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Moisture spreading in a multi-layer hydraulic sealing system (HTV-1)

Franz Königer [a], Katja Emmerich [b,c,*], Gerhard Kemper [c], Matthias Gruner [d], Wolfgang Gaβner [d], Rolf Nüesch [b,c], Rainer Schuhmann [b,c]

[a] *Institut für Meteorologie und Klimaforschung, Forschungszentrum Karlsruhe, PO Box 3640, 76021 Karlsruhe, Germany*
[b] *Kompetenzzentrum Materialfeuchte — Soil Moisture Group (SMG), Universität Karlsruhe, 76128 Karlsruhe, Germany*
[c] *Institut für Technische Chemie, Bereich Wasser-und Geotechnologie, Forschungszentrum Karlsruhe, PO Box 3640, 76021 Karlsruhe, Germany*
[d] *Institut für Bergbau und Spezialtiefbau, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 1A, 09596 Freiberg, Germany*

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Abstract

An important function of the multi-barrier system in the concept of geologic disposal of hazardous or radioactive waste is to limit water flow through the repository. The sealing system of geotechnical barriers consists commonly of bentonite with a very low hydraulic conductivity and high swelling and sorption capacity. Uniform wetting of the bentonite is a prerequisite of a high performance, but preferential flow paths partially inhibit the swelling process and increase the hydraulic conductivity of the material.

We developed a new sealing system (sandwich) that combines layers of different soil hydraulic properties. Layers with a sealing function are combined with equipotential layers (ES), that are characterized by a hydraulic conductivity several orders of magnitude higher than the bentonite. A penetrating waterfront will be homogenized in ES which supports a more homogeneous swelling process.

The HTV-1 was a perpendicular semi-technical scale experiment that reflects a typical shaft sealing construction with respect to orientation. A natural Ca/Mg-rich bentonite (Calcigel) was used for the sealing elements and a combination of fine sand together with an artificial mixture of fine sand, limestone and non-swelling clay minerals (kaolinite) was used for the equipotential layers. A rock salt brine of 1.15 g/ml was chosen to simulate natural brines. The moisture spreading was monitored by time domain reflectometry (TDR) sensors.

Artificial induced disturbance within the sealing layers forced enhanced water flow for demonstration. The moisture moved faster in this artificially disturbed region of the column than in the undisturbed part. After moisture reached an ES it spread evenly over the column cross section and wetted the lower bentonite layer from the back. Thus the HTV-1 demonstrated the functionality of the multi-layer hydraulic sealing system even under the inflow of rock salt brine, which makes it adjustable to different kinds of surrounding rocks and pore waters. All applied sensors (TDR and pressure) displayed no sign of corrosion after more than one year of operation. Therefore the sensors are suitable for intermediate to long-term monitoring.

Keywords: Brine; Hydraulic; Moisture; Sealing; Shaft; Time domain reflectometry; Waste

1. Introduction

Hazardous or radioactive waste has to be safely disposed and isolated from biosphere. At the moment the highly accepted concept is an underground storage in deep boreholes or caverns. Safety considerations led to a multi-barrier system of technical, geotechnical and natural barriers. The geotechnical barrier consists of three components: buffer, backfill and drift and/or shaft sealing (e.g. Breidung et al., 2000; Pusch, 2001).

The sealing system of geotechnical barriers in disposal concepts consists commonly of bentonite with a very low hydraulic conductivity (1E-11 to 1E-13 m/s) combined with plugs for static abutment for the reception of fluid pressure, swelling pressure and rock pressure. Bentonite is regarded as an effective barrier for hazardous substances due to low hydraulic conductivity, high swelling and sorption capacity.

* Corresponding author. Kompetenzzentrum Materialfeuchte — Soil Moisture Group (SMG), Universität Karlsruhe, 76128 Karlsruhe, Germany.
E-mail address: katja.emmerich@itc-wgt.fzk.de (K. Emmerich).

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A uniform wetting of the bentonite is prerequisite for a high functionality and performance. But fingering is a known phenomenon in soil physics that leads to an accelerated water flow on preferential pathways later followed by a lateral water break through and inhomogeneous swelling of the bentonite construction. In addition the contact zone between host rock and geotechnical barrier as well as possible monitoring elements might serve as pathways for an enhanced advective water flow.

Bentonite blocks or mixtures of pre-compressed bentonite pellets are commonly used for the construction of bentonite sealings. Hydraulic and mechanical laboratory tests during an emplacement experiment for the disposal of radioactive waste in underground repositories revealed a double structure model for granular bentonite material. It showed a high permeability during the first stage of wetting and even collapse deformation may occur (Mayor et al., 2005) resulting in enhanced water flow before permeability decreases substantially. Furthermore the amount of injected water was distinctly higher than estimated for saturation indicating that some water might be flowing around the sealing. Low contact pressures might occur locally at the interface of the sealing system and the host rock due to rough rock surfaces on an excavation site. At the moment large effort is spent to obtain smooth surfaces of emplacement excavations to achieve good contact between surrounding rock and sealing elements to avoid pathways around the sealing elements (Mayor et al., 2005).

Thus to obtain homogeneous wetting during the saturation stage and long-term stability of a closure construction, an innovative multi-layered sealing system was developed (Nüesch et al., 2002). In contrast to conventional constructions of the sealing element, consisting of only one material, the new system combines layers of different hydraulic properties. Layers of cohesive materials (e.g. bentonites) with a sealing function are combined with layers of non-cohesive materials (equipotential layers), that are characterized by a hydraulic conductivity several orders of magnitude higher than the cohesive materials. The new sealing system, simply called “sandwich”, shall prevent inhomogeneous moisture transport in the barriers. Penetrating or ahead hurrying water will be evenly distributed within the equipotential layer and will build up a new homogeneous potential surface for the following clay layer.

HTV-1 is the first of a series of semi-technical scale experiments (vertical and horizontal alignment), which is part of the “sandwich-project” (www.untertageverschluss.de). The scope of the entire sandwich-project is to design, construct and demonstrate performance of a new sealing system that guarantees the homogeneous moistening of a sealing bentonite core with the help of equipotential layers. The new barrier system offers the advantage of being perfectly adaptable to the surrounding host rock. Potential permeability around the barrier system can be minimized that way. Also possible non-homogeneities within the barrier are adjusted. The penetration of a waterfront into the barrier will be homogenized due to its layer geometry and the sealing function of the clay liner. This supports a more homogeneous swelling process and will help to increase the long-term stability of a barrier system.

The main objective of HTV-1 experiment was to demonstrate the functionality of the multi-layer hydraulic sealing system in vertical alignment (simulating a shaft sealing) under the inflow of a rock salt brine by monitoring of the moisture spreading by time domain reflectometry (TDR) sensors. While demonstrating the functionality of the system and especially of the equipotential layers we did not aim at steady state flow with this first semi-technical scale experiment. Furthermore durability of the used sensors under highly aggressive conditions should be tested. Rock salt brine was proved to influence bentonite sealing properties more intensely than other brines or pore solutions (e.g. $MgCl_2$, Q-brine or Äspö water). Hence the observed parameters of the multi-layer sealing system under the inflow of a rock salt brine are of a conservative character (Sitz et al., 2003, Herbert and Kasbohm, 2007) e.g. for the evaluation of long-term behavior.

2. Setup of HTV-1

2.1. Column description and sensor equipment

The perpendicular semi-technical scale experiment reflects a typical shaft sealing construction (e.g. NAGRA, 2002) with respect to orientation and influence of gravimetric force. The applied fluid pressure simulated a typical scenario of a fluid inflow into a deep shaft closure (Herbert and Moog, 2001).

The column is a steel cylinder (Hunger Hydraulik, Germany) of 0.8 m inner diameter and 1.8 m inner height (Fig. 1). Bottom and top cover are fixed with screws and can be removed. The bottom is fitted with a liquid supply. The top cover contains

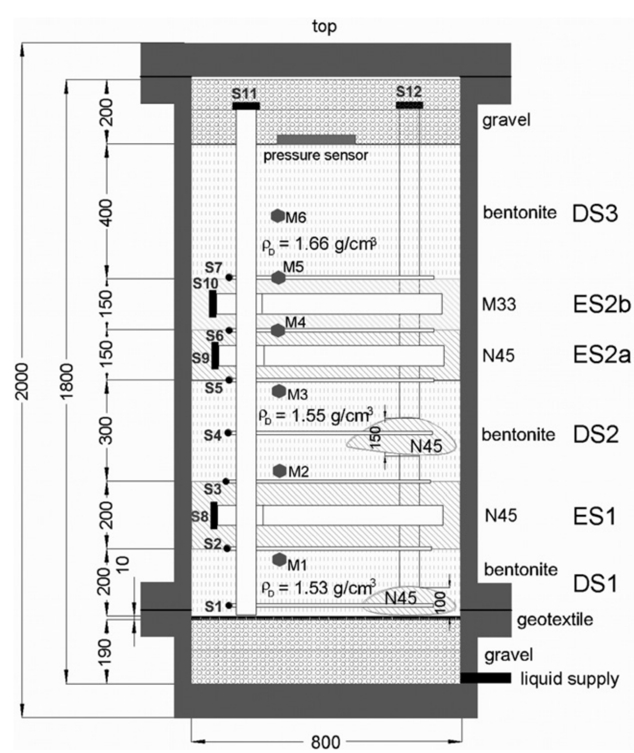

Fig. 1. Experimental setup of HTV-1; S1–S12 TDR sensors, and M1–M6 pressure sensors.

several feed throughs for sensor cables. The bottom of the column is filled with gravel that is protected against bentonite intrusion by a geo-textile liner. Through the gravel layer the brine will be homogeneously distributed over the whole cross section and singular brine break throughs are prevented.

Dimension analysis revealed an influence of the geometry on the performance of the sandwich construction. The dimension of a shaft was downscaled accordingly to the semi-technical scale and the necessary layer thickness of the equipotential segments was calculated with respect to planned drift (tunnel) sealings to enable transfer of gained knowledge and comparison of results. The dimension analysis ensured that physical parameters are not hurt by downscaling.

The gravel is covered by a layer of bentonite (Calcigel, DS1). The gravimetric moisture (w_{GT}) during installation of the experiment was about 10% in equilibrium with the relative humidity at the experimental site. The first bentonite layer at the bottom is 200 mm thick. The dry density of the bentonite was 1.53 g/cm^3 (expected max. swelling pressure: 1.0 MPa, without relaxation due to installation, Sitz et al., 2003). To achieve the required dry densities a binary mixture of pre-compressed pillow-shaped compacts (about 10 cm^3, ρ_d=1.9–2.0 g/cm^3) and compacted granules with a grain size of 0–3 mm (fuller grain size distribution) was used (Sitz et al., 2003). The low density of the first sealing layer was chosen to facilitate some brine flow through the column. A higher density would have enhanced the swelling of the bentonite. Hence time of the experiment would have been no longer reasonable. The bentonite layer DS1 contains a lens of Nivelsteiner fine sand (N45) of 0.1 m height and a diameter of about 0.3 m (Fig. 1). This sandy inclusion simulates a preferential flow path through and potential failure of a sealing system, that solely consists of bentonite.

The bentonite was followed by a fine sand layer (N45) of equal dimension (ES1). The N45 layer acts as an equipotential layer. It should interrupt locally occurring liquid flow and should distribute the liquid again over the entire cross section. Thereby the bentonite sealing layer is wetted from the opposite site (top-down) of the forced flow (bottom-up) direction. The swelling induces additional sealing.

The next bentonite layer (DS2) of 0.3 m was installed with a dry density of about 1.55 g/cm^3 (max. swelling pressure: 1.2 MPa) and contained also a sand lens of N45 of 0.15 m height and a diameter of about 0.4 m.

Above a sand layer of 0.15 m (ES2a) and an equipotential layer made of M33 (a mixture of N45, kaolin and limestone) of an equal thickness (ES2b) was installed.

Finally a 0.4 m thick bentonite layer (DS3) with a dry density of about 1.66 g/cm^3 (max. swelling pressure 2.4 MPa) followed. This dry density is in the common range of sealing systems (Sitz et al., 2003). The DS3 presents a sealing layer that should prevent further liquid movement. DS2 and DS3 were prepared of the same compacts/granules mixture like DS1.

On top of the stacked sealing system a further gravel layer reduced the resulting pressure due to swelling of the bentonite.

The bentonite mixture of DS1 was poured into the column without further compaction. To achieve the higher dry densities in DS2 and DS3 a special soil compactor with a circular perforated vibrating plate (RAVI Baugeräte GmbH) with a diameter of 300 mm and a compaction frequency of 50–100 Hz was used. The binary bentonite mixture consists of 70% compacts and 30% granules. This material design was developed in cooperation with the company "K+S" (Sitz et al., 2003). In sensitive zones (wall, around cables) the ratio of compacts to granules varied up to 60:40 to avoid liquid bypaths and around the sensors that had to be handled with great care.

The column was instrumented with 12 TAUPE sensors (S1–S12) that measure the spatial water distribution. TAUPE sensors are time domain reflectometry (TDR) sensors (Brandelik et al., 1998; Brandelik et al., 2005; Hübner et al., 2005; Stacheder et al., 2005). A TAUPE sensor consists of a ribbon cable with three electrical wires that is connected with a TDR device (TDR100, Campbell Scientific) by a twelvefold multiplexer. A computer operated the devices and collected TDR signals at time intervals between 15 min and 3 h.

Two TAUPE sensors (S11 and S12) are aligned perpendicular to the bedding. They display the progress of the moisture face. The S12 penetrates both sandy lenses in the sealing layers DS1 and DS2 and monitors accelerated water flow, whereas the sensor S11 monitors moisture motion in the undisturbed sealing layers. Both sensors reveal the functionality of the equipotential layers.

Sensors S1 and S4 are placed horizontally within DS1 and DS2. Both sensors pierce the sandy lenses. They show the horizontal extension of the brine solution in undisturbed as well as in disturbed domains.

The sensors S2, S3, S5, S6 and S7 are placed at the interfaces DS1/ES1, ES1/DS2, DS2E/S2a, ES2a/ES2b and ES2b/DS3. They monitor the moisture movement within the interfaces and give information on the wetting of the sealing systems from the above disposed equipotential layer (against to the forced flow direction).

The sensors S8 (ES1), S9 (ES2a) and S10 (ES2b) are installed endwise and annular. They seize the extent of the moisture face over the cross section and the moisture rise as sum parameter.

In addition six piezo-resistive OEM pressure transducers (M1–M6) each cast-in a silicone rubber bowl (pear-shaped) with a pressure range of 0–100 bar (Keller Druckmesstechnik) and a transducer of earth thrust type EEKE 10/20 K 200 Z4 (Glötzl GmbH) were installed. M1 to M6 are located on top of DS1, below and above DS2, at the interfaces ES2a/ES2b and ES2b/DS3 and in the middle of DS3. The earth thrust transducer was situated below the top lid of the column. The current amount of salt solution was measured gravimetrically with a force transducer type U2B with nominal force 0.5 kN (accuracy class 0.2% — Hottinger Baldwin Messtechnik). The data collection for fluid amount, fluid pressure and for all pressure transducers was performed by a Data Acquisition Switch Unit Agilent 34970A.

2.2. Materials

The bentonite used in this study is a natural Bavarian Ca/Mg-rich bentonite (Calcigel) supplied by Süd-Chemie AG (Germany). The Calcigel consists of about 67% montmorillonite,

Table 1
Grain size distribution of Nivelsteiner fine sand (N45)

Equivalent diameter	Amount
>180 μm	<2%
125–180 μm	6%
90–125 μm	62%
63–90 μm	28%
<63 μm	<2%

11% illite/muscovite, 8% carbonates (dolomite and calcite), 8% quartz and minor amounts of kaolinite and feldspars. A cation exchange capacity (CEC) of 64 meq/100 g related to the dry weight was determined using Cu-Triethylentetramin (Meier and Kahr, 1999). About 70% of the exchangeable cations are Ca^{2+}. The remaining 30% of CEC is divided into 19% Mg^{2+} and 11% Na^{+}.

Air dry Calcigel (moisture 7–10%) was used to produce pre-compacted components of the ultimate sealing layers. Those sealing elements consist of a binary mixture of bentonite-compacts (pillow-shaped) and -granules (Sitz et al., 2003). Both components of the bulk mixture were produced at the plant “Bergmannssegen-Hugo” by the K+S Group. This material defines the actual best state of the art for bentonite sealing materials for long-term stable shaft sealing systems, especially by high degree of difficulty such in salt mines.

Simple column experiments were performed to select sandy or silty materials with suitable capillarity for the equipotential layers. A rising height of at least 3 m was required. A fine sand material called N45 performed well. In addition we found that small amounts of carbonates accelerated water rise and increased the final height of the water in small test columns. Therefore an artificial mixture M33 was manufactured for the use in ES2b.

The Nivelsteiner fine sand (N45) supplied by Nivelsteiner Sandwerke und Sandsteinbrüche GmbH, Herzogenrath, Germany, consists of 99% quartz and 1% orthoclase in weight. Table 1 shows the grain size distribution of N45.

M33 is a mixture of 70% N45 with 15% processed kaolin (the product consists mainly of kaolinite) from Gebrüder Dorfner GmbH & Co., Kaolin-und Kristallquarzsand-Werke KG (Hirschau), Germany, and 15% limestone (Muschelkalk Heilbronn) produced by BMK-Steinbruchbetriebe in Talheim, Germany. M33 is composed of 71% quartz, 14% non-swellable clay minerals (mainly kaolinite, less illite/muscovite and chlorite), 11% carbonates (calcite and dolomite) and some feldspars.

A rock salt solution prepared from rock salt from Salzdetfurth was chosen as input brine to simulate natural brines. The chemical analysis of the brine is given in Table 2. Quantitative X-ray diffraction analysis yielded a composition of 98% halite and 2% anhydrite. Other salt phases were below detection limit. The solubility of NaCl at 20 °C is 26.5 wt.%. First a nearly saturated solution with a density of 1.20 g/ml (20.5 °C) was prepared. To inhibit the crystallization of salt in the fittings, this solution was diluted to obtain a brine of 1.15 g/ml, which is equal to 4 mol/l. In other words 100 g brine has a volume of 86.8 ml and consists of 20.5 g NaCl and 79.5 g water or 236 g NaCl is diluted in 1 l water.

Table 2
Chemical composition of the brine prepared of rock salt from Salzdetfurth with a density of 1.204 g/cm^3 and a dynamic viscosity of 2.97 mPa s (26 °C)

	KCl	$MgSO_4$	NaCl	$CaSO_4$	Σ
g/l	2	3	317	4	326

2.3. Brine inflow

The brine was injected from the bottom and was forced through the column by a frequency controlled pump. Thereby the fluid pressure and the brine volume were recorded. The final applied pressure corresponds to the expected hydrostatic pressure in a repository within a salt rock formation (Herbert and Moog, 2001).

Brine flow into the column was initiated on 15.02.2005 with a fluid pressure of 0.34 bar. The hydraulic pressure was increased stepwise up to 92.7 bar. Each pressure step was retained until the liquid flow was nearly constant. Table 3 and Fig. 8 show pressure steps and fluid inflow. With increasing fluid pressure the pressure control worked stable after 13 d. After 105 d a cable leakage was detected. The fluid flow rate was corrected after repairing the seep with respect to the leakage rate.

The pressure above 90 bar was retained for 6.7 months to verify the stability of the system including the sensor duration and leak tightness of the column. The experiment was terminated after little more than 1 year after the moisture reached the upper bentonite layer.

3. Time domain reflectometry (TDR)

TDR is a common method to determine the moisture content of porous materials like soils based on the dielectric constant (ε) of water (e.g. Stacheder, 1996). Nevertheless, the signal is

Table 3
Brine inflow history

Date	Time	Fluid pressure	Fluid volume	Corrected fluid volume
	[h]	[bar]	[l]	[l]
15.02.2005 10:20	0	0.34	0	
	1.6	0.34	15.1	
	6.0	0.24	57.8	
	22.7	0.51	59.7	
	26.0	1.49	62.4	
	71.5	1.65	66.7	
	145.7	2.76	69.5	
	194.7	3.11	73.2	
	309.9	5.28	78.2	
	333.4	10.14	81.2	
	479.6	20.21	91.3	
	1057.0	30.35	137.9	
	1654.9	40.76	177.4	
	2021.0	50.99	187.1	
	2253.1	60.20	192.2	
	2372.4	71.00	194.4	
	2517.1	81.18		199.9
	4052.1	91.71		211.7
20.02.2006 09:45	8878.2	92.70		239.1

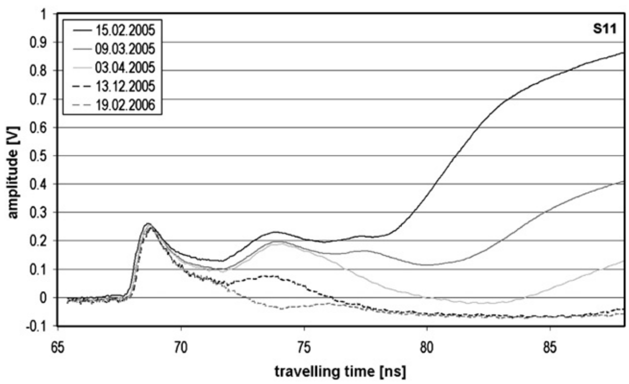

Fig. 2. TDR signals of vertical sensor S11 (disturbed bentonite layers).

determined by all soil components, but ε of free water is much higher than ε of the other soil components (gas and minerals). Still, changes in the TDR signal can be caused by changes in water content or/and density changes of the material.

Moisture propagation can be distinguished from density variations by comparison of the actual signal with the signal at the initial state of the material at the beginning of a monitoring process.

A TDR transmits a fast rise time pulse along conducting rods or cables. The resulting electromagnetic field around the conductors is influenced by the near environment. Changes in the electric properties of the surrounding material result in changes of the TDR signal, which shows the amplitude distribution along the sensor. In case of a directed wetting a parallel shift of a TDR curve along the y-axis indicates density variation while a partly diminishing amplitude at the far end of the sensor results from increasing moisture content. This means, density changes do not modify the shape of a TDR curve while the curve shape is significantly altered by intruding moisture.

TDR probes are usually between 10 and 30 cm in length. In contrast TAUPE sensors produce reliable data up to a length of 10 m (Brandelik et al., 1998, 2005). Therefore these sensors were used in the HTV-1 to monitor moisture propagation.

4. Results

Results obtained from the HTV-1 experiment can be divided into two categories. First moisture spreading was observed and TDR sensor performance was tested and second dismantling provided a snap shot analysis of moisture distribution, salt concentration and mineralogical changes. Following termination of the experiment the HTV-1 column was dismantled a) to recover and probe all sensors, b) to map the extension of the sealing and equipotential layers and c) to determine the water content, the salt concentration and mineralogical changes over the whole volume. While the present contribution is focused on the functionality of the new multi-layer sealing system, moisture movement and sensor performance under the chosen inflow regime detailed information on dismantling and the results of the geochemical and mineralogical investigations will be presented in Emmerich et al. (submitted for publication).

4.1. Wetting history

4.1.1. Perpendicular arranged sensors

The moving moisture face is detected by a beginning separation of the TDR curve from the initial TDR curve measured in the air dry material at the beginning of the experiment (15.2.2005) for sensors S11 (Fig. 2) and S12 (Fig. 3). The observed effect slowed down extremely with increasing swelling of the bentonite in the DS1 and DS2. The moisture front was detected at S12 in the disturbed zone much faster than at S11 in the undisturbed layers (Fig. 4a–e).

At the beginning the signals of S11 and S12 were congruent. The different velocity of the liquid movement caused a separation of the TDR curves measured with S11 and S12 already after 20 d (Fig. 4a).

The brine passed the sandy lens in DS1 much faster than the undisturbed bentonite in DS1 (Fig. 4a). Fig. 4a shows that the brine passed DS1 and is already penetrating ES1. Thereafter DS1 is wetted over the whole cross section from ES1 above (Fig. 4b), which is proved by the nearly identical TDR signals from S11 and S12 in the region of ES1. In contrast the deviation of both signals within the DS1 is still more pronounced. This process is still fast as the dry density of DS1 is too low for an enhanced swelling of the bentonite.

We observed that the moisture extended through DS2 on the disturbed site of the column. Three month later (Fig. 4c) the brine completely passed ES1 and the sandy lens of DS2. At this moment the signals at S11 and S12 showed large deviations. After it reached ES2a it started to spread. In DS2 still areas with low moisture content were observed.

The moisture was still moving faster in the disturbed region of the column than in the undisturbed part. Eight and a half month after the start of the experiment we detected the largest deviation of the TDR signals from S11 and S12. The left site of the column was already wet whereas the right site of the column exhibited lower moisture contents. While moisture distribution in ES2a was nearly homogeneous the moisture started to spread evenly in ES2b and to wet DS2 below (Fig. 4d). Faster equilibration of the moisture over the cross section of the M33 (ES2b) than in the pure N45 (ES2a) was observed.

The wetting of the column layers slowed down with swelling of the bentonite and compression of the material by the

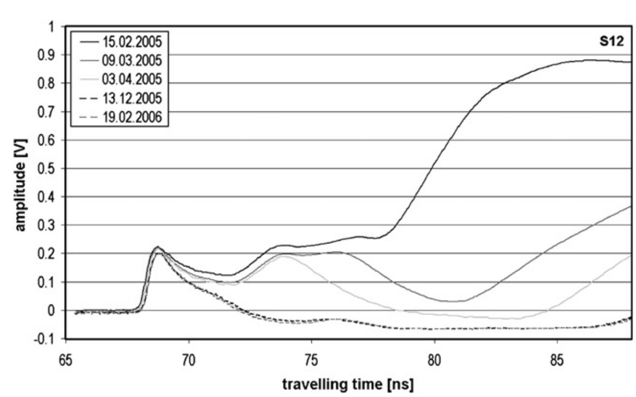

Fig. 3. TDR signals of vertical sensor S12 (undisturbed bentonite layers).

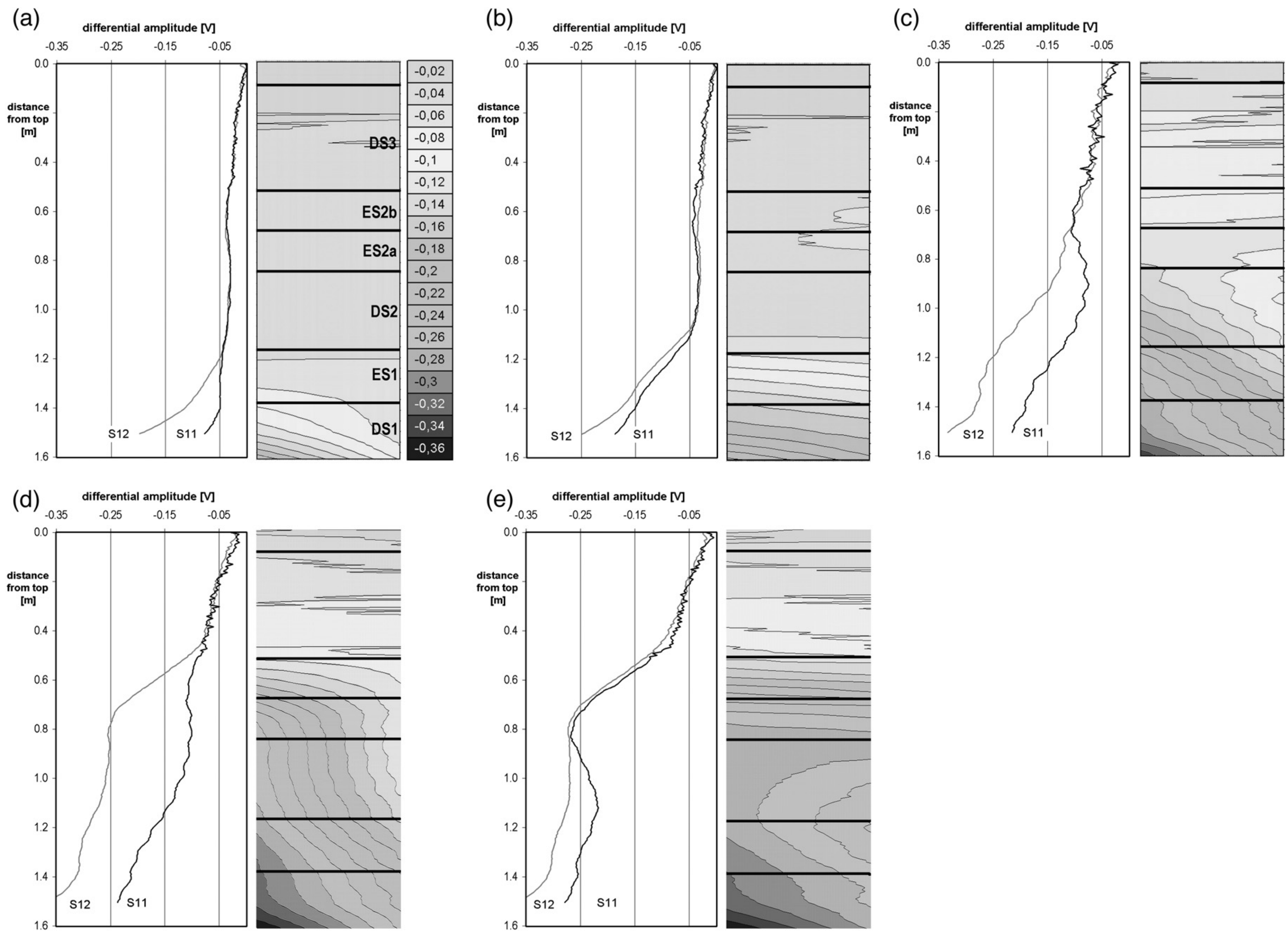

Fig. 4. a–e: Left site: differential curve of the actual TDR measurement to the TDR curve obtained in the air dry material (S11 and S12, vertical sensors), right site: interpolated changes of the TDR signal over the vertical cross section of the column. a: 7.3.2005, after 20 d. b: 28.3.2005, after 41 d. c: 26.6.2005, after 131 d. d: 24.10.2005, after 251 d. e: 19.2.2006, after 369 d.

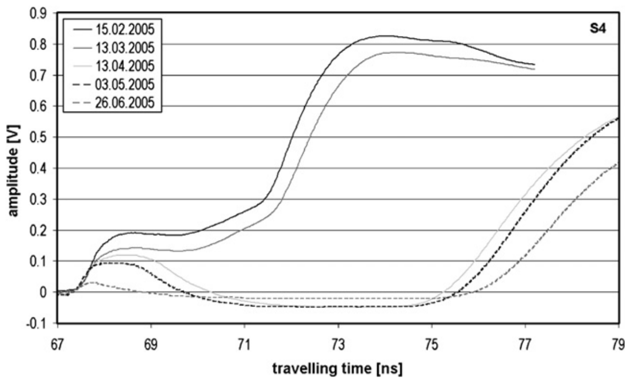

Fig. 5. TDR signals of horizontal sensor S4 in DS1.

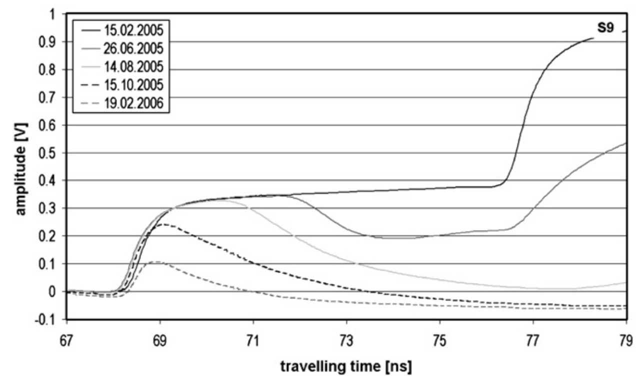

Fig. 7. TDR signals of endwise and annular sensor S9 in ES2a.

additional pressure of the brine. After one year (19.2.2005) the signals of S11 and S12 approached similar values (Fig. 4e). DS1 and DS2 are wet and nearly saturated.

At this time the interface of ES2b and DS3 happened to be wet and the experiment was terminated. Pressure relaxation was induced and the top lid of the column was removed. The whole HTV-1 column was dismantled.

4.1.2. Horizontal arranged sensors

The horizontal installed TDR sensors displayed moisture distribution in certain cross sections and revealed areas with accelerated liquid flow. Within the lower segments a fast equilibration (S1–S3) occurred because of the low dry density of the bentonite in DS1.

The sensors showed an immediate reaction within the sandy lenses in DS1 and DS2 due to wetting (S1 and S4). The reaction then extended along the entire sensor length. Flat installed sensors (e.g. S4) first reacted at the far end (Fig. 5). S5 exhibits a faster response than S4 to the brine along the whole length of the sensor (Fig. 6). That confirms the proper function of the equipotential layer ES2a. The endwise and annular installed sensors (S8–S10) first reacted in the middle prior to complete wetting (e.g. S9, Fig. 7).

TAUPE sensors reacted to the increasing pressure inside the column, too. There was a considerable difference in the behavior of the sensors in a bentonite layer and in a sand layer. In bentonite the pressure of the brine together with the swelling led to a higher density of the material, which was detected e.g. by S4 (Fig. 5). The curves shifted parallel with ongoing wetting of DS1 indicating an increased material density in DS2. On the contrary sand reacts incompressibly. No change in density occurred and the curves were not influenced by the hydraulic pressure (e.g. S9, Fig. 7).

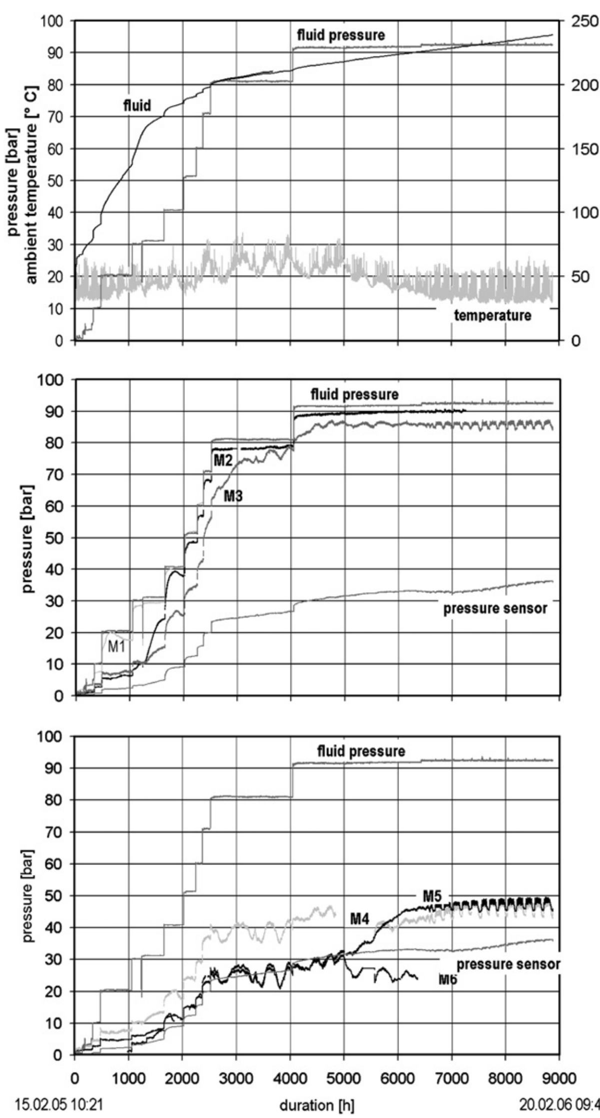

Fig. 8. Evolution of fluid pressure, fluid volume (input), temperature, total pressure (M1–M6), and earth thrust versus time.

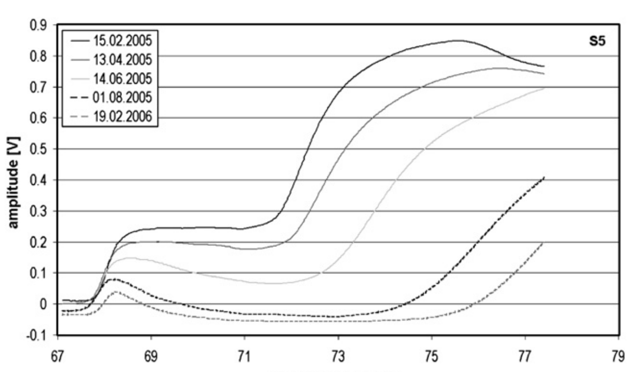

Fig. 6. TDR signals of horizontal sensor S5 at the interface of DS2/ES2a.

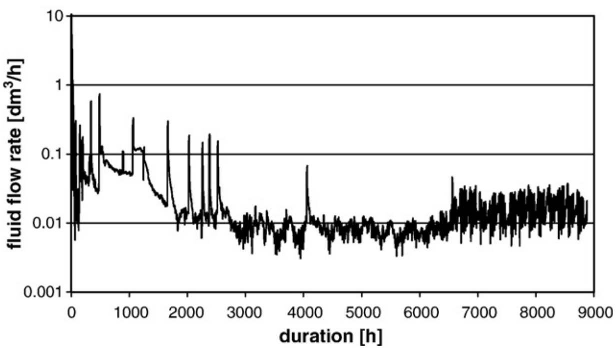

Fig. 9. Fluid flow rate.

4.1.3. Fluid pressure and fluid volume

The values of the pressure conductors M1–M6 in the sealing element followed the run of the fluid pressure (Fig. 8). The difference between the values of the pressure conductors M1–M6 and also to the Glötzl transducer of earth thrust was determined by the bentonite swelling pressure and the partial fluid pressure and by the load development in the bentonite elements. With increasing fluid pressure the fluid flow in the sealing system has stabilized (Fig. 9). The tightness of the system is illustrated by the decreasing fluid flow rate with increasing running time. At the final state with a constant fluid pressure of 92.7 bar the average fluid flow rate is less than 0.01 ml/h (Fig. 9).

No liquid bypaths along the wall or the sensor cables have been detected. This shows, that the bentonite layers in the column were assembled very well to keep a hydraulic pressure of more than 90 bar for more than half a year.

4.2. Sensor condition after dismantling

No sensor failures occurred during the experiment. All cable glands of the pressure sensors were tight against fluid penetration due to an adjusted silicon casing (pear-shaped).

The TDR sensors were in good condition. Only some dents resulting from the swelling pressure of the bentonite were observed. The measuring capability of the ribbon cables was fully maintained. Three sensors (S1, S2 and S8) showed a leakage to brine due to insufficient insulation of the interface between ribbon and coaxial cable. This will be improved in further versions of TDR-TAUPE sensors. However the sensors (ribbon cable and coaxial cable) showed no signs of corrosion after one year of operation. Furthermore, different sensor jackets (e.g. polyethylene instead of polyvinyl chloride) of the ribbon cable can be applied in dependence on the chemical composition of the fluid, which in addition provides a better environmental compatibility.

5. Discussion

The TAUPE sensors perfectly track the progress of the moisture face at different positions in the column. Especially sensors S11 and S12 which penetrate all layers are suitable for continuous monitoring. Naturally, the TDR signals are influenced by different materials in the DS and ES along the sensors. Therefore evaluation of absolute values for moisture content in each segment of the column is difficult (Schläger, 2005) and was not the objective of the present experiment.

The horizontal sensors in each layer verified the results derived from S11 and S12 and proved that no preferential flow paths were induced along the sensors.

The experiment was terminated after the moisture reached the upper sealing system and before full saturation was obtained. Thus determination of the overall hydraulic conductivity of the sandwich system was prevented because no steady state was achieved. The flow regime within the sealing system was mainly advective while diffusion became more determining in the lower sealing elements (DS1 and DS2) after the bentonite pellets started to swell and permeability decreased.

The M33 material in ES2b caused a faster equilibration of the moisture over the cross section than the pure N45 due to smaller particle size and resulting smaller pore radii and lower porosity, respectively. This would be important for the design of shaft closures. However, at the moment we do not fully understand why carbonates support capillary water rise. According to the theory the capillary water rise depends on the cosine of the contact angle. Whereas the contact angle of quartz and quartz mixed with silicate minerals varies between 0 and 41° (cos Θ=0…0.755), a contact angle of 70° (cos Θ=0.342) for fine grained calcite was measured (Hartge, 1978; Bachmann et al., 2003; Kelkar, 2005). This means lower capillary rise for carbonate containing soils, but the contrary behavior was observed. Detailed investigations on materials for the equipotential layers are under way and will be presented later. Investigation of the material with an environmental scanning electron microscope did not reveal capillary fractures that might be expected due to limestone processing and which would explain greater suction forces.

6. Summary and conclusions

The results of our semi-technical scale experiment HTV-1 prove the general concept and demonstrate the functionality of the multi-layer hydraulic sealing system consisting of bentonite sealing layers and equipotential layers of a higher hydraulic conductivity under the inflow of a salt brine for shaft closures. The moisture face was equalized every time in the equipotential layer after artificially induced preferential flow path caused accelerated flow and uneven moisture distribution in bentonite sealing layers.

All applied sensors (TDR and pressure) showed no signs of corrosion after one year of operation. So there are no restrictions for intermediate to long-term operation of the sensors during the saturation process of the sealing system in a highly corrosive environment.

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