Remediation of a partially fractured aquifer system containing a TCE source using Steam Enhanced Extraction

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

The steam and air were firstly continuously co-injected into two wells. Whereupon vapors were extracted from series of extraction wells surrounding the injection wells. After the aquifer system was completely heated through, a cyclical manner of air-steam injection took place.

Two weeks were needed to heat up the contaminated zone. Four months after the end of the heating operations, the temperature still remains elevated. During a 1-month SEE operation about 2,5 t of pure organic phase was extracted from the aquifer. At the same time TCE concentrations in the groundwater of the heated zone decreased about 1000 times.

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 (denser 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 the soil heterogeneity, the application of classical remediation technologies (e.g. pump and treat) practically excludes the possibility to reach the defined remediation limits in reasonable time horizons.

The Steam Enhanced Extraction Technology (SEE) is an innovative and very efficient remediation technology. Obtained results have reported on the ability to remove a large amount of contaminant mass and to reach defined clean-up levels in a very short period of time. In this paper the first field scale SEE technology application in a heterogeneous groundwater system in the Czech Republic is presented.

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Geologically, the site is formed by sub-horizontally layered sedimentary rocks. Alternating medium or fine-grained sandstones, siltstones and clay-stones are observed in the geological profile. During the geological prospecting, up to 3 cm of opened sub-vertical fractures in sandstone rocks were observed. Two perpendicular systems of fractures are separating 3 to 5 m blocks of solid sandstone. All of the observed fractures ended in pliable clay-stones and siltstones. *Hydrogeologically,* four above-laying aquifers represented by more permeable rocks (sand and sandstones) and separated by less permeable aquitards or aquicludes (clay-stones and siltstones) are observed at the site. At the same time opened fractures are observed representing more permeable zones (with preferential groundwater flow) and separating less permeable (porous) blocks. The first and also partially the second aquifers were dried during remediation activities. An adit with a series of subhorizontal drains located under building was used for this purpose. As a result the groundwater head was measured (during SEE technology application) at a depth of 7 m under the surface. The depth of the wells was about 9m under the surface.

The *contamination* of the site was caused by a mixture of more than 10 aliphatic chlorinated hydrocarbons, where TCE was the prevailing compound (more than 85%). The DNAPL contamination was present in the first two aquifers, mostly in the center of the contaminated profile (isolated DNAPL accumulations retarded by the clay-stone aquiclude). That is why the SEE application focused on the contaminated upper part of the aquifer system (the first and the second aquifers separated by a 0,5 m thick aquiclude). Measured initial concentrations of total CHCs in groundwater were bigger than 120 $mg.l^{-1}$. Moreover, proof of DNAPL presence in the groundwater system was done by addition of Sudan IV.

The extraction-injection system was composed of two steam injection wells and seven vapor and water extraction wells. The steam injection was made into three different horizons, the vapor extraction was provided from two different horizons by the means of four vacuum pumps with the total capacity of 600 $m^3.h^{-1}$. All of the injection and extraction intervals covered the whole of the 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 off 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. Pressure and gas flow rate measuring, combined with numerical modeling allowed the affective optimization of the extraction system. 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 six different depth intervals around the heated zone. Water and gas samples were collected and analyzed under strict QA/QC conditions by means of gas chromatography, combined with a mass spectroscopy detector, and a flame ionization detector.
The remediation concept consisted of four different phases:
1) contaminated area dewatering – to facilitate vapor extraction, 2) continuous steam/air injection – to heat up the contaminated zone as fast as possible, 3) pulsed steam/air injection and vapor extraction – to clean up less permeable zones

enhanced by high hydraulic and pressure gradients, 4) clean water injection combined with the pump and treat technology and air sparging – to complete groundwater remediation and to reach clean-up goals (present state).
Approximately four weeks were needed to heat up contaminated soil to *temperature*, which was required (89-100^{o}C). However, after more than four months the temperatures didn't reach their initial values (5-15 ^{o}C). 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 3 tones of pure TCE product were removed during SEE application.

Clean up goals in groundwater have been set as follows:
1) Facility Area, Aliphatic Chlorinated Hydrocarbons – total (CHCs) = 0.8 mg/l
2.) Environ of the Facility Area, where domestic wells are located CHCs = 0.2 mg/l.
As a conclusion, it can be said that within one year of remediation using the SEE, the clean-up levels have been obtained at all monitoring points, which are situated both inside and outside of the facility. It should be emphasized that the domestic wells together with residential area were located in a distance of not more than 30m from a couple of the steam injection wells. Any significant increase in contamination of the area outside of the extraction wells was not found. For a comparison, under the same geological and hydrogeological conditions one well was only treated by continuous pump-and-treat technique. After one year of the pumping concentrations of CHCs has been almost not changed (initial concentration PCE=4.5 mg/l, final concentration PCE = 4.3 mg/l).

Our work has documented that in case of proper SEE technology system configuration, the soil layering and heterogeneity doesn't influence significantly the remediation progress. Furthermore, a research (log well measurements through whole wells profile) has shown that soil permeability from absolute point of view has not been significantly changed. The steam injection impacted only at relative scale local heterogeneities in the soil permeability i.e. the permeability was equalized through the remediated area. For instance, before the SEE application it was obvious that DNAPL was accumulated mainly at spots with relatively low local permeability. After the SEE application overall hydraulic conductivity remained same but the spots with low local permeability disappeared. Another experiment has shown that reintroduction of bacteria after end of the SEE application was very fast, and only a lack of nutrients (P) was getting be a limiting factor for their further growth.

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