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LATEST DEVELOPMENTS IN SOIL PHYSICAL ANALYSIS: THE DYNAMIC COMPUTER TOMOGRAPHY AND RADON GAS DIFFUSION

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Abstract

In the paper principles, procedures and the applications of two analytical methods for diffusive gas permeability of a porous media have been presented: »Dynamic Computer Tomography (DTC)«, and the »Radon method (R)«. With DTC method processing the X-ray images of a soil core in a clinical tomograph the visualisation and measurments of the dynamic gas and water transport in a soil have became possible. Utilising Radon (Rn) as a radioactive tracer the assesment of a diffusive gas flow with soils in situ as well as in laboratory measurments can be quantified. Both metod have been succesfully applied in impact studies of mechanical load on forest soil after terrain traffic during logging operations.

Key words: soil, diffusive permeability, dinamic computer tomography, radon, forestry

NOVEJŠI POSTOPKI FIZIKALNE ANALIZE TAL: DINAMIČNA RAČUNALNIŠKA TOMOGRAFIJA IN PLINSKA DIFUZIJA Z RADONOM

Izvleček

V prispevku so predstavljeni principi, postopki in primeri uporabe dveh metod za določevanje propustnosti poroznih snovi za pline in tekočine: »Dinamične računalniške tomografije (DRT)« in »Radonske metode (R)«. Pri uporabi DRT metode, s pomočjo računalniške obdelave rentgenskih slik vzorca tal v medicinskem tomografu, vizualiziramo in merimo transport plinov in tekočin v tleh. Pri uporabi metode R pa uporabljamo radioaktivni izotop radon (Rn) kot sledilec pri oceni toka difundiranja plinov v tleh. R metoda je primerna za meritve »in situ«, kot tudi za laboratorijske meritve na vzorcih tal v neporušenem stanju. Obe metodi sta bili uspešno testirani pri proučevanju vplivov mehaničnega obremenjevanja gozdnih tal zaradi spravila lesa po brezpotju.

Ključne besede: *tla, difuzivna prevodnost, dinamična računalniška tomografija, radon, gozdarstvo*

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CONTENTS / *KAZALO*

1 INTRODUCTION

Gas exchange between soil and atmosphere is one of the key parameters for sustainable tree growth. However, the analytical possibilities are somewhat restricted. Most often the gas conductivity of soil samples is expressed in ki-values (intrinsic air permeability), which rely on a convective basis. Convective gas transport in the field only occurs in the topmost few centimeters of soil. For gas exchange diffusion is of greater importance. It is responsible for a suitable soil gas composition in the rizosphere and deeper zones.

In analysing diffusive gas permeability in laboratory, soil core samples of limited volume (most often 100 cm^3) are required. They are mounted in the so called "one-chamber" or "two-chamber" systems allowing to follow the changes in concentration of the gas component of interest, usually oxygen or nitrogen, in one chamber by means of a gas chromatograph or an ion-sensitive electrode. Although the analytical boundary conditions are known and can be controlled to some extent, this experimental setup neglects the environmental and climatic conditions influencing the sample in its natural setting. One possibilty to overcome this disadvantage is depth related spot sampling of soil gas in the field.

Even if reliable data about gas permeability can be obtained, a soil sample remains a "black box" of which only the input and output data are known. The transport processes within the sample mainly relying on the topology and morphology of the pore system remain obscure. It was, therefore, a challenging task to develop new analytical methods, which on the one hand offer the possibility of combined field and laboratory measurements and on the other hand allow to attribute permeability values to real existing pore space characteristics.

2 THE "DYNAMIC COMPUTER TOMOGRAPHY" (DCT)

In the late sixties Hounsfield and Cormak invented the X-ray computed tomography (CT) for medical purposes. In 1982 the first paper about the application of CT for soil related investigations was published by Petrovic et al.

(1982). Later on several soil scientists used CT in order to describe the soil structure (for example CRESTENA et al. 1986, ANDERSON et al. 1988, HOPMANS et al. 1992) and structural features caused by soil fauna (JOSCHKO et al. 1990). However, these studies were restricted to static structural descriptions solely. Since 1994 we have been working with a clinical CT using a dynamic method. For the first time, it has become possible to visualize and to measure dynamic processes like gas and water transport in soil.

The analytical principle of the CT is the density dependend attenuation of X-rays while passing matter. The higher the density, the more X-rays are absorbed and vice versa. Attenuation coefficients are normalized against water into the so called HOUNSFIELD UNITS (HU). HU (water) becomes 0, while air has HU -1000. Solid particles like for example, stones, are in the range of HU +1000 to +3000. In order to get an image, these HU values are transferred into grey values depicted on a monitor or an exposure. The striking advantage of a CT is that internal structures can be analysed in a non-destructive, location independent manner without any blurring by overlying structural features.

The basic idea of the DCT method is the subtraction of two image matrices from an identical scan position, one with normal soil gas in the pores and the other after the application of a gaseous contrasting media, in our case Xenon (Xe). As Xe has a density which is about 4,5 times higher than that of air, only pores containing a certain proportion of Xe remain visible after subtraction, while areas (image pixels) with unchanged density, like solids, are extinguished. Therefore, gas conducting pores become selectively visible. In case the diffusion velocity through a sample is of interest, several scan positions all over the sample length can be defined and consecutively scanned (Fig. 1).

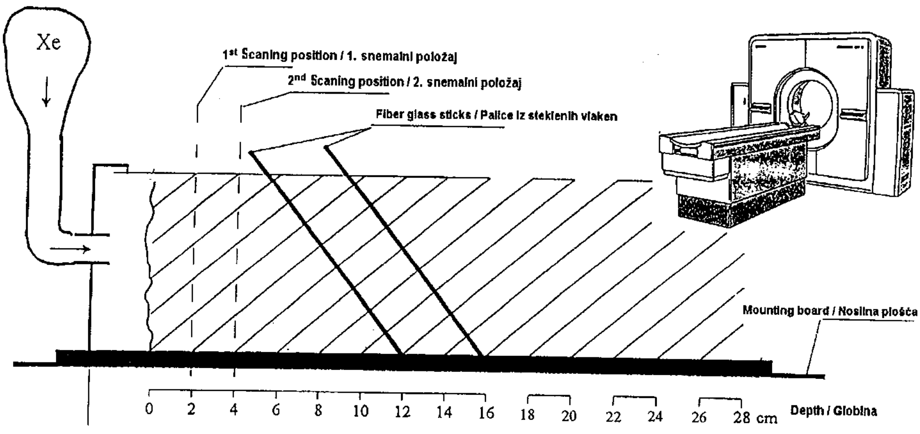

Figure 1: Schematic draft of the mounted soil sample in the CT (inlay). The Xe reservoir is connected to a plastic lid on top of the soil core.The first scanning positions are shown. Fiber glass sticks serve for the control of the relocation accuracy.

Slika 1: Shematski prikaz vzorca tal v CT (vložek). Rezervoar Xe je priključen na plastični pokrov na vrhu vzorca. Prikazane so začetne točke snemanja. Palice iz steklenih vlaken služijo za vzdrževanje točnosti.

For our studies a "SOMATOM PLUS" scanner (SIEMENS company) with an implemented SOMARIS software was used. The resolution (= pixel size) is 0,1 mm^2, which almost covers the range of coarse pores being mainly responsible for the gas exchange, with a slice thickness of 1 mm (= voxel size 0,1 mm^3). The scanning time is 2 seconds. Two program features of SOMARIS software directly support the DCT method. "Subtraction" enables the operator easily to subtract two image matrices. "ROI" (Range of Interest) allows to define an area within the image which is going to be analysed for the differential HU values in the subtraction image. In order to eliminate edge effects due to peeling off or soil disturbances in the immediate contact area to the core from diffusion analysis, an inner cross sectional area of about 50 cm^2 was defined by ROI, thus leaving an outer radial sample volume of about 0,8 cm thick out of measurement (inner diameters of the cores were 9,4 cm).

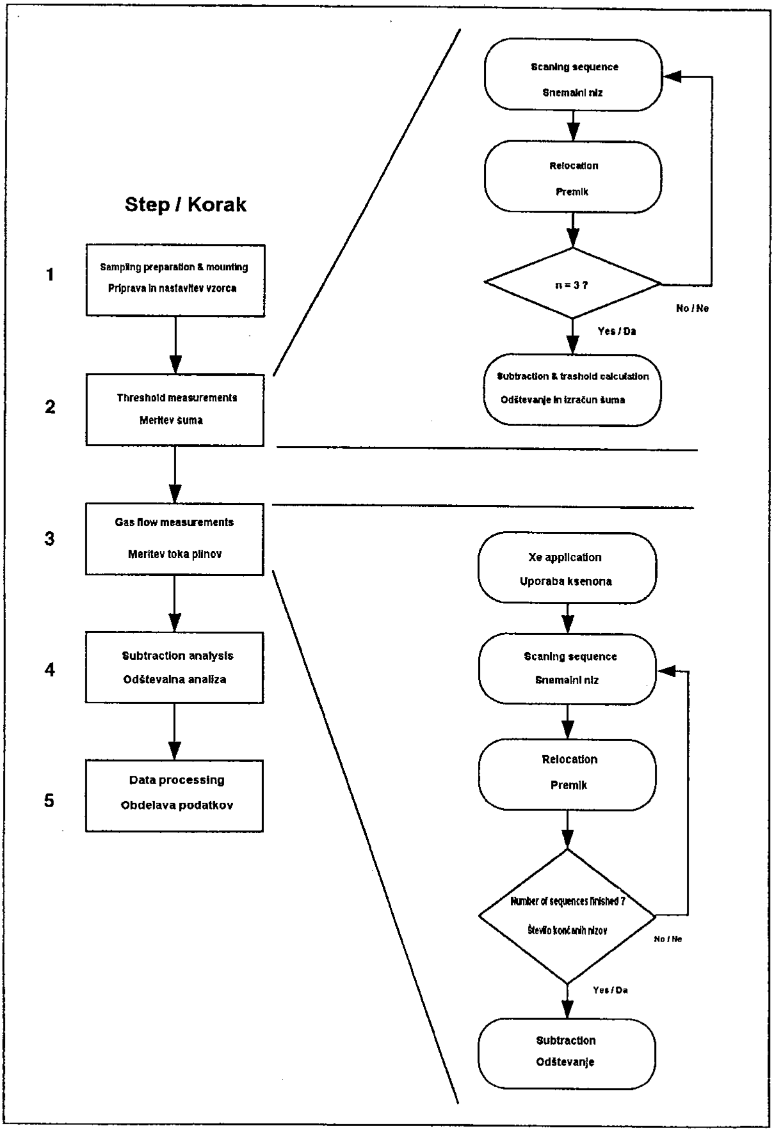

Figure 2: Flow chart of the dynamic CT method (DCT).

Slika 2: Diagram pri dinamični metodi CT (DRT).

The analytical procedure is as follows (Fig. 2):

Step 1 **Preparation**

Sealing of the sample on both sides with plastic caps, of which one carries the inlet for Xe, and tight mounting onto the patient table of the CT apparatus, then, programming of the scanning positions.

Step 2: **"Threshold" measurements**

The quality of the measurements strongly depends on the relocation accuracy of the patient table. As the methodological idea is based on the subtraction of two images from the identical scan position, any local deviation causes differential HU values, which can be attributed to slightly changed soil structure at a different scan position. In order to establish a significant HU signal from Xe, the differential HU value after application of Xe has to exceed a certain threshold, which is defined by the mean differential "background" HU value plus the double standard deviation. Therefore, at least three replications of sequence measurements without Xe have to be performed in order to achieve the "background" HU values for each individual scanning position.

Step 3: **Gas flow measurements**

Following the "background" measurements Xe from a gas reservoir is applied. The sequence measurements are repeated in constant time intervals. It was typical of our studies that we started the first sequence 2 minutes after Xe application. The following sequences were carried out at 4 minute intervals. After 1 hour we stopped the experiment.

Step 4 and 5: Subtraction analysis and data processing

Upon stopping the experiment the image subtraction follows. The differential HU values are noted and processed to cumulated HU profiles for each scanning position.

Modern scanner techniques offer additional potential for soil scientific applications. Magnetic resonance scanner, for example, is most suitable for investigations of liquid phases in porous media. Besides water, other fluids on hydrogenic basis can be detected and distinguished selectively. This can be of importance for investigations in the fields of waste deposits, environmental pollution by hydrocarbons (oil) or drinking water research. By means of a 3D Micro-CT apparatus the spatial topology and morphology of the pore space can be investigated down to 5 µm. Although the sample size is rather restricted and dynamic measurements are not possible, these apparatus will open the door towards new insights into the structure of soil and its pore system. For further information the reader should refer to Matthies (1996, comprehensive literature therein).

3 THE "RADON" METHOD

Another analytical approach for the assessment of diffusive gas flow uses Radon as a radioactive tracer. Radon (Rn) is a noble gas. Its radioactive isotopes Rn-219, Rn-220 and Rn-222 are decay products in the Uranium and Thorium decay chains with half-lives of 4 seconds, 1 minute and 4 days, respectively. As Uranium and Thorium are elements naturally occuring in the lattice of numerous minerals, the soil can be regarded as a source for Rn, while the atmosphere is its sink. From the isotopes mentioned above, especially Rn-222 is of interest for permeability studies as its long half-life of 4 days guaranties a considerable life span for penetrating several meters of bedrock or soil (up to 60 m according to literature).

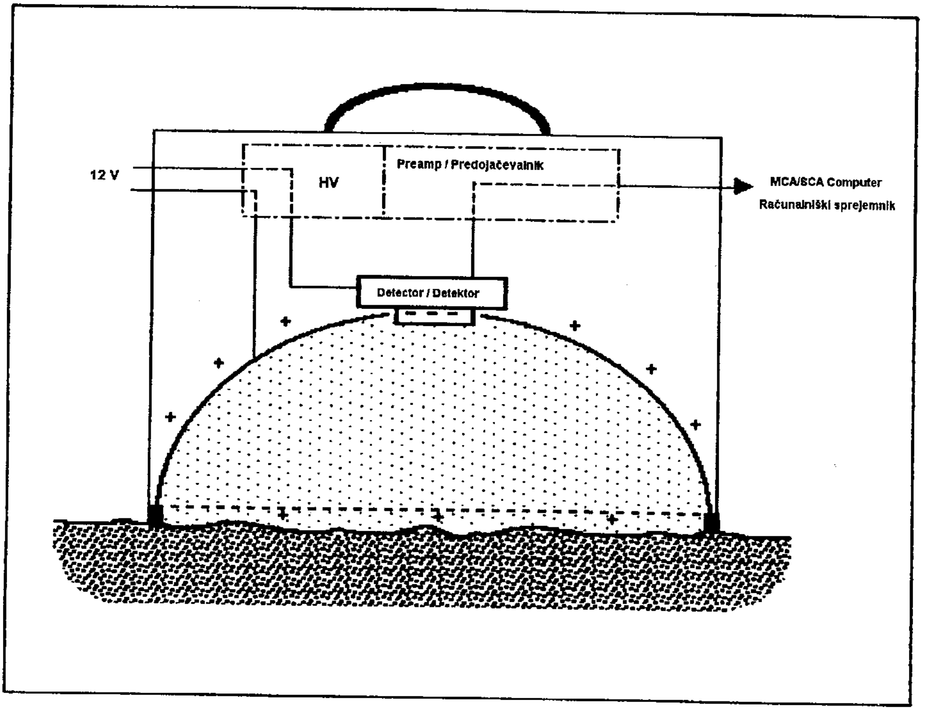

Figure 3: Technical description of the Radon chamber. (HV: High voltage; Preamp: preamplifier; MCA/SCA: Multi/Single-channel-analyser)

Slika 3: Tehnični opis radonske komore. (HV: visoka napetost; Preamp: predojačevalec; MCA/SCA: naprava za analizo z več / enim kanalom)

By means of a Radon-chamber (Fig. 3) the alpha decays of Rn-222 and its decay product Rn-218 can be detected. The amount of decays is directly linked to the number of Rn-222 atoms, which passed the interface between soil and atmosphere entering the chamber. In case of field measurements the chamber is placed on top of the soil, while for laboratory measurements a smaller version is mounted on top of a cylinder core standing on the Rn reservoir. The technical description of the apparatus and the method of sampling is published in detail elsewhere (MATTHIES 1996).

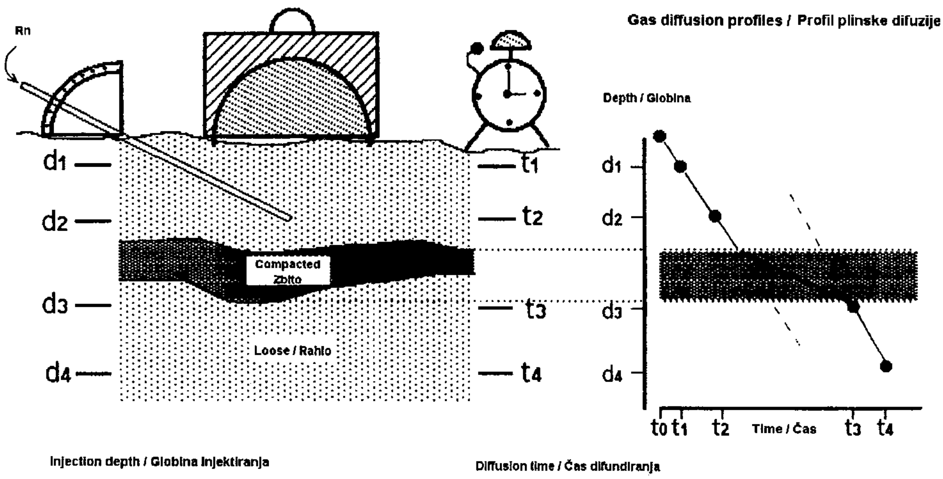

Figure 4: Field setup to measure the depth related Radon diffusion. Compacted soil layer retard the migration of Radon.

Slika 4: Struktura vzorca za merjenje globinske radonske difuzije. Stisnjena plast tal zavira premikanje radona.

Besides the application for field and laboratory measurements it is possible to monitor the natural or to analyse an artifically induced Rn-gas flow. Hence monitoring of the natural Radon background can be seen as a "whole budget" analysis, the latter serves for a depth related resolution of the permeability. For that purpose small needles are stuck into the soil to certain depth levels (Fig. 4). By means of a syringe small quantities of Rn containing air (10 to 30 ml) are injected into soil. This artifical Rn cloud introduces a distinct peak in the Radon chamber after a certain time span (Fig. 5). The diffusion time in relation to the injection depth is a direct marker for the permeability of the penetrated soil layer. A major advantage of this method is the ability to analyse structural changes due to machine traffic, for example, in the identical soil compartment. Therefore, the needles are brought into soil in a flat angle and left there, while the machine passes the spot of measurement. Statistical problems due to heterogenoity of soil do not exist in this case.

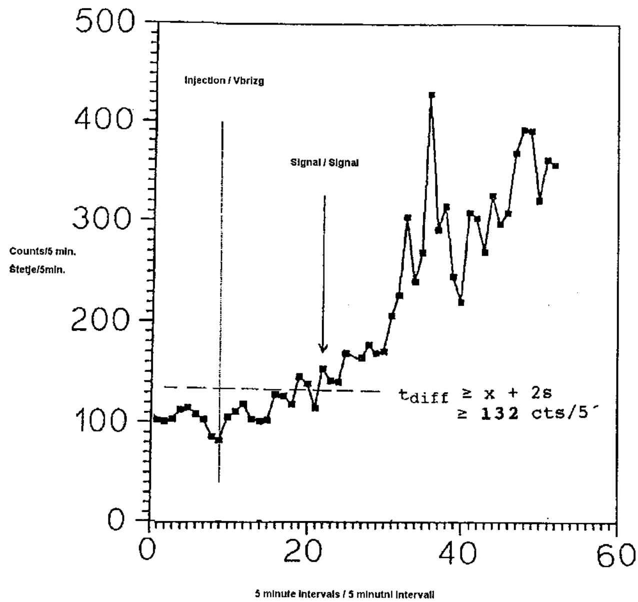

Figure 5: A typical example for a Radon peak in the Radon chamber after injection of Radon containing air into soil. The threshold is defined by the mean background counting rates until injection plus the double standard deviation.

Slika 5: Tipični primer najvišje vrednosti radona v radonski komori po vbrizgu zraka z radonom v talni vzorec. Mejno vrednost določa povprečna hitrost štetja do vbrizga ter dvojnega standardnega odklona.

4 EXAMPLES

Mechanical load alters soil structure. This can be seen in Fig. 6, which represents a CT-image from a soil in its natural status (left) and after traffic by a conventional forwarder (right). In its natural status the soil is crisscrossed by earthworm burrows (a) and roots (b). After traffic these structural features disappear almost completely. As a matter of fact air and water conductivities will be affected seriously.

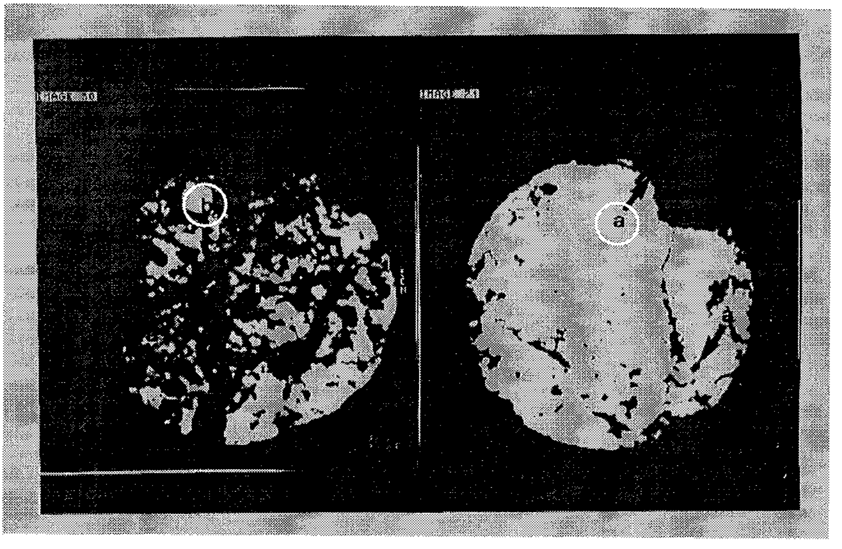

Figure 6: Mechanical load alters soil structure.

Slika 6: Mehanska obremenitev spremeni sestavo tal.

This impact is shown in Fig. 7. The left-hand digitalized images represent CT-scans at three depths from an unloaded soil sample. The black areas are Xe-conducting coarse pores. Their cross sectional area related to the entire cross sectional area of the core (50 cm^2) decreases from 6,35 % at 6 cm depth to 0,37 % at 16 cm depth. On the right the situation in a loaded counterpart from the same site is shown. The breakdown of the coarse pores and their continuities is striking. Only at 16 cm depth the cross sectional percentages are comparable, which can be taken as an indicator for the critical depth of the impact, lying somewhere between 10 and 16 cm.

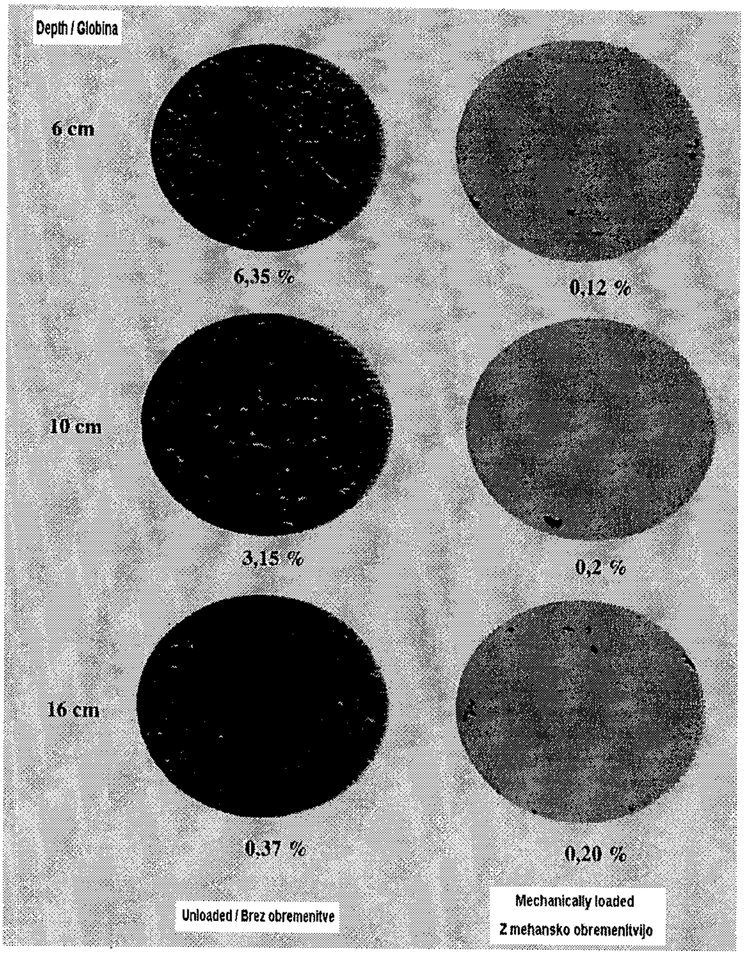

Figure 7: Gas conducting coarse pores (black areas) in an unloaded and mechanically loaded sample after subtraction analysis (digitalized images). The break down of the coarse pores and their continuities become visible. Numbers give the percentage of gas conducting cross sectional areas.

Slika 7: Pore za pretok plina (črni deli) v vzorcu brez obremenitve in vzorcu z mehansko obremenitvijo po subtrakcijski analizi (digitaliziran prikaz) Vidne so motnje v prevodnosti. Naveden je procent plinske prevodnosti prereza.

This visual impression can also be supported by analysing the time of diffusion (Fig. 8). According to the DTC procedure the diffusive Xe-gas flow through these samples was measured. In case of the unloaded sample the diffusion time, normalized for 1 cm of soil, varied between 0,20 and 0,33 min./cm with a slight increasing tendency with depth. In contrast the graph for the mechanically loaded sample differed considerably. Down to 4 cm depth the diffusion time was even less than that in the unloaded sample, which can be explained by the tearing of the soil by the lugs of the tire. This fractioning, forming artifical conductivities, could be found in almost all cases of investigation. Underneath the contact area of the lugs, the compaction leads to the expected effects. The diffusion time increases drastically from 0,15 at 4 cm up to 0,75 min./cm at 8 cm depth. Below this depth level no further Xe was detectable within the experimental time of 45 minutes. As the gas flow is hindered to a considerable extent an unsuitable change in the soil gas composition under the wheel ruts can be expected in the middle run. These finding could be proven by means of Radon field and laoratory tests.

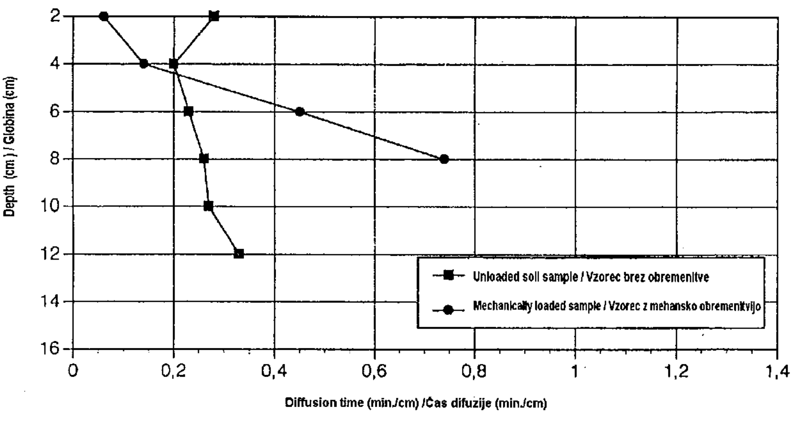

Figure 8: Mechanical load considerably retards the diffusion of Xenon.

Slika 8: Mehanska obremenitev znatno zavira difuzijo Xenona.

Finally, one example of the natural gas exchange of Radon is shown in Fig. 9. Under field conditions the Radon exhalation reveals a distinct pattern. The durnial variation is characterized by a minimal exhalation rate during the day and a maximum in the night. In Fig. 9 a four day period is depicted. The minimum and maximum plateaus are separated by sharp flanks, which are directly linked to changes in the temperature regime of atmosphere and soil. This can be expressed by the iso- and unisothermal diffusion. As soil is the source for Radon there exists a constant concentration gradient towards atmosphere. On the other hand the direction of the unisothermal diffusion component changes as soon as the temperature difference between soil and atmosphere inverts. During the night both mechanisms are equally directed, intensifying the exhalation, while during the day they are behaving in a contrasting manner, which results in low exhalation rates.

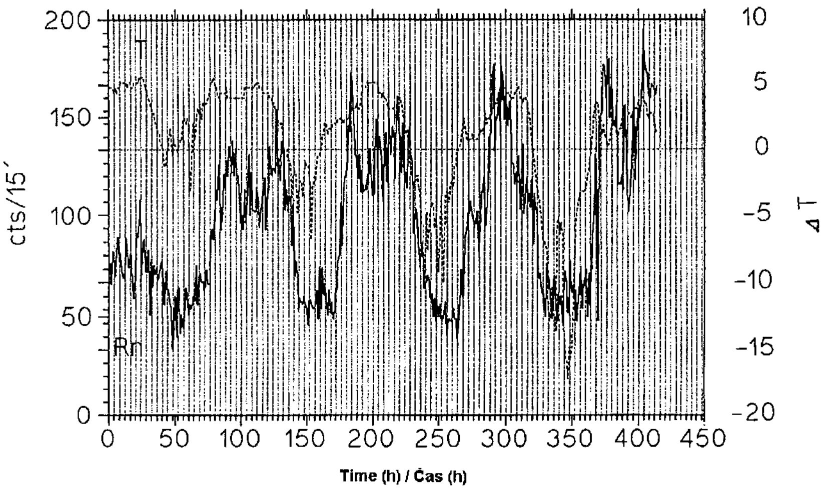

Figure 9: The diurnal variation of the natural Radon exhalation (a four day period). The exhalation rate is mainly controlled by the temperature difference between atmosphere and soil.

Slika 9: Dnevno spreminjanje naravnega izhlapevanja Ra (obdobje 4 dni). Intenzivnost izhlapevanja v glavnem določa razlika v temperaturi med zrakom in tlem.

This simple example conclusively demonstrates the dilemma of laboratory analysis disregarding the environmental factor. As, for instance, in diffusion analysis sample and gas usually have the same temperature, the measurement takes place in a situation which is comparable to the flanks in Fig. 9. A slightest change in room temperature during analysis leads to a drastic reaction of a diffusion rate in one or the other direction. While monitoring the Radon exhalation in nature we found factor 5 between day and night (literature reports up to factor 60! for uranium mining areas). Transferred to laboratory measurements this could mean a soil sample has an excellent or even poor gas permeability, only depending on the temperature regime.

5 CONCLUSION

Analysing the diffusive gas permeability of a porous media, like soil, is a delicate task. For the first time, the DCT method offers the possibility to combine pore structural features of a sample to be combined with dynamic transport processes. Gas conducting pores and gas flow can be visualized and quantitatively measured. The same is valid for transport of fluids. Measurements of the diffusion coefficients become possible at any location in the sample as the DCT method overcomes the conventional "whole budget" analysis.

The Radon method is suitable for in situ as well as laboratory measurements of gas permeabilty. Due to its non-destructive character the experimental setup in the field allows repeated measurements in the identical soil compartment. The impact of mechanical load on soil and its pore system during terrain traffic experiments, for example, can be analysed directly. It overcomes conclusions by analogy as they are necessary by core sampling.

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