Changes of thermophysical and hydraulic properties in unsaturated soils caused by heat transfer

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ABSTRACT

Due to varying thermal conditions in the ground, the local water content changes and consequently hydraulic and thermal properties change as well. It is important to make reliable forecasts of the thermal and hydraulic properties of the partially saturated soils for designing structures and constructions engaging thermal energy in the shallow ground. Resilient data of the hydraulic and thermal properties as a function of the water content is required for the simulation of changes in working conditions.

Two experiments allowing for simultaneous determination of several hydraulic and thermal parameters at variable water contents of a sample were accordingly developed. The retention characteristics of a soil sample are determined in an evaporation test, while the unsaturated hydraulic conductivity and thermal conductivity as a function of the water content is measured simultaneously. By this experiment, primarily fine clastic, undisturbed soil samples are characterized during dewatering.

Investigation of sandy soils is performed in a columnar experiment using frequency domain reflectometry sensors for the determination of the water content, tensiometers and thermal conductivity sensors at different levels of the sample. The soil samples in the column can be irrigated from the top and the bottom.

These tests are currently a variety of experiments carried out to generate a statistically representative number of measurements on different soil types. To implement this data into FEM modelling, it is necessary to describe them by mathematical expressions representing the interdependence of water retention, unsaturated hydraulic and thermal conductivity. Actual various mathematical models are developed on the basis of this data and validated against the growing data set.

1. INTRODUCTION

In the course of the growing decentralized utilization of geothermal energy, many shallow geothermal installations will be constructed, in particular in footings and paved surfaces. In moderate latitudes, the extreme conditions of slack water or complete drying of soils are encountered very rarely, however those cases are currently considered by engineers as a priority for the planning and dimensioning of geothermal buildings and facilities. The uncertainties that arise in planning and dimensioning such installations while regarding the soil as a pure two-component-system often lead to over or under sizing, misjudgment in economic analysis or in the worst case to technical failure. Usually the water content and the thermal conductivities, too, are in a wide range between these two pure component considerations.

The changes of the physical properties in such three-component systems are much more difficult to predict than in pure two-component systems, such as soil-water or soil-air because the additional third substance interacts with the two other ones.

As water has a much higher thermal conductivity with respect to air, dewatering leads to retreating water menisci between soil grains. This results in a reduction of the thermal conductive cross-section. At the same time, the increasing air proportion in the pore space decreases the hydraulically conductive cross section. In addition to a decrease in the transported heat due to convective water flow, this leads to an increased transport of water vapour.

In contrast to the heat capacity of unconsolidated rocks, which can be calculated from the heat capacity of their single components and volume fractions, thermal conductivity is not a linear function of the water content. Standards and regulations represent only approximate values for thermal conductivity dissimilar major soil types in saturated and oven-dry conditions.

The thermal influence of geothermal installations and structures in these soils leads to changes in the water content and consequently altered hydraulic and thermal properties. In dimensioning shallow geothermal installations, reliable predictions of the geothermal properties of partially saturated soils are of critical importance. To provide a technically and economically efficient heat input or heat withdrawal (e. g. through a seasonal heat storage installation), modelling of hydraulic and thermal properties of the soil requires the input of reliable thermal and hydraulic parameters.

Two experiments were developed respectively, which allow for simultaneous determination of several hydraulic and thermal parameters at variable water contents of a sample. The soil water retention characteristics of a soil sample are determined in an evaporation test, while the unsaturated hydraulic conductivity and thermal conductivity as a function of the water content are simultaneously measured. Thermal conductivity is determined using a full space line source embedded in the sample. From the data, the interrelation between thermal conductivity and water content as well as the interrelation between thermal conductivity and the water retention characteristics are derived. With this experiment it is possible to characterize undisturbed soil samples during dewatering in a wide range of capillary tensions.

The investigation of sandy soils is performed in a columnar experiment, which is equipped with frequency domain reflectometry sensors for the determination of the water content, tensiometers and thermal conductivity sensors at different levels of the sample. The soil samples in the column can be irrigated from the top and the bottom.

Suitable adaptation functions convert the obtained data into mathematical expressions representing the interdependence of water retention, unsaturated hydraulic conductivity and thermal conductivity. They are implemented in FEM modelling of the thermal and hydraulic processes in the vicinity of underground cables and geothermal installations.

2. MATERIALS AND METHODS

An evaporation test and a columnar drainage experiment were developed with continuous measuring of water content, pore pressure, and thermal conductivity at different levels of the column. These measurement techniques allow for simultaneous measuring of the hydraulic properties as well as unsaturated thermal conductivity because they are equipped with a full-space line (heat) source.

Currently many different unconsolidated rocks are examined in these experiments in order to provide the respective parameters for the development of new thermal conductivity/ capillary tension respectively saturation functions analogue to the existing capillary tension/ water content functions.

2.1 Evaporation test

An evaporation test according to Schindler (1980), a simplification of the approach by Wind (1968) allows for simultaneous detection of the water retention characteristics and the unsaturated hydraulic conductivity of a soil sample in a very wide range of relevant capillary tension measurements. By adding a full-space line source according to Blackwell (1954), thermal conductivity can be determined simultaneously during this test. This experimental setup allows for determination of relationships between thermal conductivity and capillary tension or thermal conductivity and water content in conditions of desorption. By using the method according to Schindler (2010), it is possible to determine these parameters from saturation up to capillary tensions far above 4000 hPa (usually up to 6000 hPa).

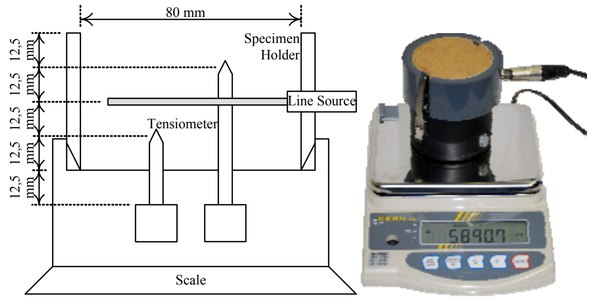

Figure 1: Left: Sectional view across the Evaporation test device type HYPROP®, according to Schindler (2010). Right: Soil measurement with the experimental setup used.

For measuring purposes, the core sample initially has to be fully saturated with water and closed on the bottom. Then the whole measuring device has to be placed on a balance. The surface of the cylindrical sample is open towards the atmosphere so the water can evaporate freely. During evaporation, the weight of the entire assembly and the corresponding capillary tension are recorded over time. The absolute water content of each single measuring process is calculated at the end of a test by determining the residual water content and the weight loss during the measuring process. From the measured capillary tension and the hydraulic gradient, the mean matrix potential and unsaturated hydraulic conductivity for the plane between the two tensiometers are calculated. From the mass differences of the water, the flow of water is calculated. From these values, thermal conductivity, capillary tension as well as unsaturated hydraulic conductivity in dependence of the water content are derived.

With increasing dehydration of the sample by evaporation, the capillary tension increases progressively (figure 2). By using special Tensiometers it is possible, to measure the capillary tension to a point well above the boiling point of free water. With increasing capillary tension cavitation occurs. The measured tension falls down abruptly on to the vapor pressure of water (about 1000 hPa). From this point on, the measured values are no longer directly representative of the surrounding soil water pressure.

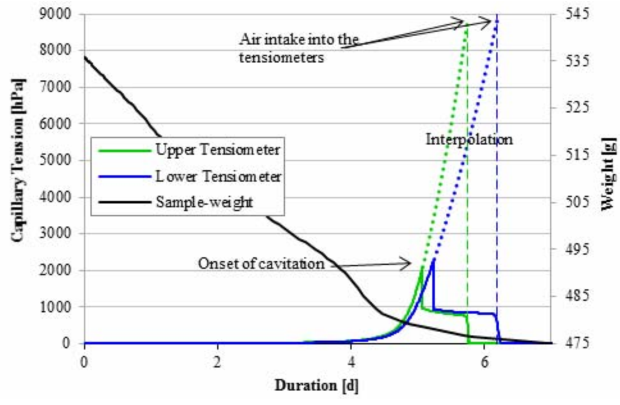

Figure 2: Tension and weight of a sand sample during an evaporation test.

If the capillary tension of the sample increases up to the known air entry point of the tensiometer ceramic, the measured soil water pressure drops down to zero. The water content at this point regarded as an additional point for the air entry pressure of the ceramic cup of the Tensiometer. Between the onset of cavitation and the point of air intake, capillary tensions are obtained by extrapolation (according to Schindler, 2010).

With increasing evaporation of water from the sample, thermal conductivity decreases, while the tension at the location of thermal conductivity measurement rises increasingly.

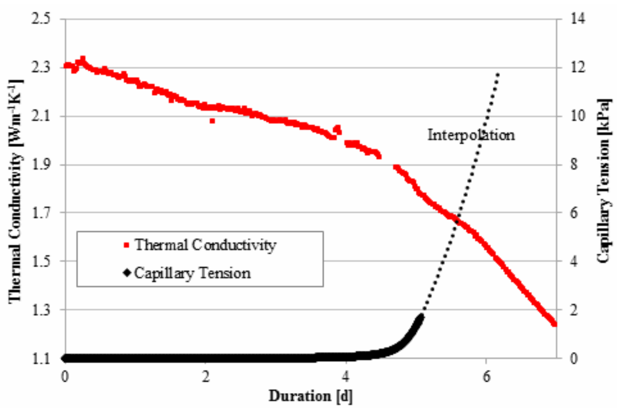

Figure 3: Thermal conductivity and capillary tension of a sand sample during an evaporation test.

2.2 Columnar test

In a columnar test apparatus (Fig. 4) with a height of 100 cm and an internal diameter of 22 cm, the soil sample will be placed on a 79 cm high sand bed which includes measurement technology and is saturated with water. The water level is gradually draining step by step down to a depth of 89 cm below the measuring level. After each step, the respective equilibrium conditions will be reached, the capillary tension and the associated volumetric water content by means of sensor technology and frequency domain-reflectometry FDR laboratory-tensiometers can be measured. Thermal conductivity is measured by various line sources (Figure 5)

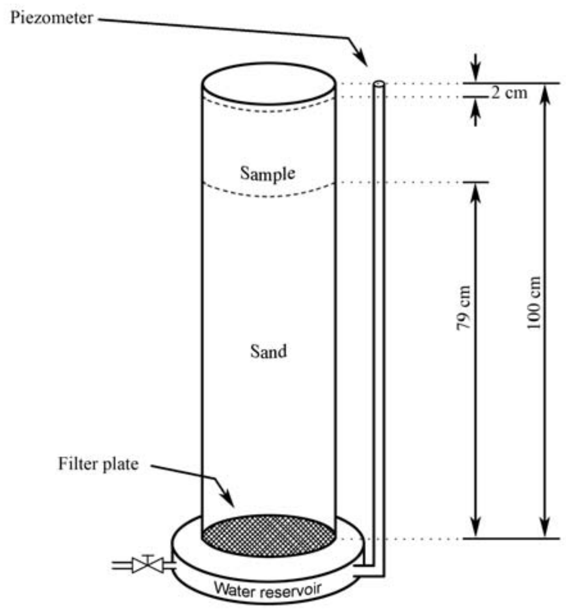

Figure 4: Sketch of the used column-experimental equipment. To a height of 79 cm, a sand bed is placed under the 20 cm thick sample. Inside the column the measurement technique is installed in planes ("measuring planes").

This experiment allows for investigation of disturbed soil samples under realistic irrigation and drainage conditions. Measurement results show that a capillary tension / saturation curve will develop for drainage and irrigation. Capillary tension measurements can be conducted from 0 to 90 hPA. Different soils and probes may be installed at different layers.

At the beginning of the experiment, the soil is saturated. Then the water is drained in sections. After reaching the respective equilibrium state, the volumetric water content is measured by FDR sensors and the associated capillary tension by means of tensiometers. The measurement of thermal conductivity is carried out the same way as in the evaporation experiment by using probes according to the line source theory.

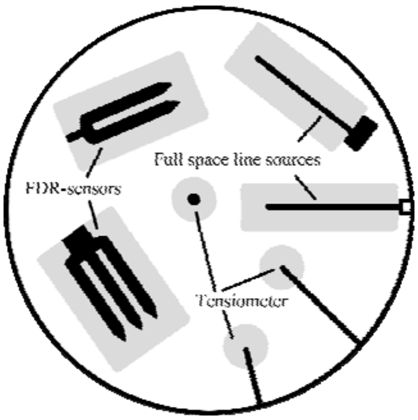

Figure 5: Typical arrangement of probes at one level within the column. Line sources devices to measure thermal conductivity, tensiometers to measure capillary tension and FDR-sensors for measuring water saturation. The corresponding measuring range is coloured grey.

Measurement of soil moisture using FDR sensors out indirectly by measuring the electrical capacity of a soil. To achieve accuracies of 2% of the measured volumetric water content, soil-specific calibrations to Starr & Paltineanu (2002) are performed.

Due to the large differences in the dielectric constants of water, air and soil components (~ 80, ~ 1 and ~ 6) from the measured capacitance, the quantitative composition of the soil - air - water system is derived.

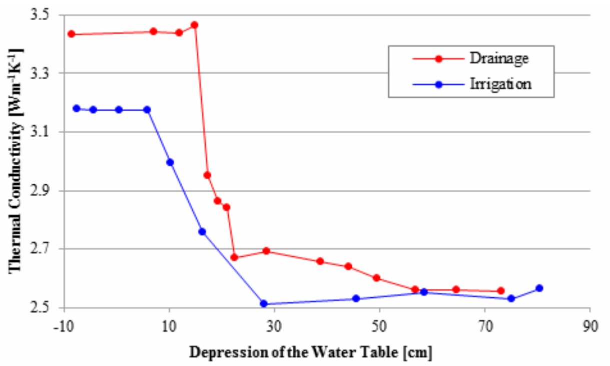

Figure 6: Mean values of the measured thermal conductivity to equilibrium conditions. The measured depression of the water table corresponds to the capillary tension.

In the example of non-uniform sand illustrated in Figure 6, the thermal conductivity decreases significantly with a reduction of the capillary tension of 10 cm to about 30 cm away to its first approaching of a constant value. Even in the low range of the applied capillary tension, a clear hysteresis effect of thermal conductivity is visible.

3. RESULTS AND OUTLOOK

To simulate thermally induced water movement and the related interactions to variable thermal characteristics of a soil into models, it is necessary to have precise mathematical characterization of these properties. A common diagram of measurement results of the thermal conductivity of different sand samples over their saturation clearly illustrates the soil-specific differences. In VDI 4640 Part 1, the thermal conductivity of dry sand is indicated with a value of 0.3 to 0.8 $Wm^{-1}K^{-1}$, the one of saturated sand with 1.7 to 5 $Wm^{-1}K^{-1}$.

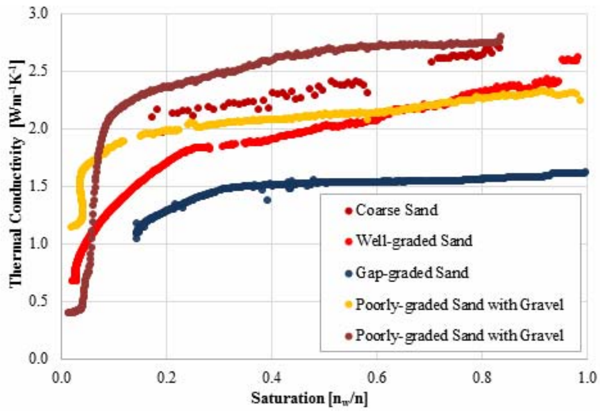

Figure 7: Laboratory investigation of the thermal conductivity of sand samples as a function of saturation.

Sands featuring one pre-dominant particle size are described as poorly-graded, whereas well-graded sands are homogeneous mixtures containing diverse particle sizes. Intermittently-graded sands feature several pre-dominant particle sizes.

Figure 7 shows that based on a predominant grain size only a rough estimation of a possible thermal conductivity can be taken at a certain water content.

The course of the thermal conductivity between the saturated and the dry condition largely depends on the properties of the pore space, mainly its tortuosity, size and shape. These parameters are controlled by the matrix, which is mainly characterized by grain size, shape and surface characteristics as well as the degree of consolidation.

The distribution of the soil water in defined pore spaces at different water contents is represented by the capillary tension/ saturation relationship, a correlation between the thermal conductivity to these parameters will be useful.

In the illustration of the measured values in Figure 7 above, the soil water tension (Figure 8), the differences of the thermal-hydraulic characteristics are more apparent. In poorly-graded sand (Figure 8, brown) large pores dominate the heat conduction, which can be drained at low capillary tensions. According to DIN 18196 specified as the same (Figure 8 yellow), due to its wide staged showing pore size distribution more uniform decrease of thermal conductivity with the tension.

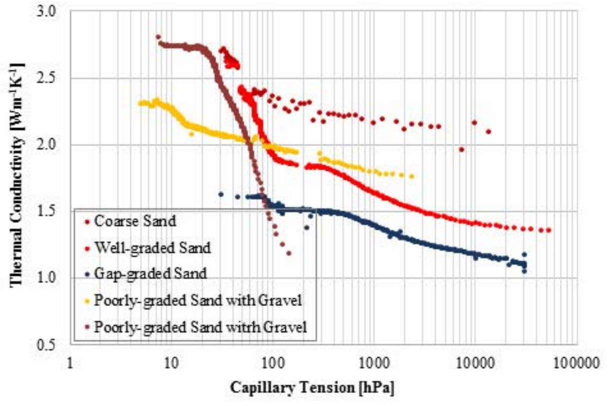

Figure 8: Thermal conductivity of sand samples as a function of capillary tension.

Currently many unconsolidated rocks are examined to investigate the analogies between the course of the capillary tension/ thermal conductivity function and the corresponding capillary tension/ water content functions.

The aim of further studies is to create a statistically representative database of various soil types in order to derive suitable models for the mathematical description of the thermal conductivity/ capillary tension, respectively thermal conductivity / water content relationships.

All results will be validated against high resolution field experiments.

Currently, the transferability of various conventional hydraulic models, features to customize the capillary tension/ saturation relation for example regarding to van Genuchten (1980) (after Sass and Stegner, 2012), are tested for the mathematical expression of the capillary tension/ thermal conductivity relationship.

$$\lambda(\psi) = \lambda_r + \frac{(\lambda_s - \lambda_r)}{\left[1 + (\alpha_\lambda \cdot |\psi|)^{n_\lambda}\right]^{m_\lambda}} \quad (1)$$

With:

$$m_\lambda = 1 - n_\lambda^{-1} \quad (2)$$

Where is:

λ_r	$[Wm^{-1}K^{-1}]$	Drained thermal conductivity
λ_s	$[Wm^{-1}K^{-1}]$	Saturated thermal conductivity
α_λ	$[m^{-1}]$	Scaling parameter
n_λ	[-]	Inclination parameter

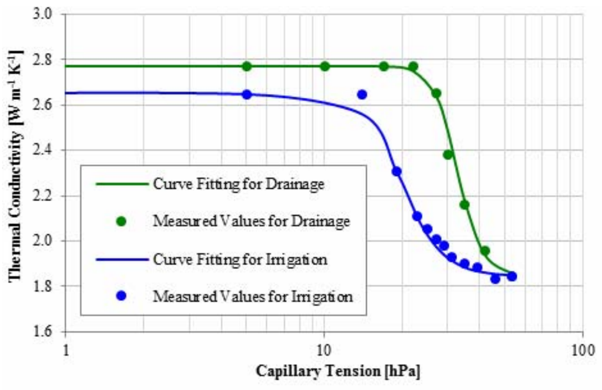

Figure 9: Curve fitting to the observed values of thermal conductivity in dependence of capillary tension of poorly sorted medium-grained sand.

This function was tested on different datasets. It allows for a description of sigmoidal curves in an adequate way. For a description of frequently observed thermal conductivity/ capillary tension trends with several turning points, appropriate adaptation functions will be required.

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