases, the water retention curve, which covers a range between 0 and 10^6 kPa, has a characteristic „S“ shape (Fredlund & Xing, 1994). Since suction values can be very high, retention curves are usually presented as graphs on a logarithmic scale.

A typical water retention curve is shown in Figure 1, where three identifiable sections can be observed: the saturation zone, the desaturation zone, and the residual zone. Two changes in the slope can also be seen, one at the point of air entry and the other at the point of residual water content. The soil is completely saturated in the saturation zone, where the suction is too small to drain the pores. Between the air-entry value and the point of residual water content there is a desaturation zone. This is the zone where the water in the pores is increasingly displaced by air. Within this zone, the suction is higher than the suction at the air entry value (Kayadelen et al., 2007). The air entry value is the point where the large pores begin to be drained due to the increase of suction (Fredlund et al., 2011), as air enters them. The residual zone is an area where the transport of water in the soil is only possible by means of water vapour.

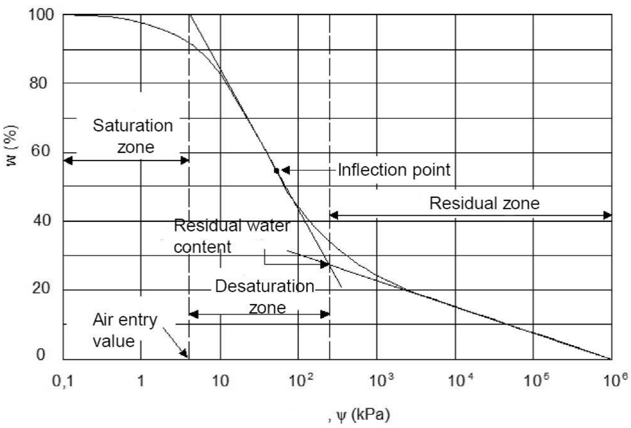

Fig. 1. A typical retention curve (SWCC: soil-water characteristic curve) (after Fredlund et al., 2011 and Kayadelen et al., 2007).

The water retention curves could represent the drying phase (desaturation) or the rewetting phase (saturation). In the paper the results for the drying phase will be presented.

Mathematical models for water retention curves

Various authors have suggested different empirical equations and mathematical models for water retention curves. They can be defined as a function of the suction depending on the degree of saturation, or on the normalized water content. The following models are most frequently used, in which the water retention curve is expressed as a function of the volumetric (i.e. normalized) water content.

Brooks & Corey (1964):

$$\begin{cases} \theta(\psi) = \theta_{sat} & \psi < \psi_{ae} \\ \theta(\psi) = \theta_{sat}\left(\dfrac{\psi}{a}\right)^{-n} & \psi \geq \psi_{ae} \end{cases} \qquad (3)$$

where: a and n are the fitting parameters determined by the method of minimum square roots,

ψ is the soil suction, θ_R is the residual water content, θ_{sat} is the volumetric water content at complete saturation, and ψ_{ae} is the air-entry value .

Brooks and Corey (1964) divided the equation into two parts. In the first part the suction is smaller than the air-entry value, whereas in the second part it is greater than the air entry value (Fredlund et al, 2011).

Fredlund & Xing (1995):

$$\theta = \left[1 - \frac{ln\left(1+\frac{\psi}{\psi_R}\right)}{ln\left(1+\frac{10^6}{\psi_R}\right)}\right] \cdot \left[\frac{\theta_{sat}}{\left(ln\left(e+\left(\frac{\psi}{a}\right)^n\right)\right)^m}\right] \quad (4)$$

where: θ_{sat} is the volumetric water content at complete saturation, ψ is the soil suction, ψ_R is the soil suction at the residual water content, and *a, n,* and *m* are curve-fitting parameters.

van Genuchten (1980):

$$\Theta_n = \frac{\theta - \theta_R}{\theta_{sat} - \theta_R} = \frac{1}{\left[1+\left(\frac{\psi}{a}\right)^n\right]^m} \quad (5)$$

where: θ_R – is the residual volumetric water content, and *a, n,* and *m* are curve-fitting parameters.

Soil suction retention curves were in the presented paper calculated by using the described mathematical models. The function parameters were determined in Excel by using the Least Squares Method, and the retention curves which best fitted with the measured values were defined.

Experimental techniques

Several different methods can be used for soil suction measurements. In the paper the results of measurements carried out on very stiff sandy silt in a Bishop - Wesley double-walled triaxial cell are presented and compared with the results of soil suction measurements performed by means of a potentiometer (WP4C).

Soil suction measurements using a Bishop-Wesley double-walled triaxial cell

The double wall triaxial cell is an improved traditional triaxial cell. Its advantage lies in its double wall cell, which provides constant conditions and thus enables the performance of accurate measurement of the changes which occur in the sample‘s volume. In conventional triaxial systems water can enter into the saturated sample, or can be pumped out of it. At the same time the air pressure in the sample can be changed, which could influence to the volume expansion of the sample.

On the other hand, in the double wall triaxial cell, the same cell pressure inside and outside the cell ensures that the volume changes of the water in the inner cell is only the consequence of changes in the volume of the sample and not due to external influences (e.g. changes in the cell volume due to the water temperature). These changes lead to changes in the volume of water in the outer cell, which provides constant conditions for the internal chamber.

The double wall triaxial cell ensures accurate measurement of matric suction within the range from 0 to 1500 kPa, depending on which porous plate is used.

The main parts of the double triaxial cell are (Fig. 2):

- a base pedestal on which the sample is placed,
- an inner cell and outer cell that are both cylindrical in shape and, after installation, are filled with water,
- a vertical force transducer together with a hydraulically powered system for vertical loading,
- a pore pressure transducer,
- an axial displacement transducer,
- a pressure gauge in the lower chamber,
- 5 electromechanical volume pressure controllers (VPC) for measuring and setting the air and water pressures and for measuring the volume changes,
- a coarse porous disk
- a porous plate with high air-entry value (a HAEPD: high air entry porous disk).

The entire system is computer-controlled, with corresponding acquisition and storage facilities.

The method of measurement of soil suction in the double-walled triaxial cell is designed in such a way that the sample is pressurized by air and water, i.e. by suction (Figure 3). The volume change at which equilibrium is established in the soil sample is measured. Depending on the volume change of the sample at certain controlled

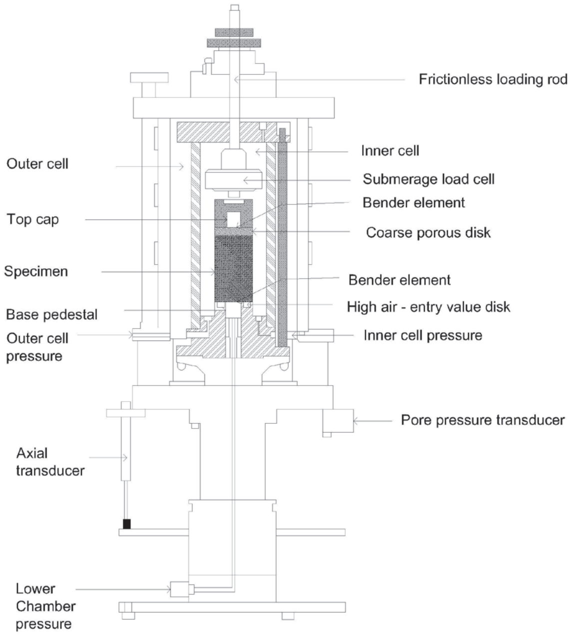

Fig. 2. The Bishop-Wesley double-walled triaxial cell.

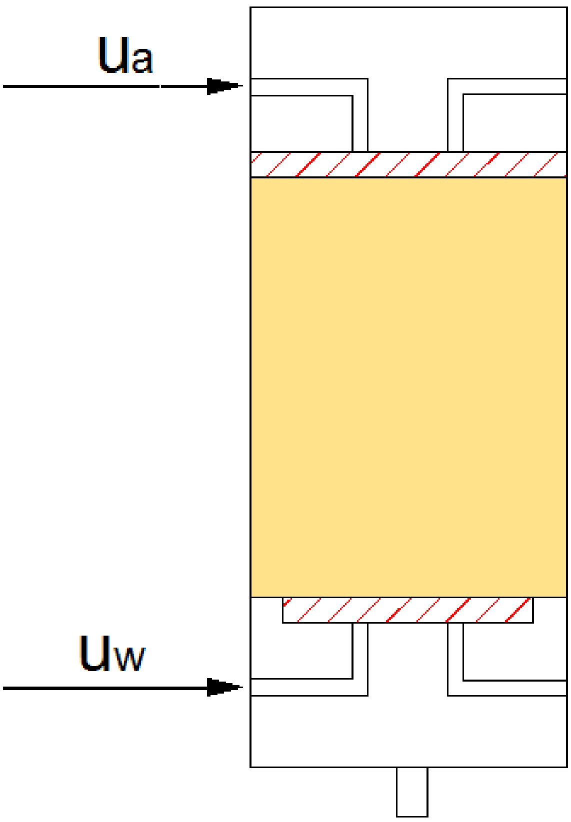

Fig. 3. Pressurizing the sample with an air pore pressure air (ua) and a water pore pressure (uw) (net effective stress controlled stage).

suction, information about the water content of the soil as a function of suction can be obtained by back analysis. Under controlled effective net stress state (suction stage) the change in the volume of the pore water and in the volume of the pore air are measured by volume measuring devices. With the use of appropriate equations the change in the volume of the pore water is calculated as the result of suction.

When measuring suction using the Bishop - Wesley double-walled triaxial cell, the volume change of the pore water is calculated, for each of the suction stages, from the obtained data. The last measured level of the volume change for a given suction stage is taken into account in the calculations. When the values of the volume change are known for each suction stage, then the volumetric and gravimetric moisture content are calculated, as well as the degree of saturation.

Soil suction measurements using a potentiometer (WP4C)

Soil suction was also measured by means of a WP4C (Fig. 4). This particular kind of potentiometer is a device for measuring water potential using a chilled mirror. The device is easy to handle, and measurements are carried out quickly and fairly accurately. The measurement range for suction is between 0 and 300 MPa, and its accuracy is ± 0.05 MPa over the measurement range between 0 and 5 MPa, and 1 % over the range between 5 and 300 MPa. The accuracy of the device also depends on proper calibration of the instrument and on the ambient temperature at which measurements are performed.

Fig. 4. The WP4C potentiometer.

The potentiometer works by measuring suction on the principle of the relative humidity in the air. The specimen is inserted into the machine into the sealed chamber, which is equipped with sensors, a mirror, and a ventilator. The sensors measure the temperature of the mirror, and the ambient temperature. The temperature of the mirror is precisely measured by means of a laser beam, which operates on the principle of the Peltier effect, in which a photo-detector operates by precisely detecting the point at which condensation occurs on the mirror for the first time. The potentiometer directs the light beam onto the mirror so that it is reflects into the photo-detector. When condensation occurs on the mirror, the photo-detector senses the change, and at the same time the thermocouple in the mirror records the temperature at which condensation has occurred. At the point of equilibrium the water potential of the air in the chamber is equal to the potential of the water in the sample. Soil suction is then determined according to Equation 10 (WP4C, 2013).

$$\Psi = \frac{RT}{M} * ln\frac{p}{p_0} \quad (10)$$

where: Ψ is the water potential, R is the gas constant, T is temperature in the sample in Kelvin, M is thermolecular mass of the water, p is the pore pressure of the air, and p_o is the vapour pressure at the temperature of the sample.

Experimental results

The goal of the suction measurements was to determine the value of suction of very stiff preconsolidated sandy silt in the Krško Basin, where it is expected that some large geotechnical structures will be built in the next few years. The suction measurements were performed in the above-mentioned Bishop-Wesley double-walled triaxial cell (sample V1) and potentiometer (sample V2).

Soil studied

The stiff sandy silt (sample V1) which was studied in the Bishop-Wesley double-walled triaxial cell was similar but not identical to the sandy silt (sample V2) which was used for the measurements in the potentiometer. However, using both measurement methods it was possible to compare data obtained by means of two different suction measurement techniques.

The soil physical parameters are presented in Table 1. The results of the granulometric analysis showed that samples V1 and V2 can be classified as sandy silt (saSi) according to the standard SIST EN ISO 14688-1, and silt (ML) according to the standard JUS U.B1.00.

Water retention curves

The measured data of the sandy silt sample V1 are shown in Figure 5, where the retention curves were calculated by using the van Genuchten, Brooks and Corey, and Fredlund and Xing. With the Bishop-Wesley double-walled triaxial cell the suction is measured in the volumetric water content.

From the retention curves it can be seen that the air-entry value for sandy silt V1 (ψ_{ae}) occurs at a suction of 40 kPa. The suction which corresponds to the natural gravimetric water content of the sample (i.e. 27.7 %) amounts to about 3-4 kPa which means that the sandy silt is at natural water content fully saturated. The slope of the curve in the middle section is steep, which means that most of the water in the sandy silt is bound in the capillaries, so that the material is able to release it at low values of suction.

Table 1. The geomechanical characteristics of the sandy silt V1.

Sample	Water content	Density	Dry density	Specific density	Granulometric analysis		
Designation and unit	w (%)	ρ (Mg/m^3)	ρ_d (Mg/m^3)	ρ_s (Mg/m^3)	sand content (%)	silt content (%)	clay content (%)
Sandy silt V1	27,2	1,93	1,58	2,80	33,3	63,8	2,5
Sandy silt V2	25,3	1,99	1,53	2,76	42	57,8	0,2

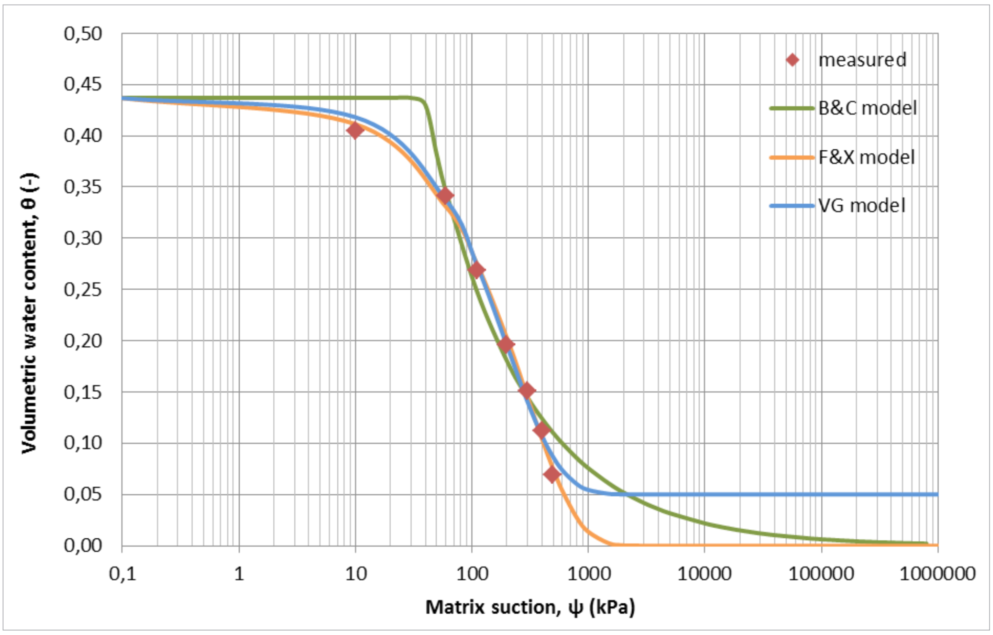

Fig. 5. Comparison of the retention curves obtained by using the different models for the sandy silt sample V1.

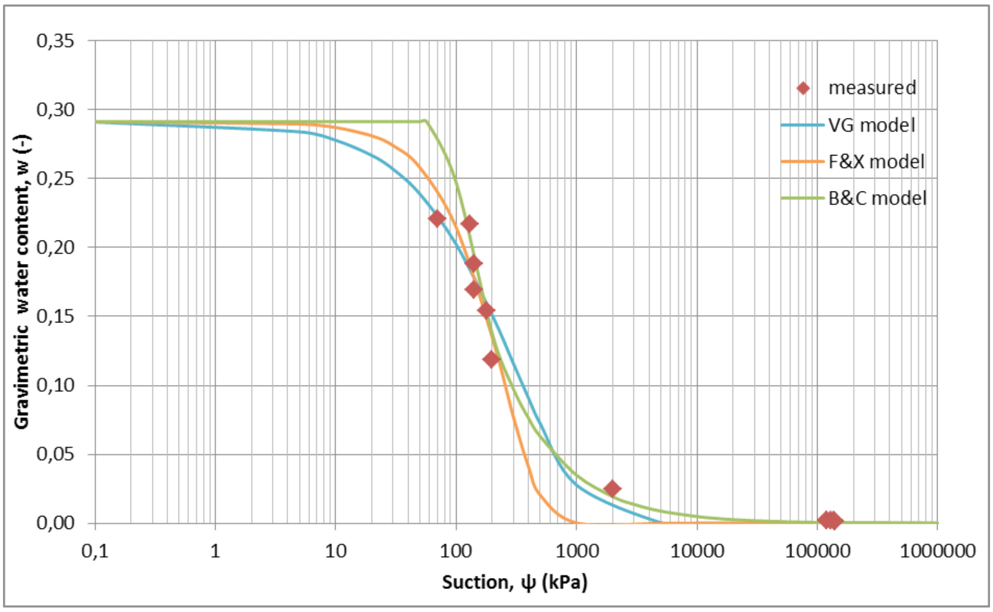

Fig. 6. Comparison of the retention curves obtained by using the different models for the sandy silt sample V2.

The retention curve corresponding to the sandy silt of sample V2 was determined by using the potentiometer (Fig. 6). With the potentiometer suction is measured in the gravimetric water content. The residual moisture point occurs at almost zero water content, at a suction of about 500 kPa, whereas the air-entry point occurs at a suction of 60 kPa. The measured value for the suction at 70 kPa and 22 % of gravimetric water content is questionable, since potentiometer measurements at suctions of up to 100 kPa are inaccurate. The slope of the retention curve is fairly steep. It can be seen that the moisture content decreases very rapidly, even at low values of suction. This indicates that the water between the grains is bonded only in the capillaries, so that the material is able to release it at low values of suction.

Discussion

Soil water retention curves were prepared on the basis of the models proposed by Brooks and Corey, Fredlund and Xing, and van Genuchten.

Based on the comparisons which were made between the different models, we tried to determine which water retention curve best fitted the measured values. From Figures 5 and 6 it can be seen that the measured values fit best when the Fredlund and Xing or van Genuchten model is used. In the case of the Brooks and Corey model, good agreement was observed with the measured values in the middle part of the curve, whereas at low suctions the fit was poorer. A sharp transition curve can be observed at the air-entry point, which makes identification of this point easy.

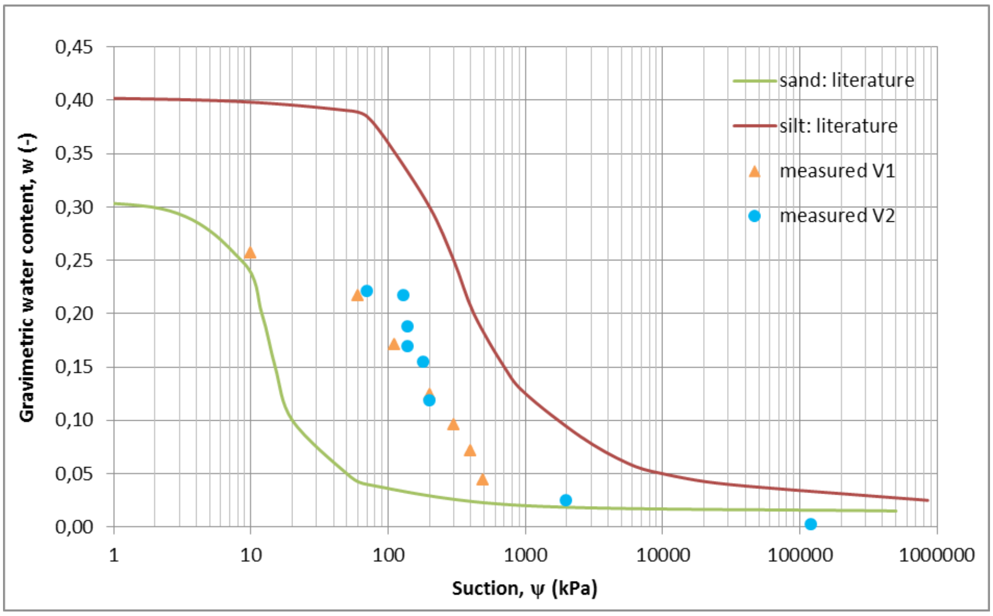

Fig. 7. Comparison of the measured values with data from the literature (the retention curves are according to Fredlund et al., 2011).

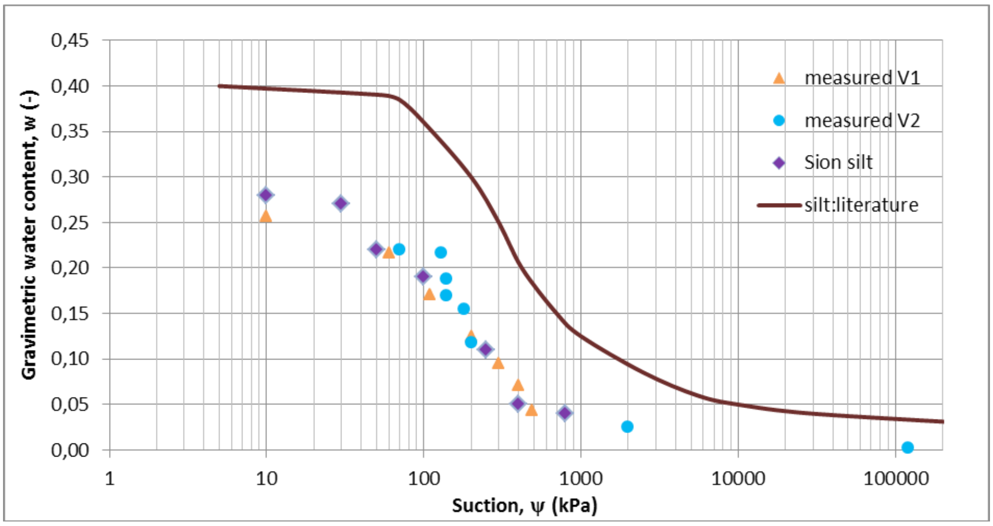

Fig. 8. Comparison of the measured values of sandy silt (samples V1 and V2) with Sion silt and data from the literature (the retention curve is according to Fredlund et al., 2011).

The sharp transition curve is due to the splitting of the model into two parts, where, in the first part of the equation, the moisture content is assumed to be to fully saturated. For this reason in its initial part the curve is flat, whereas in the part from the air-entry point onwards it enters a sharp transition. In the case of the sandy silt V2 the retention curves are located somewhat below the measured values.

Although each type of soil has its own kind of retention curve it is generally considered that various groups of soils have retention curves which are characteristic for them. The measurements results were also checked against data which can be found in the literature. Figure 7 shows the measured values of the retention curves for stiff sandy silt and a typical retention curve for sand and silt. The results of sandy silt V1 and V2 are shifted more in the direction towards retention curves which are typical for sand.

The results were compared with the Sion (Geiser, 1999) silt which is by the structure the most similar material to the Krško valey sandy silt (Table 2). It has a lower percent of sand and the sample was reconstituted before the testing and the consolidated to the primary stress value. If we compare curves of the samples V1 and V2 with the results of the measurements of the Sion silt we can see that there are quite similar in spite of the fact that the samples V1 and V2 are preconsolidated (Fig. 8). The preconsolidation pressure was obtained by the pressuremeter and oedometer tests and it was found that the OCR is approximately 2. From the results we can conclude, that the presonsolidation ratio of samples V1 and V2 is not enough high to have an influence on the level of suction. Higher influence on the results have the sandy component in the silt.

Based on our experiences with testing of stiff silt material we could conclude that each of the

Table 2. The geomechanical characteristics of the Sion silt.

Sample	Liquid limit	Specific density	Granulometric analysis		
Designation and unit	w_l (%)	ρ_s (Mg/m^3)	sand content (%)	silt content (%)	clay content (%)
Sion silt	25,4	2,74	20	72	8

described methods of measurement of soil suction has its advantages and disadvantages. From the point of view of accuracy, the Bishop - Wesley double walled triaxial cell has a big advantage, since very accurate measurements can be made of the changes occurring in the pore water volume and the air volume, and, as well as this, accurate measurements can be performed at low matric suction values. Additionally, the Bishop -Wesley double walled triaxial cell provides constant conditions throughout the duration of the investigation, which reduces the possibility of errors due to the impact of the environment (e.g. temperature changes). The advantage of the cells lies also in the fact that measurements are made on only one of the samples, so that errors due to sample preparation can be avoided. However, in comparison with the potentiometer, the work is much more difficult and requires more knowledge of how to handle with the device, and the measurements are also time-consuming.

Complete investigations in a Bishop - Wesley double-walled triaxial cell, from the sample saturation and consolidation to the measurements of soil suction may last as long as several months, whereas entire measurements in the potentiometer take no longer than a week or two. Apart from making possible faster performance measurements, handling of the potentiometer is much simpler. The disadvantage of the device lies in the fact that the potentiometer does not give good results in the low suction range, and it is also very important to reduce the effect of temperature changes on the soil suction results. The disadvantage of performing measurements with the potentiometer is that the measurements are made on a small amount of the sample having an unknown density, which has a considerable effect on the soil suction values obtained. A small amount of a sample can also increases the possibility for making errors in the measurements. At the same time this might be an advantage, since there is no need for a large amount of the sample for the performance of the measurements.

From the geotechnical point of view, the authors were particularly interested in the matric suction, which has an effect on the stress - strain properties of soils. Matric soil suction can be precisely measured only in a double-walled triaxial cell, whereas in measurement performed with a potentiometer only the total suction is measured, assuming that the osmotic suction is zero.

Conclusions

So far, most research of soil suction has been performed on clay and silt material, whereas measurements of the soil suction of stiff preconsolidated sandy silt have not been performed yet. Very stiff silt is typical of the Krško Basin where, in the future, some very important geotechnical structures will be built. In particular, knowledge is needed about the behaviour of such soil at increased or decreased water content is essential.

In the paper the results of measurements that were carried out on very stiff sandy silt in a Bishop - Wesley double-walled triaxial cell for the very stiff preconsolidated sandy silt are presented, and compared with the results of soil suction measurements performed with a potentiometer (WP4C). Both methods were presented in detail. The results of the measurements were evaluated on the basis of already known results that have been presented in the literature, using the three most commonly used mathematical models which are used for the definition of retention curves.

On the basis of the results of the laboratory tests of unsaturated soils, with an emphasis on measurements of suction in a Bishop - Wesley double-walled triaxial cell and using a potentiometer, it can be concluded that both of these methods of measurements provide useable results. The obtained results are in a good agreement with the results which are already known from the literature, and the models used to describe the soil retention curve fit the measured values very well.

The results were compared with the Sion silt (Geiser, 1999) which is by the structure the most similar material to the Krško valey stiff sandy silt. From the comparison it can be concluded, that the presonsolidation ratio of samples V1 and V2 is not enough high to have an influence on the level of suction. Higher influence has a presence of the sandy component in the silt material.

The disadvantages of most methods for measuring soil suction in the laboratory lie in the inaccurate and unreliable measurements which occur in the low suction range, i.e. up to about 100 kPa. According to the obtained results, the Bishop - Wesley triaxial cell can provide accurate measurement in this range. The specially designed double-walled cell enables accurate measurements of the volume changes which occur in the water and air in the pores, without being affected by outside effects (e.g. changes in temperature) The absolute advantage of this cell lies in the fact that the suction is measured only a single sample, so that the effect of errors in the preparation of the sample, or of its non-homogeneity, can be reduced.

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