STEAM ENHANCED EXTRACTION (SEE) AS INNOVATIVE APPROACH FOR TCE REMOVAL

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Abstract

The Steam Enhanced Extraction (SEE) technology was successfully used to remove a TCE source (DNAPL) from a layered aquifer system at a heavily exploited industrial area near Prague, Czech Republic. Geologically, is the site formed by alternating sandstone (containing groundwater) and siltstone or claystone (representing an aquitard and/or aquiclude) layers.

The steam and air were firstly continuously co-injected into two wells. Whereupon vapors were extracted from a series of extraction wells surrounding the injection wells. After the aquifer system is heated to the maximum temperature (equal to the local boiling point of water), the cyclical manner of air-steam injection takes place. The objective of the cyclic operation is to remove TCE from the less permeable block, separated by more permeable zones.

The steam was injected into the soil during three steam injection cycles. During the first cycle, two weeks were needed to heat the contaminated zone to the maximum temperature. During (in total) 3 months of SEE operation about 5 t of pure organic phase (TCE) was extracted from the aquifer. At the same time TCE concentrations in the groundwater of the heated zone decreased about 2000 fold. Four months after the end of the heating, the temperature still remained elevated.

Dense Non Aqueous Phase Liquids (DNAPLs) are common groundwater contaminants, but with a particular interest. This interest results from their physico-chemical properties compared to water (low solubility, dense and less viscous). These properties make them particularly mobile in an aqueous environment, but very difficult to extract. In the case of DNAPL presence combined with soil heterogeneity, the application of classic remediation technologies (for example pump and treat technology, SVE) practically excludes the possibility of reaching the defined remediation limits in reasonable time horizons. The Steam Enhanced Extraction Technology (SEE) is an innovative and very efficient remediation technology. The results obtained reflect the ability to remove large amounts of contaminant mass and to reach defined clean-up levels in a very short period of time. The first full scale SEE technology application in the Czech Republic is presented in this paper.

Introduction

Geologically is the site formed by sub-horizontally layered sedimentary rocks. In the geological profile are observed alternating middle or fine-grained sandstones, siltstones and clay-stones. During the geological prospecting were observed up to 3 cm opened sub-vertical fractures in sandstone rocks. Two perpendicular systems of fractures are separating 3 to 5 m blocks of hard sandstone. All observed fractures ended in pliable clay-stones and siltstones. *Hydrogeologically* are observed at the site four above-laying aquifers (1, 2A, 2B, 2C) represented by more permeable rocks (sand and sandstones) and separated by less permeable aquitards or aquicludes (clay-stones and siltstones). The permeability of the 1st upper aquifer The initial groundwater head level was found 5 m under the ground level. The lower 2nd-A aquifer is confined with the permeability in the order 10^{-5} $m.s^{-1}$, and the initial groundwater level found at 3 to 5 m under the ground level. The first and also partially the second aquifers were dried during performed remediation activities (water pumping from shaft / adit with sub horizontal wells). As a result was the free groundwater head measured (during SEE technology application) at a depth of 7 m under the ground surface.

The initial *contamination* of the site is composed by the mixture of more than 10 DNAPL compounds (PCE:TCE:DCE:VC = 7,6%:86,1%:6,4%:0,1%). The DNAPL contamination was present in only in the first two (1-st and 2A) (upper) aquifers, but mostly in the center of contaminated profile (isolated DNAPL accumulations retarded by the clay-stone aquiclude). That's why all remediation activities (and also all presentations) cover only contaminated upper part of the aquifer system (the first and the second-A aquifers are separated by 0,5 m thick aquiclude). Measured initial concentrations of total CHCs in groundwaters were bigger than 100 $mg.l^{-1}$ (proof of DNAPL presence in groundwater system).

Materials and methods

The extraction system ten vapor and water extraction wells. All around the heated zone was constructed 6 additional SVE and pumping wells to prevent further contaminant migration to the site surrounding. For the same purpose was constructed 50 m long horizontal adit under the main production building with the system of 19 subhorizontal "drainage and SVE" wells. The vapor extraction was provided from two different horizons by the means of four vacuum pumps of the type SD6 with the total capacity of 600 $m^3.h^{-1}$.The total groundwater extraction rate from the site was 0,3 $l.s^{-1}$.

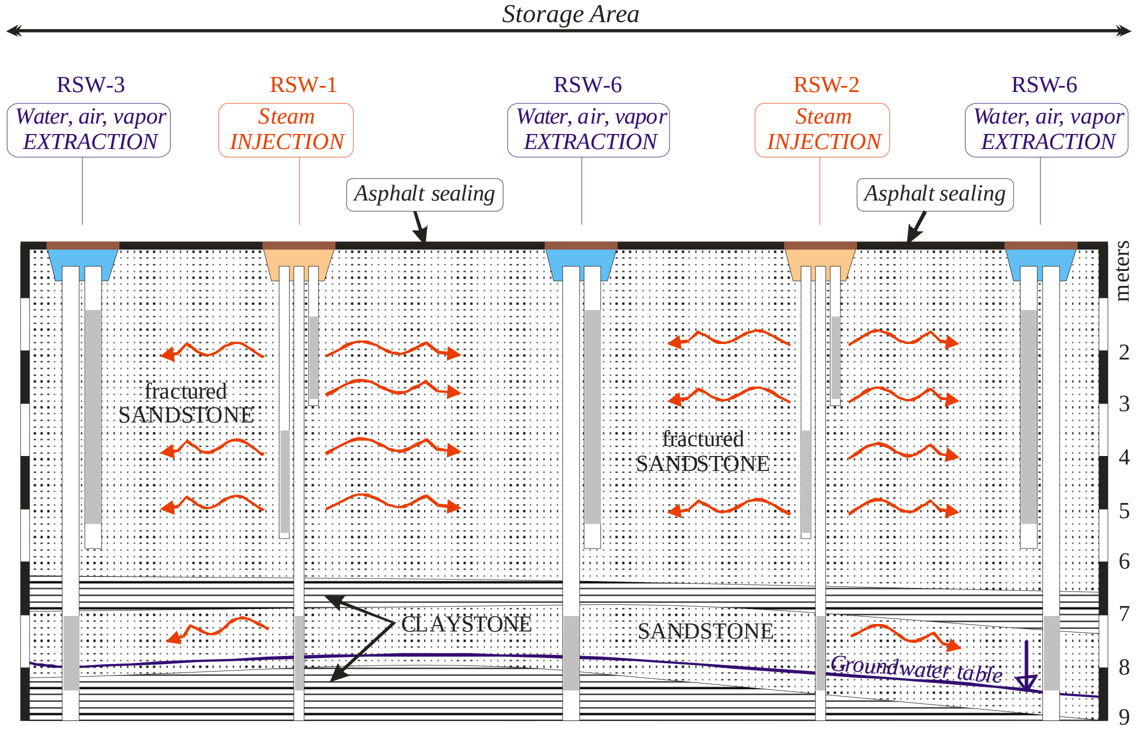


Figure 1: Vertical schema of the injection-extraction system and hydrogeological conditions.

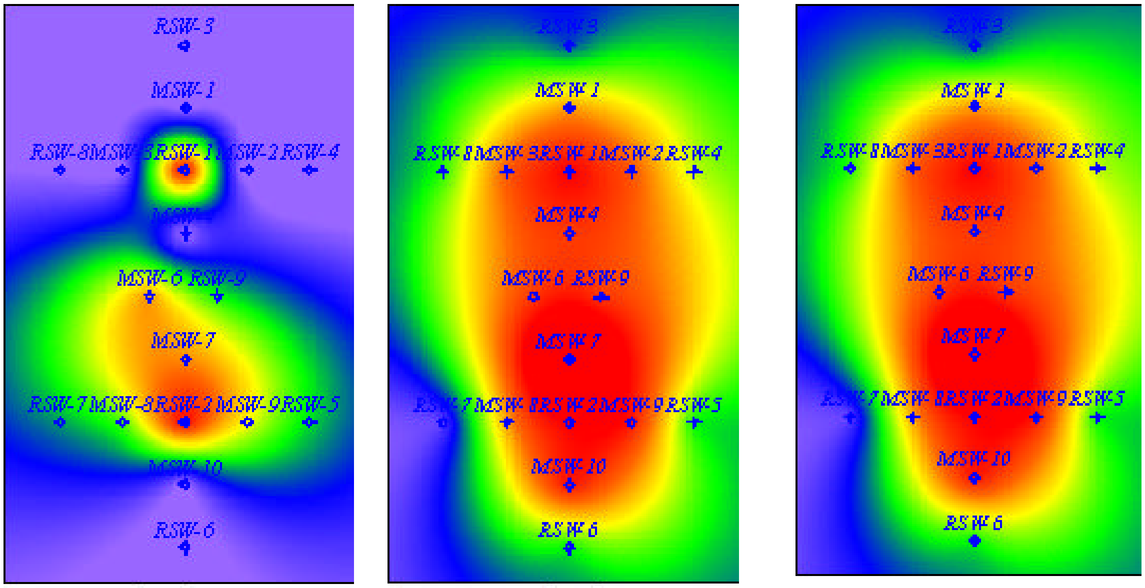
The steam and water injection system consist of three steam injection wells and three water injection wells. The steam injection was allowed to three different horizons (see figure 1), with the total injection rate of 250 g.h^{-1}. All injection and extraction intervals covered all contaminated profile, but the water and vapor communication between two aquifers was prevented by the bentonite and cement well packing. Because of numerous obstructions above ground and very limited access to heavily exploited areas of the plant the water/gas treatment station must be situated out of the site, and all pipes and cables underground.

The monitoring system allowed the observations of time and spatial evolution of temperatures and contamination concentrations in water and gas phases. Pressure and gas flow rate measuring, combined with numerical modeling allowed the optimization of the extraction system effectivity. All parameters allowed the control of remediation progress and the prevention of undesired DNAPL dispersion out of contaminated zone. Temperatures were collected (twice a day) by means of a 100 resistive thermocouples placed to three different depth intervals all around of heated zone. Water and gas samples were collected and analyzed by means of the gas chromatography, combined with the mass spectroscopy detector, and the flame ionization detector.

The remediation concept consist of four different phases: 1) contaminated area dewatering – to facilitate the steam injection and vapor extraction, 2) continuous steam/air injection – to heat the contaminated zone as fast as possible to maximum temperature, 3) pulsed steam/air injection and vapor extraction – to clean less permeable zones enhanced by high hydraulic gradients, 4) clean water injection combined with the pump and treat technology – to complete groundwater remediation and to reach fixed remediation limits (present state).

Results and discussion

The soil *temperature* distribution is demonstrated at the figure 2. Almost two weeks were needed to reach the local boiling point temperature of water. The fastest temperature growth was observed in deeper intervals of soil, and slowest in more shallow intervals of soil (what corresponds to higher injection rate to deeper zone as well as to the influence of soil cooling by the atmosphere). Also more shallow soil zone was cooled faster, but generally after more than four months the temperatures didn't reach their initial values.



4-th day 14-th day End of SEE

Figure 2: Soil temperature evolution at the depht of 4,5 m under the ground surface.

The SEE technology efficacity is documented by the total CHCs concentration evolution in groundwaters from the monitoring well MW-18 (located in the center of DNAPL contamination zone, see figure 3). The initial concentrations indicated the presence of the DNAPL (45 mg.l^{-1}). During the SEE Technology application, the total CHCs concentrations decreased more than 2000 times. After more than 1 year of post-remediation monitoring, the CHCs concentration in groundwater still remains below given target limits.

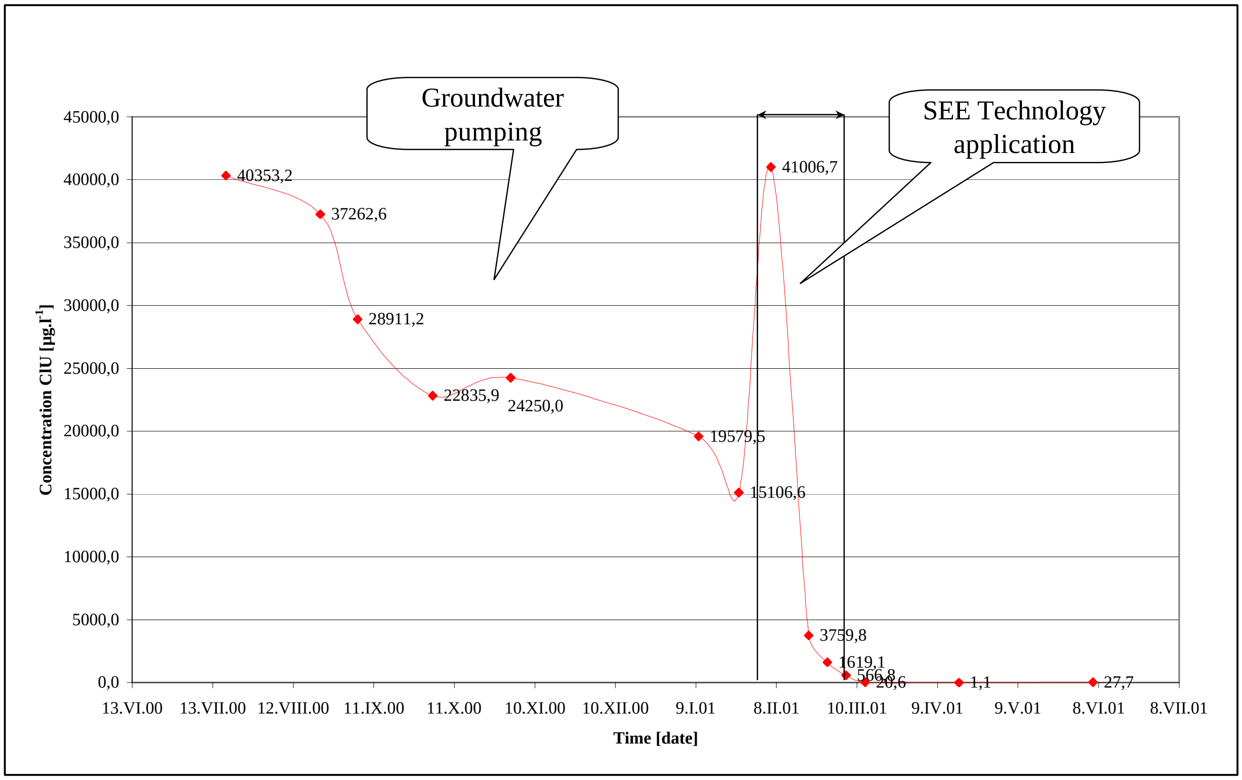


Figure 3: Total CHCs concentration evolution in groundwater from the well MW-18, placed in the centre of DNAPL contamination zone.

During SEE application was the major part of contamination extracted in vapor phase. Total CHCs *concentrations* in extracted gas increased more than 200 times. At the same time was measured fast groundwater contamination disappearance. Total CHCs concentrations in groundwater decreased 1000 times during one month of SEE application. Almost 5 tones of pure TCE product were removed during SEE application. The remediation success is documented on figures 3 and 4.

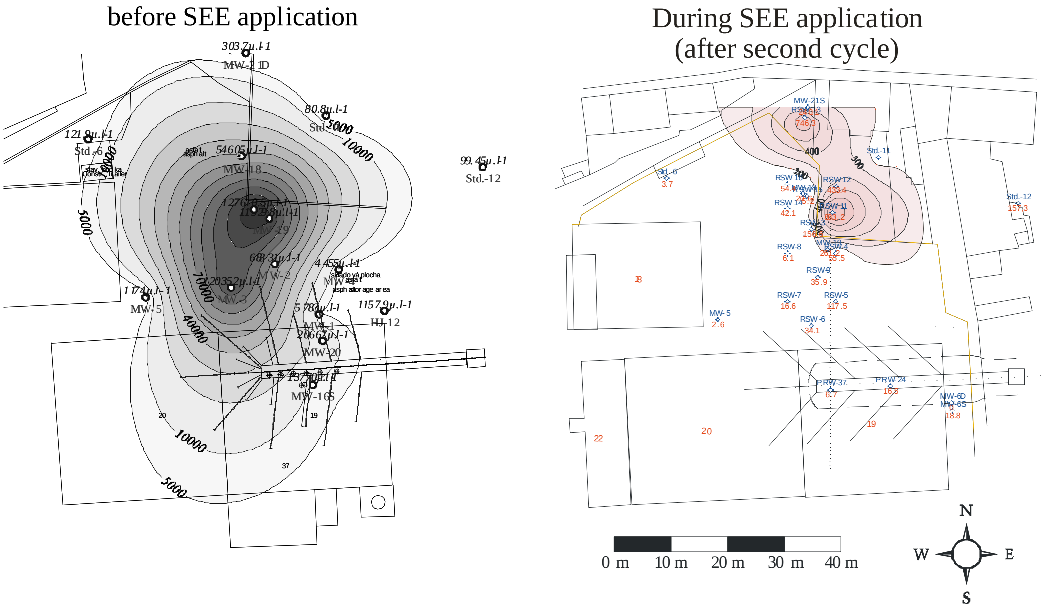


Figure 4: Comparison of the initial and intermediate contamination distribution.

To help with the optimization of SEE extraction system efficacity the numerical modeling of gas flow field around the venting well system as well as of temperature field around the SEE system. The gas flow model was performed by means of the Visual MODFLOW code. Three dimensional, multilayered model was constructed. Gas pressures were expressed (and used) in the equivalent pressures to mm of H_2O. The input parameters were characteristics of soils, parameters of wells, and injection – extraction pressures and rates. The model gave a good response especially about the pressure gradients around the aquiclude separating two contaminated aquifers. This information was important to prevent downward migration of contamination during SEE application. The temperature field was modeled by means of the three dimensional multilayered numerical simulations performed by means of the code M2NOTS. Good coherence between modeled and observed results was obtained.

Conclusions

Our work has documented that in the case of optimal SEE technology system configuration, the soil layering and heterogeneity does not significantly influence the remediation progress. No rebound effect was observed after the end of SEE technology application and site closure (during more than 1 year of post-remediation monitoring). The results obtained reflect the ability to remove large amounts of contaminant mass and to reach defined clean-up levels in a very short period of time.