CHC-REMEDIATION OF THE SATURATED ZONE BY STEAM-AIR INJECTION

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ABSTRACT: In the first part of this paper, the general physical behavior of steam and steam-air injection in saturated porous media will be discussed. Two-dimensional lab-scale experiments were carried out to demonstrate the dominating parameters for an application of these thermal remediation methods in non-stratified aquifers. Numerical simulations are used to transfer the experimental results to various soil structures. In the second part of this paper, a case study, where combined steam-air injection was successfully applied to a site contaminated with CHC, will be discussed.

INTRODUCTION

With respect to the potential hazard, the number of field sites and the typical clean-up time, the removal of chlorinated compounds from the saturated zone remains one of the major challenges in subsurface remediation. The major problem in the remediation of CHC-sites is the low effective mass-transfer rate of contaminants in the saturated zone resulting from diffusion limited processes. Steam injection is a promising technology, which has proven its potential efficiency in many applications. By injecting a saturated steam-air mixture (Färber, 1997), the risk of mobilization and undesired downward migration of organic contaminant phase can be minimized. This has been successfully demonstrated in the unsaturated zone for both LNAPL and DNAPL. It has yet to be proven for applications in the saturated zone where additional buoyancy and capillary effects appear. Thus the cost-effective applicability of both steam and steam-air injection will be restricted by physical limitations.

EXPERIMENTAL AND NUMERICAL STUDIES

As shown in experimental studies for the unsaturated zone (Schmidt et al., 1997), the combined steam-air injection method is superior to ordinary steam injection. All thermal remediation techniques accumulate the condensing liquid contaminants within their heat front, therefore increasing the local NAPL-saturation and its mobility under gravity forces. Depending on the site specific circumstances this may increase the risk of uncontrolled downward migration of the contaminants, which could potentially never be recaptured by the heat front. By adding air to the injected steam, a non-condensable carrier medium for contaminants is created, which continuously removes contaminant mass from the front toward the extraction wells. Although not yet proven, this principle will be relevant for both the unsaturated and saturated zones.

The effects of temperature on thermodynamic laws enhancing soil remediation apply only to those zones which are reached by the heat. Thus a crucial point in designing thermally enhanced site remediations is predicting the heat front movement. Van Lookeren (1983) derived the heat front behavior for linear and radial steam drive processes used in oil reservoir engineering. These findings were further developed for subsurface remediation processes by Basel and Udell, 1987. However, a basic assumption being made for these approaches is the existence of an upper impermeable boundary layer (e.g. rock layer), impeding an upward movement of the steam zone caused by strong buoyant forces. Without such a boundary layer, soils of fair hydraulic conductivity cannot be treated in an economical way using the techniques of steam injection or combined steam-air injection. This will become evident in the following discussions.

The dominating forces for steam injection into saturated homogeneous porous media, that affect the heat front propagation are, apart from heat transfer aspects, represented by the gravity number

$$\mathrm{Gr} \equiv \frac{\mu_g \, \dot{m}_g}{\rho_g \, (\rho_w - \rho_g) \, g \, K \, H} \approx \frac{\mu_g \, \dot{m}_g}{\rho_g \, \rho_w \, g \, K \, H} ,$$

where index '*g*' denotes the gas phase (steam) and '*w*' the aqueous phase; μ is the dynamic viscosity, ρ the density, K the intrinsic permeability, H the domain height and $\dot{m}$ the mass flux density per width of injected steam. The lower the gravity number, the greater the influence of buoyancy compared to that of friction. The only variable parameters for practical applications are the steam rate, soil permeability and the characteristic domain height, whereas the fluid properties and gravity are relatively constant. It is noteworthy that the buoyant effects are quite strong, because the density difference between steam and water amounts to three orders of magnitude.

Three experiments with similar boundaries, yet with different gravity numbers will be shown. Steam at a constant rate was injected from the lower left corner into a plane two-dimensional set-up filled homogeneously with sandy porous media (fig. 1). A constant head of the aqueous phase was provided at the right side. All other boundaries were no-flow boundaries. The three figures show the temperature distribution for the three experiments at time steps of approximately the same accumulated energy input. Experiment #1 (Gr = 0.08) was carried out with coarse sand, while Experiments #2 (Gr = 0.4) and #3 (Gr = 0.8) had a medium sand matrix with a permeability one order of magnitude lower than that of #1. The difference between #2 and #3 was the steam rate for each, whereas #1 and #3 were run with the same flux. The shape of the heat front reveals a significant difference between the experiments: the larger the gravity number, the less noticeable the tendency of the heat front to move upward.

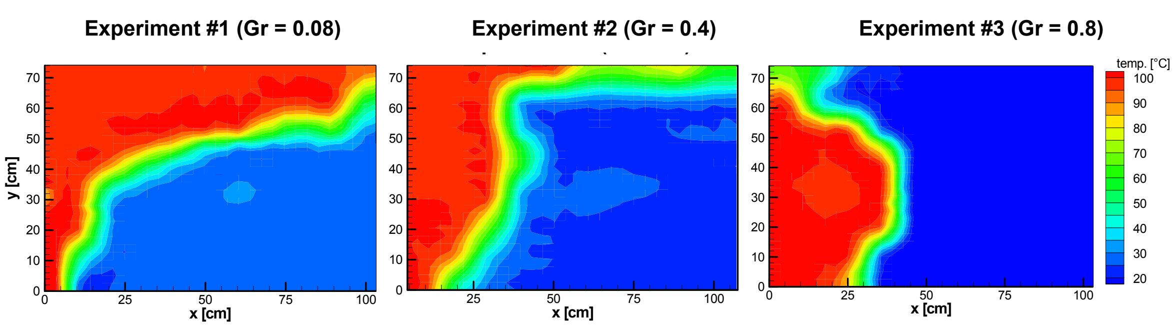

FIGURE 1. Heat front propagation in a 2-D setup during steam injection into saturated porous media; three experiments with different Gravity number Gr.

Lacking an upper no-flow boundary, the heat front in #1 will, unlike in the shown experiment, move straight upward with a small lateral expansion. In #2 the upper boundary has just been reached, resulting in a sudden horizontal expansion. The lateral influence of the injection well in #1 is very small compared to #2 and especially #3. By further increasing the gravity number, the buoyancy influence will no longer be noticeable, and the heat front propagation will look rather isotropic. It should be emphasized that enhanced contaminant removal only takes place within the heated zone. Additional wells must be installed to ensure the heating of the entire soil volume.

The strong effect of buoyancy leads to the following conclusions for practical applications: the plane 2-dimensional setup compared to cylindrical-coordinate well geometry overestimates the lateral expansion, so the radius of influence further decreases. With decreasing radius of influence, the number of wells needed on an area of a field site increases by the square. Thus for soils of high permeability (gravel or coarse sand aquifers), the required well density will become unreasonably high. For a given soil permeability and well density, the only variable parameter of the gravity number, which can be influenced by technical means, is the injected steam flux. The larger the flux is, the better the lateral heat front expansion. One general operating rule is to maximize the injection power, since it is accompanied by a reduction in remediation time. Unfortunately the largest possible power input per well for a given soil permeability is limited by the risk of hydraulic base failure resulting from too high injection pressures. Sites with contaminant sources located near to the ground surface (down to circa 10 m) allow for only moderate injection pressures, while deep wells can stand much higher rates. For soils with very low permeability the convective heat transfer is too small for reasonable soil heating, thus setting yet another limit. From our experience, the possible range of application extends over a narrow bandwidth of hydraulic conductivities from 10^{-5} to 10^{-7} m/s, as a rule of thumb. Distinct stratification, however, may allow an application of steam injection for soil strata of even higher permeability. Also, the range of application varies somewhat depending on individual circumstances at sites.

To assess the behavior of injection into more complex soil structures numerical models are important scientific tools for analyzing the coupled physical processes. Fig. 2 shows numerical results obtained with the multiphase simulator MUFTE_UG (Helmig et al., 1998). The application of inverse modeling techniques allows to identify the relevant physical parameters and processes by sensitivity analyses or best-fit estimates.

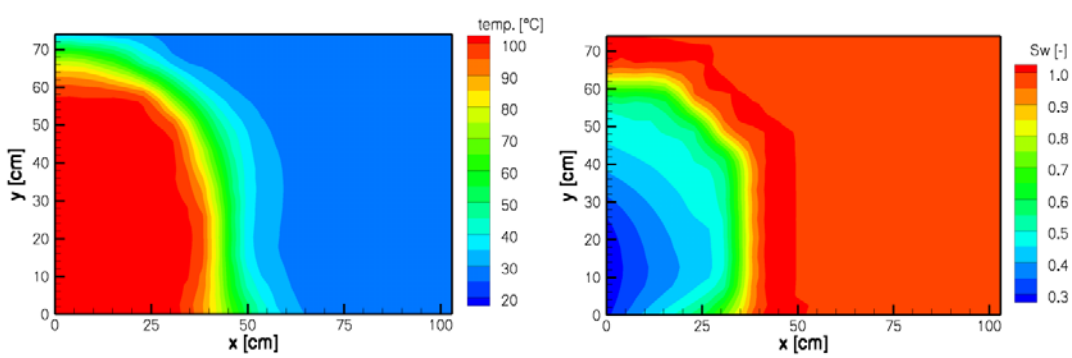

FIGURE 2. Results from numerical simulations: distribution of temperature (left) and water saturation for a gravity number of 0.8 (right).

FIELD APPLICATION

A site contamination with the chlorinated hydrocarbon PCE affected both the saturated and unsaturated zone underneath a factory building. A total volume of 250 m³ of soil was to be treated covering an area of 8 x 6 m and a depth of 6 m. The soil can be characterized as "difficult for clean-up" due to a heterogeneous structure consisting of small strata of silt, clay, marl and limestone with rather low permeability (fig. 3 and 4). The confined aquifer stretches over 2 m depth with heads and fluxes fluctuating greatly from rainfall.

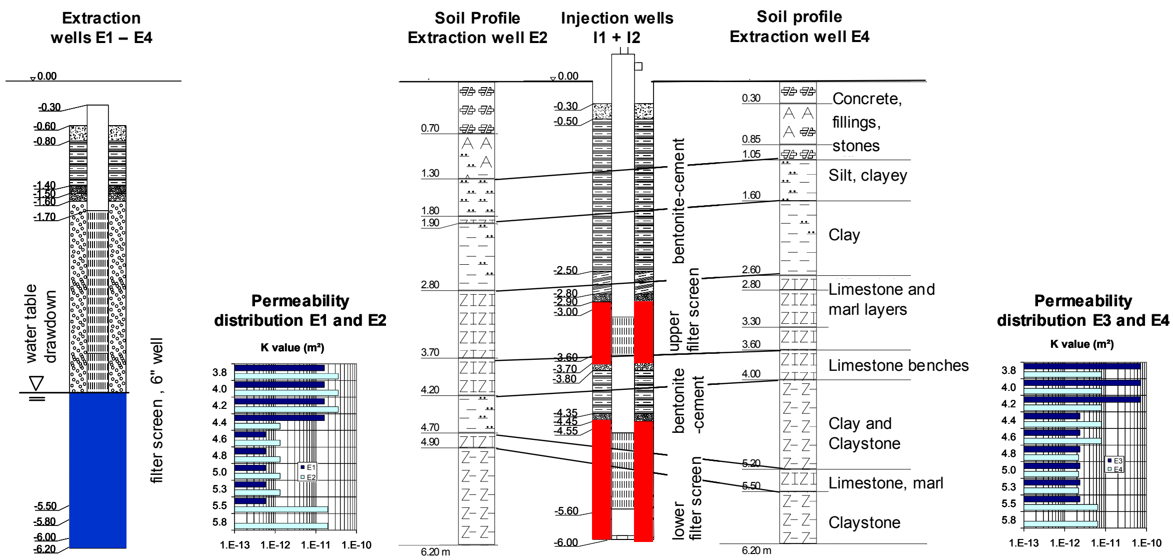

FIGURE 3. Hydrogeological situation and filter sections of the wells.

Several in-situ remediation technologies, such as pump-and-treat, soil vapor extraction (SVE) and in-well stripping, were operated throughout the last 10 years. In total, a contaminant mass of 36 kg was removed, mainly by pumping groundwater, while the soil vapor extraction and in-well stripping, contributing to only 1.75 kg, were not successful. After this period, the total costs had summed up to US$ 600,000, and the low contaminant removal rates and the remaining high levels of PCE-concentrations did not encourage expectations of finishing the clean-up within the next decades. Nevertheless, due to high groundwater concentrations of PCE exceeding by far the required threshold values the local authorities insisted on continuing the remediation.

In order to evaluate the feasibility of the steam-air injection method some investigations were carried out. Flow-log investigations revealed the vertical variation of soil permeability (fig. 3). The soil sampling campaigns carried out over the last decade showed great spatial variation in contaminant concentration and indicated a total mass of PCE between 500 g to 11 kg contained in the treatment volume.

Prior to starting the clean-up, air injection tests with SF_6-tracer were carried out. This was necessary to confirm the ability of the extraction wells to capture all of the injected air together with volatilized contaminants. The tracer response was quite fast, showing arrival times between 5 and 33 minutes and depending largely on the level of the groundwater table, which was regulated by groundwater pumps. The additional occurrence of twin-peaked recovery curves of the tracer illustrated the stratified soil structure and the existence of non-predictable preferential pathways for gas migration, thus stressing the necessity of such tests. Nevertheless, all tests resulted in a complete tracer removal, confirming a safe operation of the gas injection.

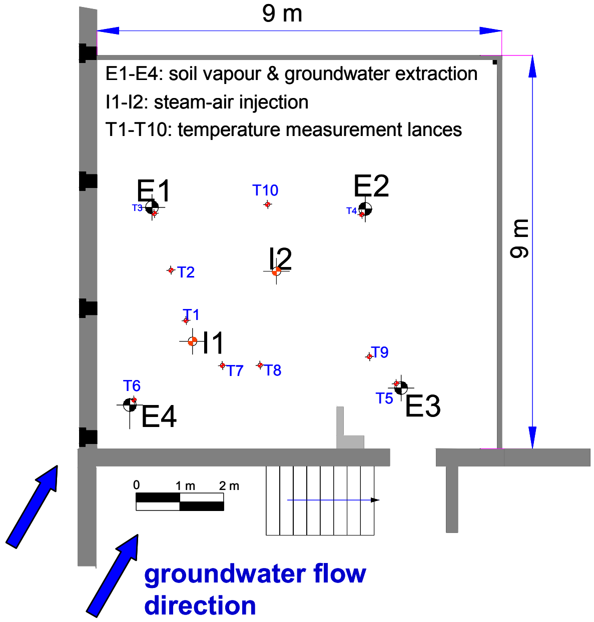

FIGURE 4. Plan view of the site: extraction wells E1 to E4, while I1 and I2 serve as injection wells for steam-air; T1 to T10 are positions of thermocouple bundles.

A steam-air system generator was installed to remediate both the saturated and unsaturated zone, enabling the injection of 50 kW power with variable air fraction over two central injection wells at different injection levels (cross section in fig. 3). The extraction was designed as a combined SVE and groundwater pumping system using four surrounding wells (fig. 4). The spatial heat front movement was continuously monitored by temperature sensors installed in the subsurface. Mass fluxes and contaminant concentrations in the extracted soil vapor were measured continuously.

The whole remediation could be successfully terminated within less than 3 months. Over this period different operation modes for the injection were applied, which is shown together with the contaminant concentrations and the accumulated PCE-mass extracted via SVE in figure 5. After one week of air-sparging the steam-air injection was started. This resulted in a strong increase of PCE-removal whenever a breakthrough of the heat front at the extraction wells occurred (the time scale is set to zero here). Within the first 30 days of constant operation, the target zone was heated up to temperatures above 90°C. After one month compressed air pulses at higher pressures were released in addition to a continuous steam-air flux, resulting in increased contaminant concentrations. After 51 days the injection was switched partly to the upper layer, causing another significant increase in concentrations. Followed by a constant decrease over the next month concentrations reached a level close to the detection limit. After 84 days the steam injection was stopped and simultaneously the air flux suddenly doubled for one day, which caused a small concentration peak. The final air-sparging into the heated subsurface continued over another two weeks, leaving gas concentrations at a low level.

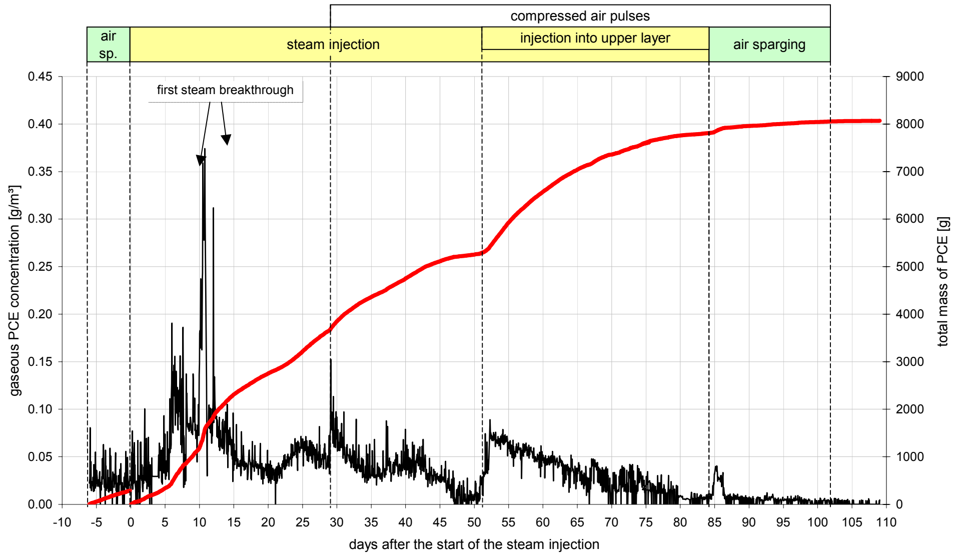

FIGURE 5. Gaseous PCE concentrations and total mass of PCE removed via SVE.

The groundwater concentrations in fig. 6 are indicated for each extraction well. The groundwater extraction, which was started two weeks before air-sparging, reduced the concentrations significantly, whereas air-sparging did not show noticeable effects.

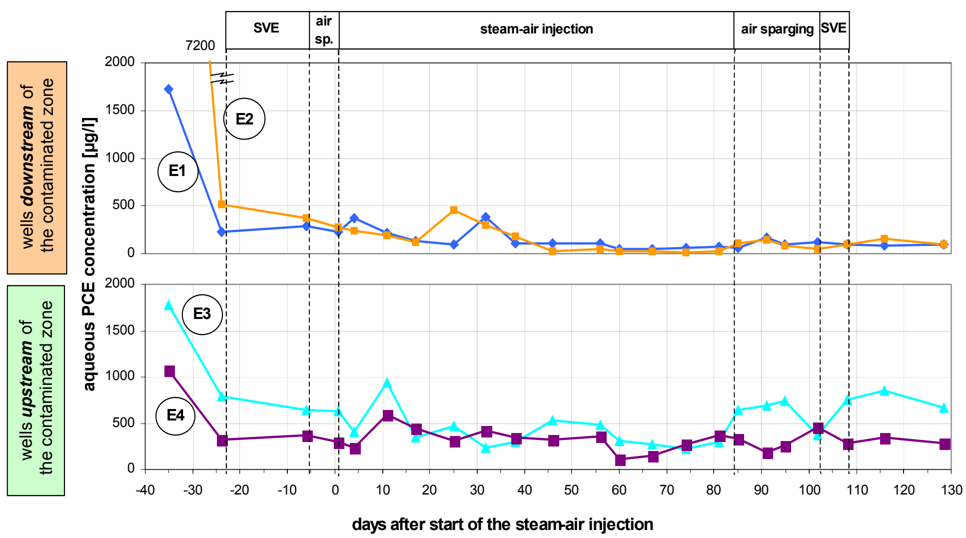

FIGURE 6. PCE concentrations in the removed groundwater.

Also, a discernable difference was observed depending on the location of the wells in the groundwater flow field: compared to the initial air-sparging period the concentrations in the two upstream wells, E3 and E4, did not change significantly during the thermal remediation process. The slight increase of upstream concentrations after the steam injection was stopped most likely resulted from a contaminant source located upstream, a fact which was later confirmed by the local authorities. The stripping and removal of contaminant nests within the heated zone showed strong effects at the wells E1 and E2, located downstream. The concentrations there reached threshold values. Obviously the hot water captured by E1 and E2 has already been stripped off efficiently from contaminants, whereas the water from upstream is almost not affected from the downstream heating and stripping processes.

The heat propagation is visualized in the spatial temperature distribution after 5, 40, 65 and 90 days (fig. 7). In general, a fast heating can be observed. However, the lower section near I1 and E4 is cooler, indicating the strong influence of cooling water coming from upstream. Likewise the levels above 3.5 m bgs., having a lower permeability (limestone and marl) remain cooler. After 40 days the temperature field reaches nearly steady state conditions, as heat "losses", mainly caused by groundwater pumping, almost compensate for the total power supplied from the steam injection. The situation after 65 days shows the increased energy input in the "unsaturated" level (above 3 m depth), although this section seems to be rather impermeable. After 84 days the steam injection was stopped, and the fast cooling process can be observed in the 90-day's plot.

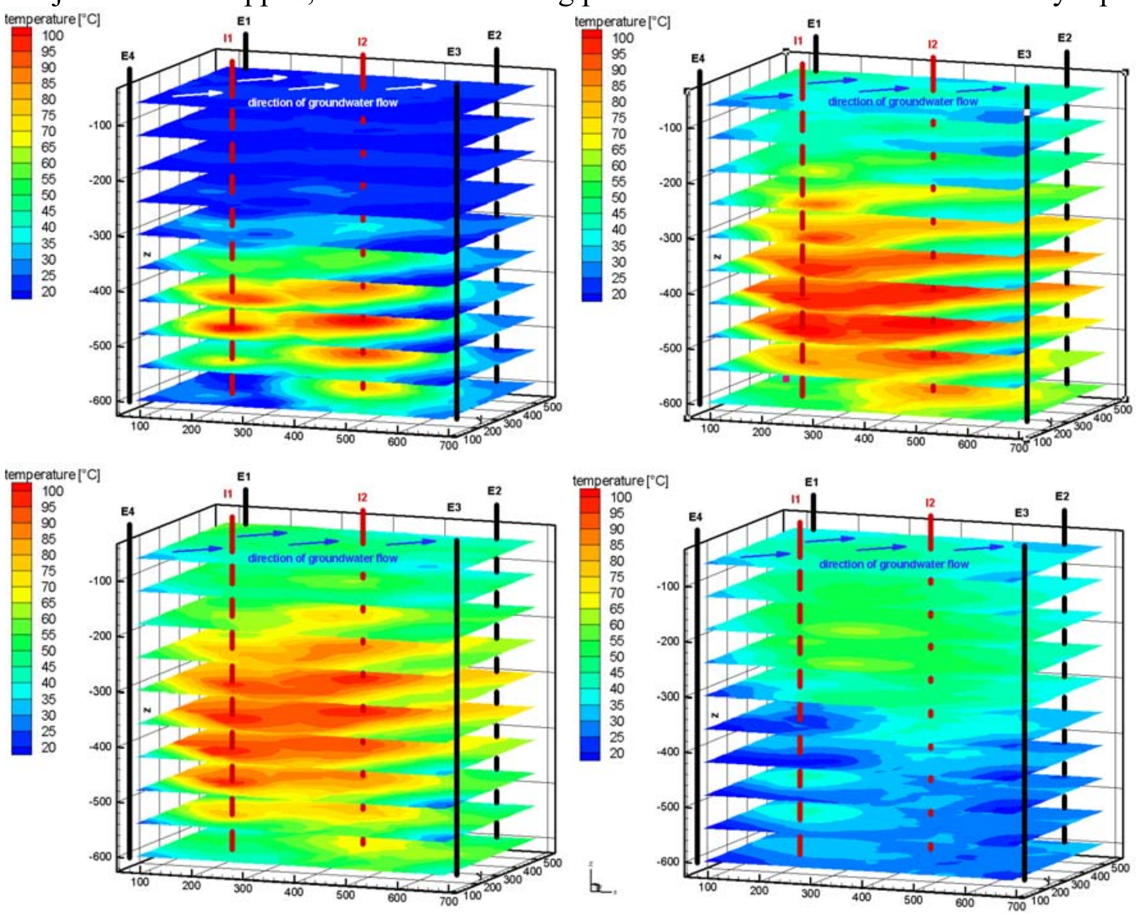

FIGURE 7. Spatial temperature distribution at 5, 40 (top), 65 and 90 (bottom) days after starting the steam-air injection (lengths indicated in cm).

From the total 11.25 kg of PCE removed over three months, the major fraction (8,25 kg) was extracted via the air path, while 3 kg were removed through groundwater pumping. This far exceeded the removal rates achieved by the "cold" remediation methods applied throughout the previous 10 years.

SUMMARY AND CONCLUSIONS

Steam-air injection into the saturated zone was used as a remediation technique to clean up a small site with difficult boundary conditions. In comparison to a conventional pump and treat remediation, which was formerly operated at this site, the steam-air injection has proven itself to be a very fast and effective method for cleaning up CHC-contaminations in the saturated zone. Because of a safer operation, reducing the risk of unwanted mobilization of condensed contaminants, it is superior to steam injection, assuming that the injected air loaded with contaminants can be fully recovered. A large amount of money could have been saved on this site, if initially thermal remediation had been used.

From data observed in the laboratory and during field investigations, severe limitations could be identified, restricting the application of steam or combined steam-air injection. The heat and mass transfer processes in heterogeneous soils in the saturated zone are highly complex and largely dependent on hydrogeological conditions. Additionally, heat losses from groundwater pumping cannot be neglected. If the soil structure is homogeneous and has rather high permeability, the influence of buoyant forces limits the lateral propagation of the heat front, requiring the installation of an unrealistically high number of injection wells. On the other hand, if soils show a very low permeability the small heat fluxes make steam or steam-air injection impractical. These two limits describe the small bandwidth of application for these methods (hydraulic conductivities of about 10^{-5} to 10^{-7} m/s), which can be either slightly extended or even more restricted by distinct heterogeneities of soil structures.

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