MONITORING CONTROLLED DNAPL CONTAMINATIONS USING GPR

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INTRODUCTION

The Versuchsanstalt für Grundwasser- und Altlastensanierung (VEGAS) in Stuttgart, Germany, provides excellent conditions to test various methods which are designed to monitor, probe and clean aquifers. In December 1996 an experiment was carried out at a water-saturated model aquifer to monitor firstly the infiltration of 100 litres of Trichlorethene (TCE) and secondly the remediation of the model aquifer.

Beside different in situ measurements a Ground Penetrating Radar (GPR) experiment has been carried out to answer the question, if under such conditions GPR can be used to detect and monitor a contamination with a dense non aqueous phase liquid (DNAPL). In addition to the field experiment different simulations of the electromagnetic wave propagation based on a Finite-Difference-(FD)-scheme were carried out.

DESIGN OF THE MODEL AQUIFER

The model aquifer consists of a sand pit with a length of 637 cm, a height of 265 cm and a width of 40 cm. One side of the pit is made of glass, allowing the aquifer to be observed (Fig. 1). Different lenses have been incorporated into the pit using different sand types (fine, middle, coarse sand and at the top of the aquifer a pure quartz sand). The physical properties of the used materials, that are relevant for the electromagnetic wave propagation, are the relative dielectric

Fig. 1: Photograph of the side of the sand pit after TCE infiltration.

Table 1:

	Φ [%]	ϵ_r	σ [S/m]	μ_r
Quartz	44,0	4,500 *	$5 \cdot 10^{-15}$ *	1 *
fine	43,6	4,632	0	1
middle	35,1	4,176	0	1
coarse	39,5	3,758	0	1
TCE	-	3,42 *	10^{-6} *	1 *
Water	-	80,0 *	0,1280	1
Air	-	1 *	0 *	1 *

*: Schön, 1996.

constant ϵ_r , the conductivity σ , the relative magnetic permeability μ_r and the porosity Φ of the dry sands (see table 1).

Using a HP-Vectoranalyzer, ϵ_r of the fine, middle and coarse sand has been determined, ϵ_r of pure quartz was found in Schön, 1996. For further information of the hydraulic parameters of the sands refer to Hoffmann, 1996, and Josef et. al., 1997. The conductivity σ of the water inside the model aquifer was measured. The other physical properties of water, air and TCE are given by Schön, 1996.

FD-MODELLING

For the simulation of the electromagnetic wave propagation in the model aquifer we applied an O(2/4)-staggered-grid-scheme on the Maxwell's equations (Yee, 1966).

Different mixing formulas were used to determine the model-parameters :

Dobson et. al. (1985) developed a semi-empirical formula for the 'Physical Earth Model' to calculate the dielectric constant ϵ_r :

$$\epsilon_{r, soil} = [V_{sand} \sqrt{\epsilon_{r, sand}} + V_{water} \sqrt{\epsilon_{r, water}} + V_3 \sqrt{\epsilon_{r, 3}}]^2 \quad (1)$$

$\epsilon_{r, soil}$: Relative dielectric constant of the mixture

V_{sand} : Volume fraction of the sand

$\epsilon_{r, sand}$: Relative dielectric constant of the sand

V_{water} : Volume fraction of the water

$\epsilon_{r, water}$: Relative dielectric constant of the water

V_3 : Volume fraction of the third component (air or TCE)

$\epsilon_{r, 3}$: Relative dielectric constant of the third component (air or TCE)

For the calculation of the conductivity σ of sand-water-mixtures we used the 1st Archie equation valid for sands with a porosity ranging from 25% to 45% (Parkhomenko, 1967, Schön, 1996):

$$\sigma_{brine} = \frac{\sigma_w}{0,88} \Phi_s^{-1,37} \quad (2)$$

σ_{brine} : conductivity of the water-saturated mixture

σ_w : conductivity of the water

Φ_s : porosity of the sand matrix

To determine the conductivity σ of three-phases-mixtures (sand-water-air or sand-water-TCE) the 2nd Archie equation was applied (Schön, 1996):

$$\sigma_p = \sigma_{brine} S_w^2 \quad (3)$$

σ_p : conductivity of the partially water-saturated mixture

S_w : Water saturation

The regions in which the TCE remained after infiltration can be seen in Fig. 1 as grey and black dots. The white dots indicate the structures of the model-aquifer.

For the simulation of the propagation of the radar waves in the contaminated aquifer the dotted regions were interpreted as following: In all TCE pools, which have not been influenced by any structural inhomogeneity, we assumed a TCE-saturation of 10%. In those regions, where the TCE has been concentrated due to a structure, we assumed saturation gradients, e. g. from 20 % to 70% in the centre of the DNAPL pool above the uppermost structure.

The DNAPL pools were constructed by regions of different shapes and gradients in ϵ_r and σ . The modelling was carried out for a frequency $f = 500$ MHz. We used the Exploding Reflector Model for constructing zero offset lines.

RESULTS OF THE FD-MODELLING

In Fig. 2 the resulting velocity models and the synthetic migrated radargrams are shown. On the left hand side of Fig. 2 (model without TCE contamination), only small reflections from the lower part of the model aquifer can be seen. This is due to small reflection coefficients at the boundaries of different water-saturated sands and the high damping of the water. The reflections from the two upper structures are clearly visible and correspond very well with the model.

Fig. 2: Velocity-models and migrated synthetic radargrams.
 Left: Before TCE infiltration Right: After TCE infiltration

On the right hand side (model with TCE contamination) again these two elements are visible, but the reflections are also dominated by the TCE pool above the uppermost lense. The reflections from the regions, in which the TCE remained with a concentration of 10%, can be distinguished, too.

In addition, there are also distinct reflections from the lower part of the model aquifer. They correspond exactly with the structural boundaries in that region. In comparison with the non-contaminated model, here the concentration of the TCE leads to higher reflection coefficients. In these regions the contamination can be detected, if the state before infiltration is known.

FIELD EXPERIMENT

The measurements took place at three different times: Before and after infiltration and after remediation of the TCE. Many different probing instruments like Fibre Optics, Time Domain Reflectometry (TDR) and Fluorometer were installed to study the movement of this DNAPL inside the water-saturated sand. Unfortunately these metallic elements dramatically disturbed the GPR measurement. Only these elements could be recognized in the recorded data because of their high reflectivity. That is why no comparison of the real data with the synthetic radargrams can be made.

CONCLUSIONS

The results of the modelling indicate that DNAPL contaminations in an aquifer can be detected even if it is water-saturated. In most cases the detection only seems to be possible, if the state before contamination is known, so monitoring is required. Without this information there will be no direct possibility to distinguish the reflections of the DNAPL pools from other reflections, e.g. caused by structures. A further field experiment is necessary in order to confirm the modelling results and the possibilities of GPR in monitoring DNAPL contaminated aquifers and their remediation.

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