Influence of soil suction on trench stability
Influence de la suction matricielle sur la stabilité des tranchées

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ABSTRACT

For the moment, common design methods which are applied in Belgium for trench and slope stability do not take into account the suction which can be present in silty and sandy unsaturated soils. This suction is one of the reasons that steeply inclined slopes remain stable, while this stability can not be proven by common design rules. Because of the large occurrence of unsaturated loam and sand soils (possibly after water lowering) during excavations, a research project on the stability of temporary trenches in unsaturated soil is carried out in Belgium. The main objective of the project is to evaluate the seasonal variations of suction in the soil and to quantify the consequences of these suction variations on trench stability. This paper presents the strategy adopted within the framework of the research project, along with current results and intermediate conclusions.

RÉSUMÉ

Les méthodes de calcul conventionnelles qui sont appliquées en Belgique pour le dimensionnement de fouilles et de talus ne tiennent pas compte actuellement de la succion matricielle qui peut être présente dans les sols non saturés limoneux ou sableux. Cette succion est l'une des raisons pour lesquelles des pentes très raides restent stables alors que leur stabilité n'est pas justifiée pas les méthodes de calcul. Etant donné le grand nombre d'excavations effectuées dans des sols non saturés sableux et limoneux (après un rabattement de nappe éventuel), un programme de recherche sur la stabilité des fouilles temporaires dans des sols non saturés est conduit en Belgique. L'objectif principal du projet est d'évaluer les variations saisonnières de la succion dans le sol et de quantifier les conséquences de cette succion sur la stabilité des fouilles. Cet article présente la stratégie adoptée dans le cadre de cette recherche. Les résultats actuels et les conclusions intermédiaires sont présentés.

1 INTRODUCTION

The execution of temporary trenches in unsaturated soils is common practice in geotechnical engineering, e.g. for building constructions or civil engineering works. One can often observe steeply inclined slopes that remain stable, while conventional soil mechanics do not prove their stability. Presumably, the difference between predictions and observations is due to the degree of saturation-dependent strength of soil which is not taken into account in common design rules.

To meet this issue, a national research project on the stability of temporary trenches in unsaturated soil is actually going on in Belgium [2003-2009]. The main objectives of the project are (1) the evaluation of the seasonal variations of soil suctions, (2) the quantification of the effect of the soil suction on trench stability, and (3) the establishing of practical guidelines for the execution of temporary trenches. In order to achieve these goals, different actions have been tackled. First, in situ measurements of soil suction have been performed in common Belgian soils. Secondly, lab tests have been carried out to characterise the shear strength of unsaturated soil. Finally, a full scale instrumented test trench with vertical sides has been realised and monitored to compare predictions and observations.

The strategy adopted within the framework of this project is presented in this paper. Preliminary results are also briefly described and commented.

2 BASIC PRINCIPLES OF UNSATURATED SOILS

With regard to the widely accepted Mohr-Coulomb failure criteria, the shear strength τ_f of saturated soils is provided by Equation (1).

$$\tau_f = c' + (\sigma - u_w)\tan\varphi' \tag{1}$$

where c' is the effective cohesion [kPa], σ is the total stress [kPa], u_w is the pore water pressure [kPa], and φ' is the effective friction angle [°].

The presence of water tends to decrease the shear strength of saturated soils. Consequently, the water phase can be seen as unfavorable for trench stability. This latter trend becomes more predominant if the loading induced by water flowing is taken into account.

For unsaturated soils, the pores between solid particles are filled with air and water. A key feature of such a composition is that the interface between air and water can exert a tension force. As a consequence, negative pore water pressure may be induced by tension surface forces. The pore water pressure deficit towards the atmospheric pressure which is produced in the pores of an unsaturated soil by the soil-water interaction is referred to as the soil suction (matric suction).

The soil can be characterised by its retention curve, also commonly named soil water characteristic curve (SWCC). As illustrated in Fig. 1, the level of matric suction depends on the water content of the soil. In ground civil engineering, the typical values range from 0 to 150 kPa.

Bishop suggested in 1959 a relationship (Equation (2)) which has gained widespread reference for determining the effective stress of unsaturated soil as a function of the matric suction.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \tag{2}$$

where u_a is the atmospheric pressure (generally $u_a = 0$), and χ a dimensionless parameter related to the degree of saturation (χ tends towards 0 when the soil is dry and towards 1 when the soil is saturated).

Several authors suggested expressions for Bishop's parameter χ, as e.g. Khalili & Khabaz 1998 or Oberg & Salfors 1995. According to Oberg & Salfors 1995, χ can be replaced as a first approximation by the degree of saturation S_r.

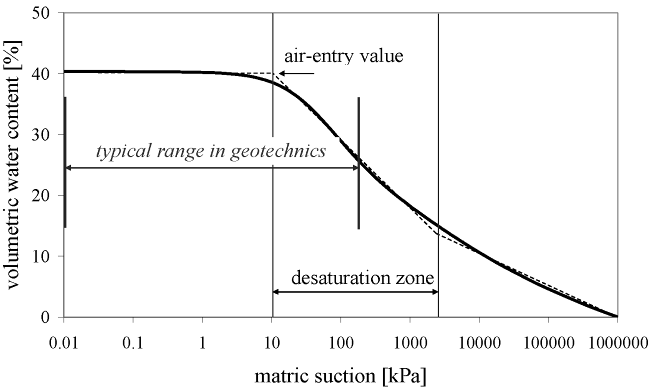


Figure 1. Typical retention curve of a soil.

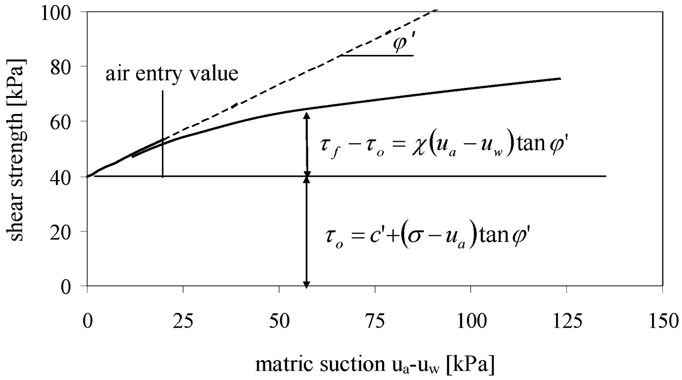


Figure 2. Influence of soil suction on shear strength.

Within the concept of effective stress, the shear strength τ_f for an unsaturated soil is given by Equation (3) and depicted in Fig. 2.

$$\tau_f = c' + [(\sigma - u_a) + \chi(u_a - u_w)]\tan\varphi' \tag{3}$$

Compared to the shear strength of dry soils, Leclercq and Verbrugge 1986 stated that unsaturated soils exhibit an apparent cohesion c_a expressed as:

$$c_a = \chi(u_a - u_w)\tan\varphi' \tag{4}$$

From this statement, it can be assumed that matric suction has a beneficial effect on slope stability. For practical design of e.g. trench stability in dry sand, the apparent cohesion could be taken into account instead of the effective cohesion. Great care should however be paid by considering an apparent cohesion in geotechnical design. If pore water pressure may involve a beneficial effect on trench stability by introducing apparent cohesion, this latter can change and be removed in small time when the soil saturation increases due to e.g. precipitations.

In practice, difficulties arise from the determination of the matric suction profile since it depends highly on several variable parameters such as the ground surface conditions (dry and wet seasons), the vegetation, the position of the water table, and the permeability of the profile. Fig. 3 depicts a typical

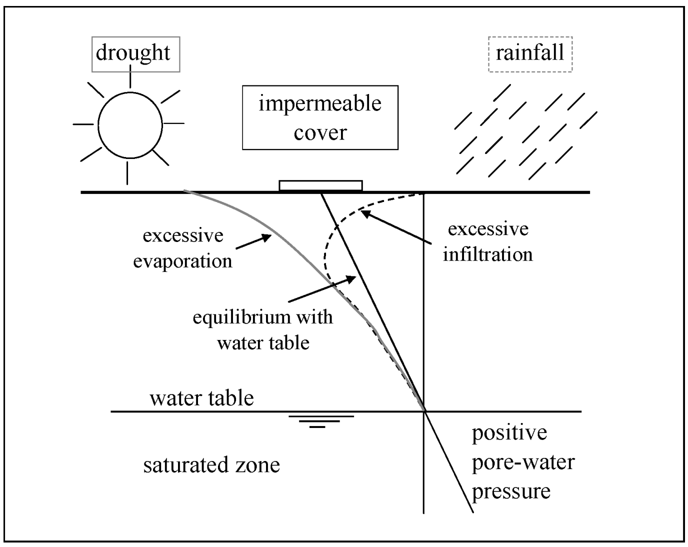


Figure 3. Typical soil suction profile.

pore-water pressure profile. Depending among others on the climatic conditions, the matric suction may be completely different. The variability of the soil suction profile explains why it is so difficult to determine the apparent cohesion and so to provide safe guidelines for contractors.

3 STRATEGY OF THE PROJECT

For a better understanding of the stability of temporary trenches in unsaturated soils a research project has been undertaken in Belgium. As reminded previously, the matric suction is a key feature of unsaturated soil. In this project, emphasis has been put on the evaluation of matric suction profiles, and their influence on the shear strength of the soil. The actions undertaken to achieve these goals can be classified into three categories: (1) in situ measurements of matric suction, (2) laboratory tests for characterising the shear strength of unsaturated soils, and (3) monitoring of a full scale experimental trench.

It was decided to focus on soils commonly encountered in Belgium, i.e. quaternary loam and Brusselian sand. Among others, the site of BBRI at Limelette where the subsoil consists of overlying quaternary loam was selected. An extensive investigation of the site is described in Van Alboom & Whenham 2003.

3.1 *In situ measurements of matric suction profiles*

At the site of BBRI, a total of about 80 tensiometers have been installed in the unsaturated loam at different depths. As the variation of soil suction with time is of a great interest, measurements have been performed every week with additional measurements when climatic changes occurred.

Fig. 4 provides the monthly average matric suction measured during three successive years in the quaternary loam at the site of BBRI, while Fig. 5 presents the corresponding rain measurements. The water table is situated at a depth of 55 m, implying that it has no effect on the soil suction for the investigated depths. As a first approximation, changes in soil suction would result mainly from infiltrations and/or evaporations. With regard to Fig. 3, the measurements are kept close to the ground surface since the maximum investigated depth (3.5 m) is by far lower than the water table depth.

It is clear from Fig. 4 that the soil suction remains relatively constant for depths larger, than 2 m while it changes excessively for lower depths. Comparison of Fig. 4∼5 reveals that a relationship exists between the matric suction at shallow depths (< 2 m) and the rainfalls. For instance, the heavy rains of August induce a reduction of the soil suction at shallow depths. During winter (from December to March), the high frequency of rainfalls coupled with the lack of evaporation induces a decrease of the soil suction and soil suction tends towards zero. At greater depths, the matric suction has a more global behaviour i.e. it changes only if an accumulation of evaporation and/or

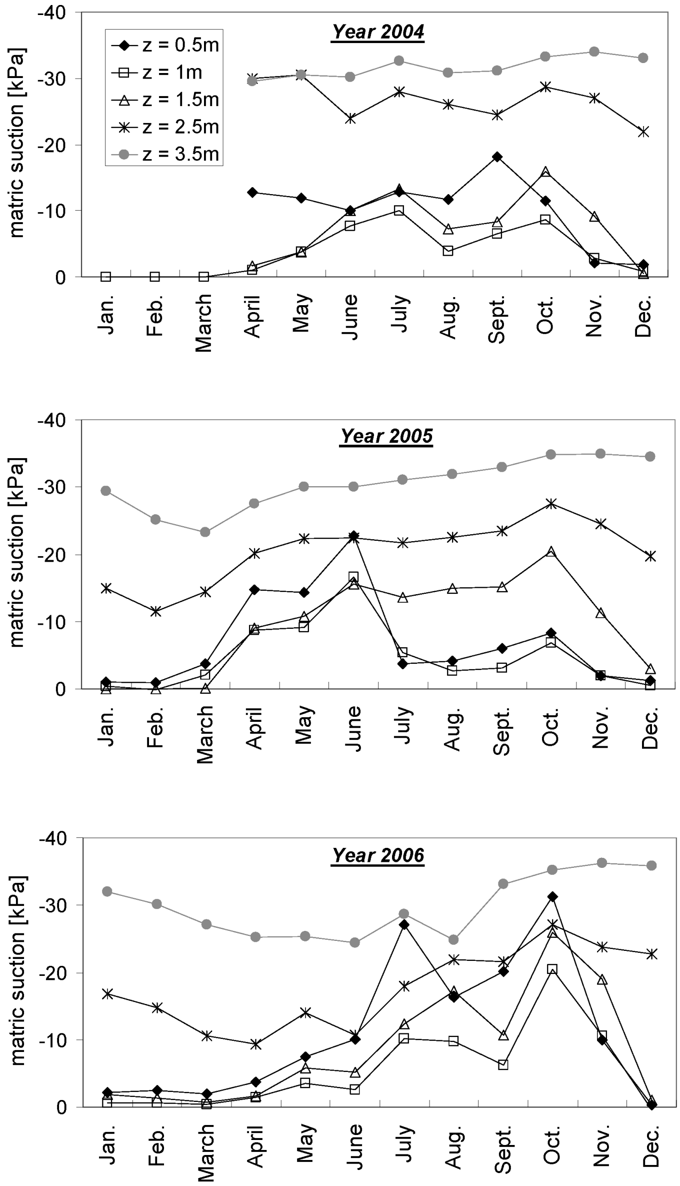


Figure 4. In situ measurements of matric suction carried out at the site of BBRI for the years 2004, 2005 and 2006.

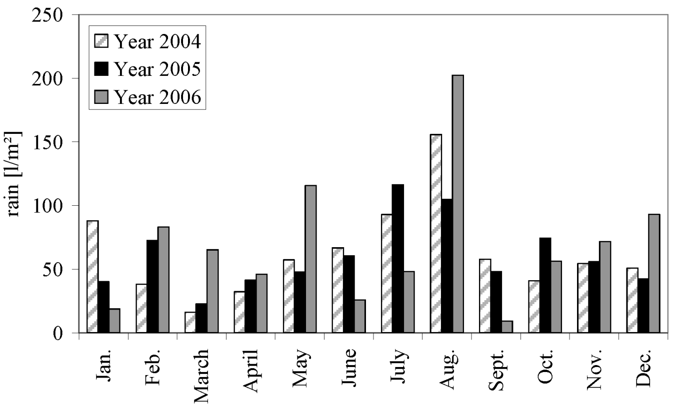


Figure 5. Mean rain for the years 2004, 2005 and 2006.

infiltration occurred during a large period. A delay in time is observed between the soil suction measurements and the climatic conditions.

The difference between the behaviours at low and great depths can also be seen in Fig. 6 which points out matric suction profiles deduced from all the data recorded for three years. Distinction is made between

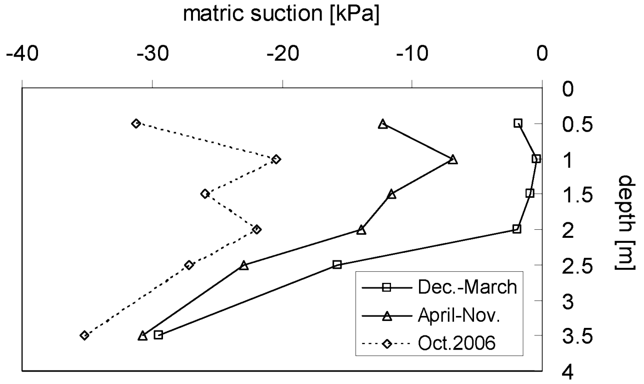


Figure 6. Mean matric suction profiles in the quaternary loam at the site of BBRI over three years.

winter and the rest of the year. For information only, the suction profile measured during October 2006 is also given. During September and October 2006, little precipitation and quite high temperatures have been recorded inducing high suction levels close to the ground surface.

3.2 *Determination of shear strength of unsaturated soils*

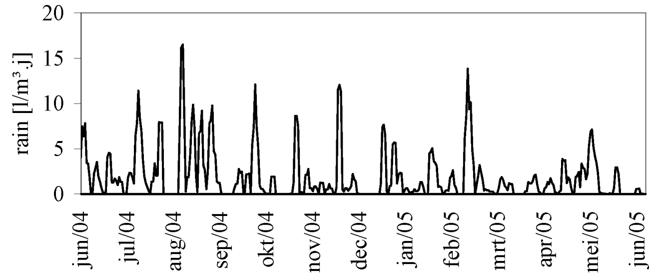
There is a need to better understand the relationship between the shear strength and the soil suction for unsaturated soils. In this project, the approach suggested by Vanapalli et al. 1999 has been selected to that end. It consists of conducting unconfined compression tests on unsaturated specimens. Such tests can provide the shear strength of the specimen as a function of the matric suction (as presented in Fig. 2). From the shear strength, the apparent cohesion can be derived.

Without such experimental results, it is possible to predict the apparent cohesion thanks to e.g. the theory of Oberg and Salfors 1997.

3.3 *Application to a test trench*

A 20 m long and 3 m deep experimental trench has been executed in the unsaturated loam of the site of BBRI in June 2004. The objective of the experiment was to visualise the influence of the seasonal variation of soil suction on the stability of a full-scale trench. The geometry of the trench has been chosen in accordance with this objective, i.e. it should remain stable during the dry season due to apparent cohesion while it should collapse during winter (when the soil suction decreases). For satisfying this criteria, preliminary investigations have been conducted to evaluate (1) the effective strength parameters *c'* and *φ'* (triaxial tests were carried out on undisturbed specimens), (2) the in situ soil suction as presented in Fig. 4 and (3) the degree of saturation of the soil (SWCC have been determined in the laboratory to derive the degree of saturation of the soil based on the in situ soil suction measurements).

The excavation depth was determined by Equation (5) proposed by Terzaghi in 1943 in which H_c is the critical height for a vertical unsupported trench. In this expression, c can be assumed as being the apparent cohesion, as defined in Equation 4. The parameter γ



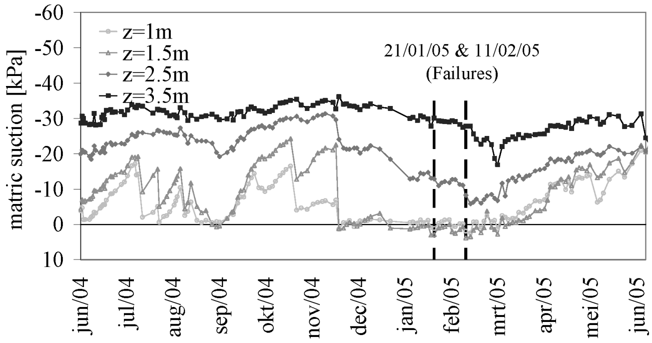


Figure 7. Rain measurement and averaged soil suction measurements.

is the unit weight of the soil.

$$H_c = \frac{2.67.c}{\gamma} \tan\left(45 + \frac{\varphi'}{2}\right) \tag{5}$$

Based on the preliminary investigations, and due to its great occurrence in practice, a 3 m height excavation has been chosen as representative.

Fig. 7 shows the rainfall from June 2004 to June 2005. The corresponding averaged matric suction measurements are also provided. Compared to Fig. 4, the soil suction is more accurately described as a function of time. Fig. 7 clearly points out that each decrease of soil suction value corresponds with a rain period. The influence of rainfall on soil suction appears mainly near the ground surface (1 m and 1.5 m depth). Moreover, it can be highlighted that during summer, the evaporation involves a relatively rapid increase of matric suction near the ground surface after a rain event. This observation is not valid in winter.

A first collapse of the trench appeared on 21 January 2005 after an important rainfall. From December 2004 till 21 January 2005, the soil suction value was about 0 near the ground surface (depth < 1.5 m) while it decreases from 20 kPa to 10 kPa at 2.5 m depth. Further failures occurred during the next days as shown in Fig. 8, particularly on 11 February when a rain event induced a nearly complete loss of matric suction at 2.5 m.

4 GUIDANCE FOR CONTRACTORS

The final objective of the research is the elaboration of guidelines for contractors in order to improve the current geotechnical design of slopes. Basic recommendations on the value of the apparent cohesion as a function of the nature and the state of the soil as well as the period of the year should be a key parameter in this context. However, because of the great variabil-

Figure 8. Illustrations of the experimental trench: June 2004 – Jan 2005 – Feb 2005.

ity of matric suction and its corresponding influence on the shear strength, great attention has to be paid in such recommendations. It is the authors' opinion that, depending on the implication of the contractor, different safety levels should be taken into consideration. That point of view is in fully accordance with the philosophy adopted by the Eurocodes. For instance, the three following broad categories could be considered:

a) the contractor does not carry out any measurements to characterise the matric suction – high safety margin on the apparent cohesion suction must be adopted;
b) the contractor executes measurements of the water content and simultaneously conducts laboratory tests for determining the retention curve - medium safety margin on the apparent cohesion can be adopted;
c) the contractor ensures a continuous monitoring of the matric suction and determines the shear strength of the soil – low safety margin on the apparent cohesion can be adopted.

5 CONCLUSIONS

In Belgium, a great share of slopes is executed in unsaturated soils. Experience reveals that in most cases conventional design methods do not allow to prove the stability or instability of such real slopes. A presumable reason is the effect of soil suction on the shear strength of unsaturated soils completely neglected by the conventional methods.

A research project is actually going on in Belgium in order to investigate the behaviour of a slope in unsaturated soils. If the project aims to give insights about the beneficial effect brought by the soil suction on the soil strength within the framework of slope stability, its final objective is the elaboration of safety guidelines for contractors.

This paper describes the strategy adopted within the framework of this project. It explains that in situ measurements performed since 3 years have been combined with laboratory tests, and a full-scale trench has been excavated. In situ measurements point out the important seasonal variation of soil suction. The full-scale experiment proved that trench stability is related to the soil suction. The experimental trench remained indeed stable during periods with the soil exhibiting high soil suctions, while it failed once the soil suctions became minimal in the winter. All these findings emphasize the importance to adopt a great caution with the elaboration of guidelines for taking into account the soil suction in slope stability. Guidelines should consider the implication of the contractors in the evaluation and the monitoring of the soil suction.

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