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# Capillarity, matrix potential and water permeability in unsaturated soils

## Capillarité, potentiel matricielle et perméabilité de sols non saturé

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**ABSTRACT:** This paper deals with the influence of the capillary suction onto the results of in situ tests with a standpipe to determine the coefficient of saturated permeability.

Aim of the investigation is to specify with these in situ tests a Darcy's k-value related to saturated conditions and comparable to the tests in a triaxial permeability cell in the laboratory. The principle of these tests is to let water with a certain amount of pressure inflow from a defined area at the surface into the subsoil.

Until now these tests were interpreted only on the base of the theory of potential flow. The influence of capillarity was assumed but hitherto neglected. The presented investigations demonstrate that the influence of the capillary onto the results of the in situ tests to determine the coefficient of saturated permeability especially in the first stage of the test cannot be neglected.

**RÉSUMÉ:** Cet article présente l'influence de la succion capillaire sur les résultats d'un essai in situ avec tube montant pour déterminer le coefficient de perméabilité en état saturé.

Le but de ces examens est d'évaluer un coefficient de perméabilité de Darcy en état de saturation qui est comparable à celui des tests en cellule triaxiale conduit en laboratoire. Le principe de ces examens est de laisser infiltrer de l'eau avec une certaine pression d'une surface définie dans le sol.

Jusqu'à ce jour ces examens sont seulement interprétés sur base de la théorie de l'écoulement à potentiel. La capillarité n'a pas été prise en compte. Les examens conduit démontrent l'influence de la capillarité sur les résultats des tests in situ pour déterminer le coefficient de perméabilité en état saturé. Une influence qui est importante surtout dans le premier stage de l'examen.

## 1 INTRODUCTION

At the Geotechnical Laboratory of the Institute for Soil Mechanics and Foundation Engineering of the Graz University of Technology research work is carried out for determination of the permeability of shallow layers by in situ tests with a standpipe from the surface of the halfspace. These tests are needed for general subsoil investigations in situ and the testing of compacted clay liners during the construction of waste disposal sites. Their advantage is that the testing is non-destructive.

The aim of the investigation is to specify a Darcy's k-value related to saturated conditions and to compare it to the tests in a triaxial permeability cell in the laboratory. For the determination of the k-value in the permeability cells in the lab a undisturbed soil sample of category A is needed which can be obtained by open tube samplers or piston samplers or rotary core samples (ENV 1997-3, 1999).

In the case of soils containing coarse grains it is not possible to obtain undisturbed samples for permeability testing. Therefore it is necessary to determine the permeability of the subsoil by such an in situ test under conditions of vertical inflow into the partially saturated soil from the surface of the halfspace (Horn 1986).

To get the coefficient of permeability from these tests a theoretical model is needed. Until now these tests were interpreted only on the basis of the theory of potential flow. The influence of capillarity was assumed but hitherto neglected.

## 2 THE PHENOMENON OF CAPILLARITY

The surface-tension  $T_s$  [ $\text{kN m}^{-1}$ ] of water with its specific weight  $\gamma_w$  [ $\text{kN m}^{-3}$ ] causes its rise in small tubes with the diameter  $d$  [m] up to the capillary elevation  $h_k$  [m] (Figure 1).

$$h_k = \frac{4 \cdot T_s}{d \cdot \gamma_w} \cdot \cos \alpha \quad [\text{m}] \quad (1)$$

$\alpha$  ..... capillary wetting angle (for glass it is  $\alpha \sim 0$ )

In the capillary tube the water has a tension  $Z$ , which increases linearly from the free ground water table to the capillary meniscus up to  $\gamma_w \cdot h_k$  [ $\text{kN m}^{-2}$ ].

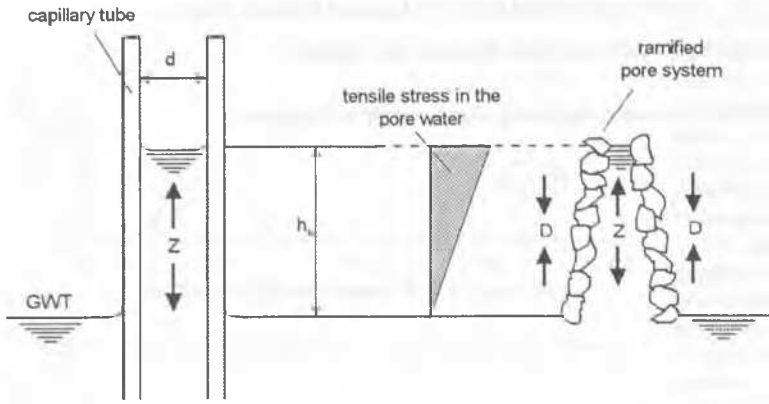
The water column being subjected to this tension causes additional compressive stress  $D$  in the grain skeleton, defined as capillary pressure (Figure 1). This additional capillary pressure increases the adhesion between the grains.

To investigate the capillary rise and its development over time, a laboratory testing-stand was constructed to give the opportunity to observe visually the progress of the capillary rise over the time (Figure 2). Dry sand was filled in standing tubes of about 2 m height with a 4,5 cm inner diameter, consisting of separate perspex-segments, each 100 mm high.

This laboratory testing-stand was put into a water basin with the water table rising up to the height of the lower edge of the first perspex-segment.

Figure 3 shows the results of the measurements of the capillary rise in four loosely packed uniform sand-columns.

In contrast to the conventional technical understanding capillarity only as the appearance of the capillary rise it includes however all additional effects caused by the property of the surface tension of the water. In this context capillarity is an all around and universal acting force, which amongst others vertical upwards counteracts the force of the gravity and on the other hand acting downwards is supported by the gravity. For that reason it is better to speak of a capillary potential or matrix potential  $\psi$ . This definition includes all influences on the water caused by the soil matrix.



$Z$  ..... tensile force in the water  
 $D$  ..... capillary compressive force in the grain skeleton surrounding the water filled void-tubes

Figure 1. Capillary elevation  $h_c$  and its consequences

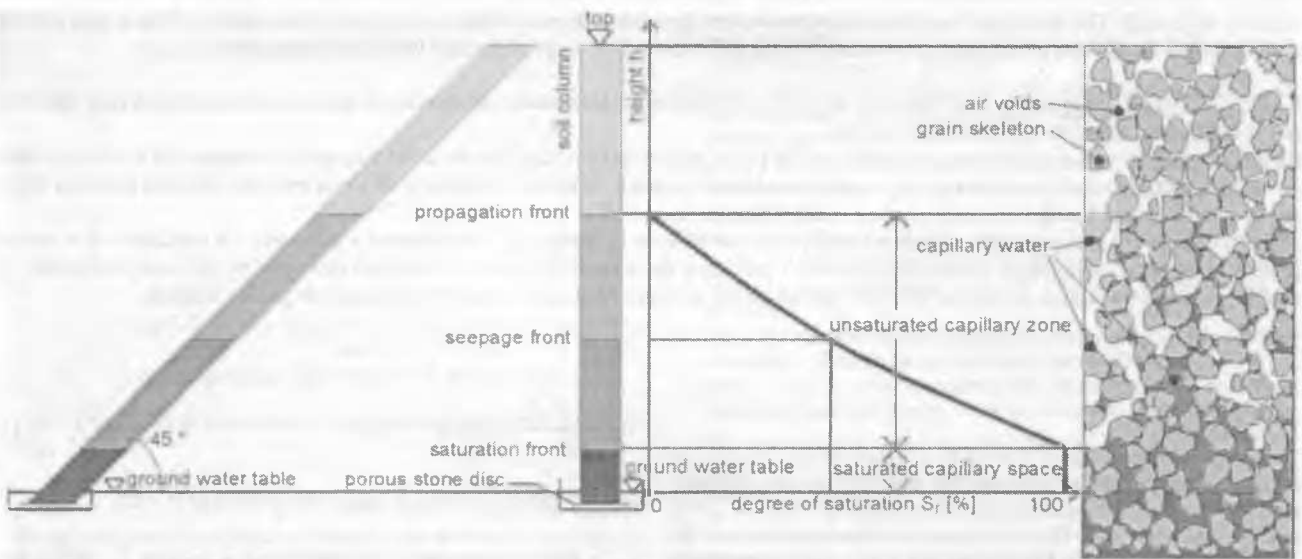


Figure 2. Investigations on soil columns – definitions

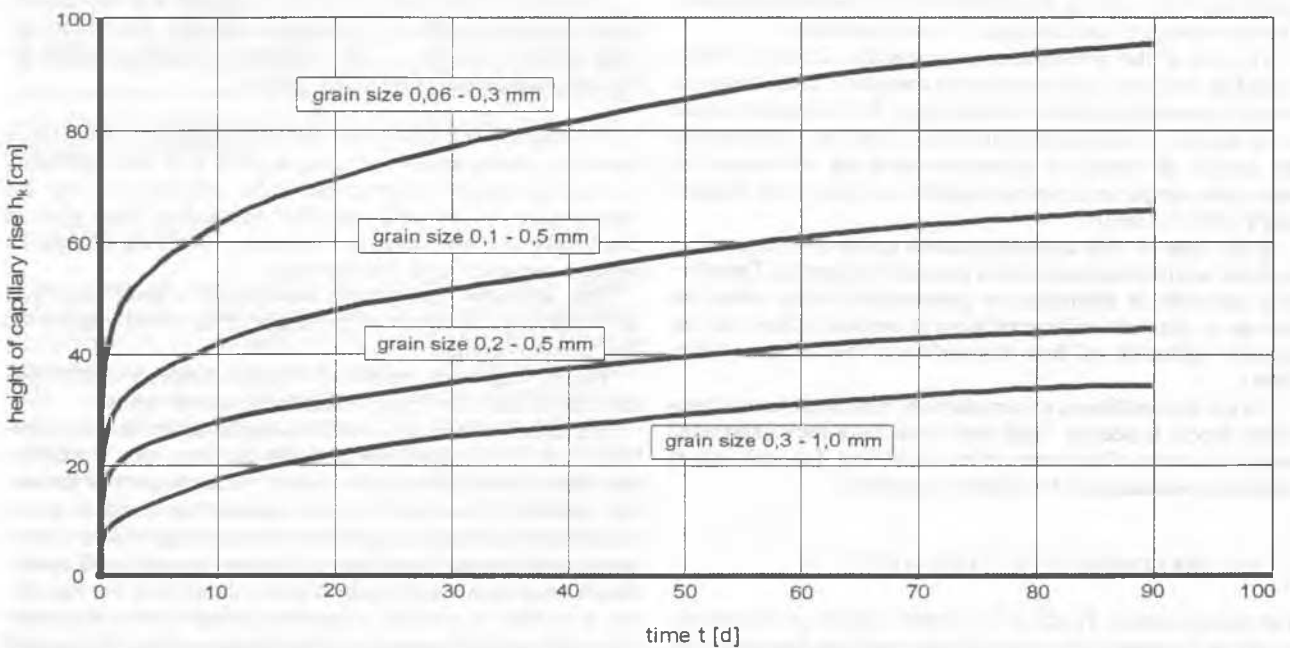


Figure 3. Height of capillary rise in four loosely packed uniform sand-columns (Henoegl, 2000)

The matrix potential is equivalent to an energy and is able to cause external physical processes, e.g. the lesser water in a soil the stronger are the bindings of this water to the soil skeleton implied by the forces of the matrix.

There is a definition of this matrix suction stress in the German standard DIN 19683-5: it is the stress that adheres the water to the soil skeleton. It is measured in millibar and already Schofield has in 1935 created the name „potentia Force“ or pF-value. The water content in this context is specified in volumetric percentage.

This means that with decreasing water content the matrix potential and the suction tension as well as the negative pore water pressure is increasing. When it comes to a water ingress from the surface the suction of the soil matrix superposes the permeability of the soil skeleton and therefore accelerates the flow of the water downwards into the soil.

### 3 VERTICAL INFLOW INTO PARTIALLY SATURATED SOILS FROM THE SURFACE OF THE HALFSPACE

#### 3.1 Theoretical approach

In the following explanations it is assumed that the soil representing the halfspace consists of three phases: the grains or solid components, water and air in the voids.

In the traditional soil mechanics the velocity of the water flowing in the soil is defined by Darcy's law (Figure 4a). In reality the water is moving only in the voids. Therefore it is impossible to observe  $v_{Darcy}$  in an experiment. Instead of that one can observe a inflow situation only determined by the mean velocity

$\bar{v}_a$  of water flowing through voids, described as follows (Figure 4b):

$$\bar{v}_a = \frac{v_{Darcy}}{n} \quad (2)$$

$v_{Darcy}$  Velocity of the flow of water in soil after Darcy [m/s]  
 $n$  Voids content [-]

Here it is neglected that over the cross section of the voids the water flows with an unequal but symmetrical distribution of velocity (Figure 4c).

Figure 5 shows a schematic sketch of the vertical inflow into the halfspace.

It is assumed that the inflow into the soil forms a saturation front parallel to the surface. In idealisation that implies that the diameters of the void channels of the soil are constant. This imagines that many very small flow-tubes of the same diameter stand next to one another. The saturation front is the borderline between fully saturated and partially saturated soil.

The vertical advance of the saturation front downwards during the inflow of the water can be formulated mathematically as a function of time as follows (Schneider 1988):

$$\bar{v}_a = \frac{dz}{dt} \quad (3)$$

With equation (2) it results in

$$\frac{dz}{dt} = \frac{k \cdot i}{n} \quad (4)$$

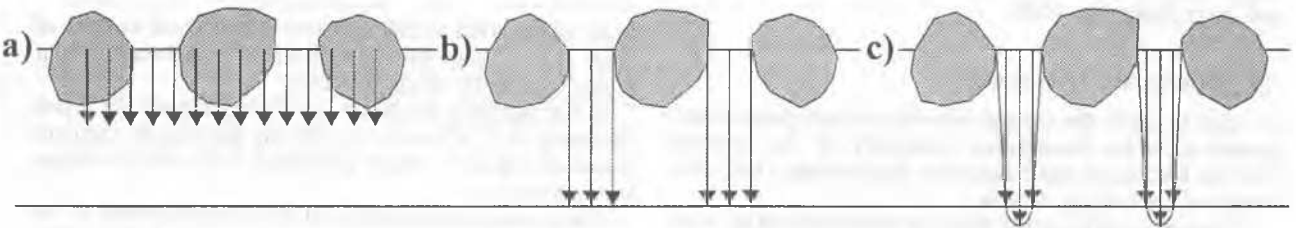


Figure 4. Mean distribution of velocity of the flow of water in soil after Darcy (a), mean velocity (b) and real distribution of velocity of water flowing through voids (c) (after Kolymbas 1998)

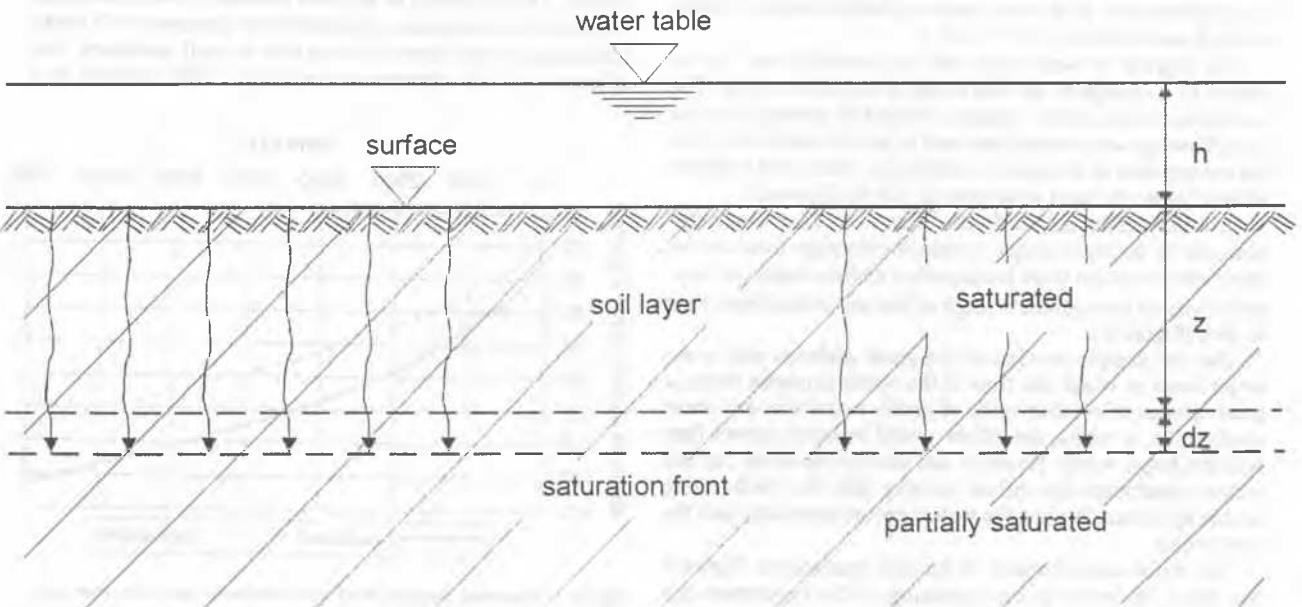


Figure 5. Schematic sketch of the vertical inflow from the surface into the halfspace (Schneider 1988)

- k Darcy's coefficient of water permeability in saturated soil [m/s]
- i hydraulic gradient

Figure 5 shows that the hydraulic gradient can be calculated by

$$i = \frac{h+z}{z} \quad (5)$$

Put into equation (4) gives

$$-v_a = \frac{k}{n} \cdot \left( \frac{h+z}{z} \right) \quad (6)$$

$$\int dt = \frac{n}{k} \cdot \int \frac{z}{h+z} dz \quad (7)$$

$$t = \frac{n}{k} \cdot [z - h \cdot \ln(h+z)] + C \quad (8)$$

Considering the condition  $z_{(t=0)} = 0$ , C can be calculated and therefore the result is

$$t = \frac{n}{k} \cdot \left[ z - h \cdot \ln \left( \frac{h+z}{h} \right) \right] \quad [s] \quad (9)$$

With this equation one is able to determine the time which the saturation front needs to proceed the distance z into the soil-layer (Schneider 1988).

### 3.2 Experimental Investigations

In order to verify this concept laboratory investigations were carried out at the Geotechnical Laboratory of the Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology, Austria.

However it can be stated that it is not possible to get a totally saturated soil only from this inflow. Nevertheless there will be air-voids which will be entrapped by the water within the soil skeleton during this inflow and therefore cannot escape furthermore. In this way one can obtain a degree of saturation  $S_r$  only between  $0,97 < S_r < 1$ .

The ingress of water into the soil normally can be observed by a change of the soil colour from light to dark. The borderline of this colour change, defined as seepage front in the following, was investigated and is not the saturation front but corresponds to a degree of saturation, which lies a certain amount under the total saturation of 100 % (Figure 2).

In reality there are voids of different sizes and seepage channels of different length so that the seepage front can be never the saturation front but signals a certain degree of saturation visible through the change of the soil colour from light to dark (Figure 6).

The soil sample consists of the grain skeleton with some larger voids in which the flow of the water is maybe faster, a great amount of smaller voids of nearly equal size and some small voids, in which the inflow would be much slower than into the larger voids. However the suction forces of the soil matrix superposes the inflow velocity into the voids acting contrarily by accelerating the water ingress especially into the small voids.

The initial water content of the soil specimen in Figure 6 was zero. Therefore at the beginning of the experiment the soil specimen was completely dry. The change of the colour of the soil from light to dark during the inflow of the water

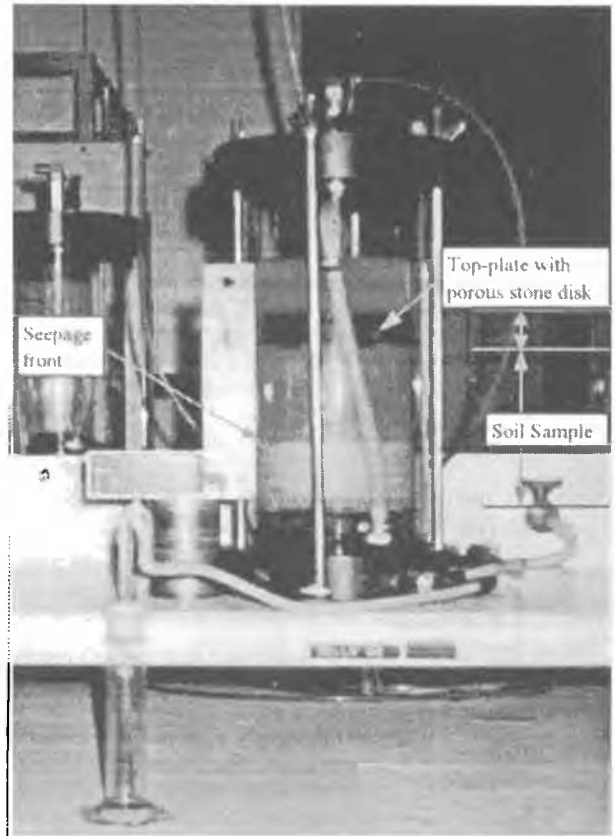


Figure 6. Borderline of change of colour of the soil from light to dark, defined as seepage front (in a triaxial permeability cell).

could be observed visually up to a initial water content of about 15 %. Beyond that the observation of the seepage front is only possible by means of tracers.

In the following the results of the experiments for a soil consisting of 17,8 % clay, 41,4 % silt und 40,8 % sand are presented (Figure 7), which are typical of all other investigations made so far.

These results demonstrate that the vertical advance of the seepage front downwards into the soil during the inflow of the water happens much faster than the theoretical calculated saturation front after equation (9). This is due to the capillary suction. The difference in advance between observed seepage front and the calculated saturation front increases with depth continuously until about 120 mm into the soil specimen. The difference of this advance makes about 2600 seconds at a

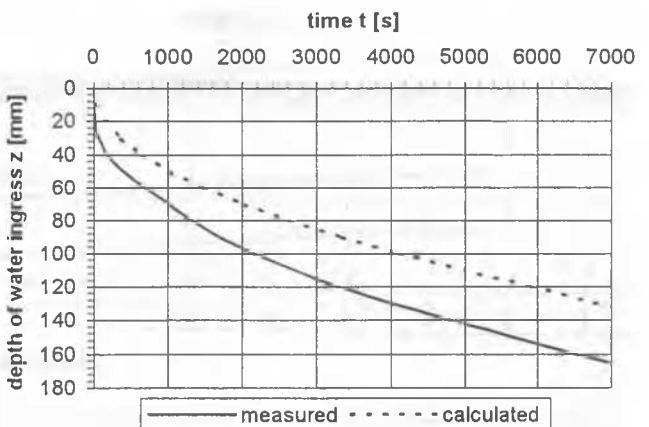


Figure 7. Measured seepage front and calculated saturation front plotted over the depth of inflow of the water from the surface against the time

depth of about 120 mm (Figure 7). During the inflow procedure the water flowing into the soil from the surface also saturates the specimen. After about 120 mm of inflow distance the difference between the two curves in Figure 7 remains constant. The influence of the capillary tension on the inflow velocity decreases with increasing depth.

#### 4 CONCLUSIONS

The investigations presented here demonstrate that the influence of the capillary on the results of in situ tests to determine the coefficient of saturated permeability especially in the first stage of the test cannot be neglected.

Therefore a much more sophisticated and comprehensive theoretical model is necessary which includes the theory of multi phase flow in partially saturated soils.

First steps have been done with the research-work presented here. The implementation of a more comprehensive evaluation model of these tests is in progress.

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