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A Study on Unsaturated Zone Characterization and Feasibility of Soil Vapor Extraction at a DNAPL-contaminated Site in Korea

Man Na Mi Lee · In Wook Yeo*

Department of Earth and Environmental Sciences, Chonnam National University, Gwangju, Republic of Korea

ABSTRACT

This study aimed at characterizing unsaturated zone at the source zone area contaminated by DNAPL and investigating feasibility of soil vapor extraction (SVE). Five boreholes with three multi-level screens at the depth of 3.0~4.5 m, 5.5~7.0 m, and 8.0~12.0 m were installed at the source zone. Pneumatic tests were performed to determine the permeability of porous medium. Permeability was estimated to be 81.6 to 203.7 darcy, depending on the applied solutions, which was contradicted by grain size analysis of cored soil samples leading to 3.51 darcy. This is due to air flow through gravel pack during the early stage of pneumatic test. Pressure-drawdown curve in the late stage also well showed the leaky aquifer type, indicating air leakage to the ground. Air flow tests were also carried out to investigate air flow connectivity between multi-level wells, indicating that the horizontal air flow was well developed between the lower screens of the wells, not between the upper and middle screens due to the leakage to the surface. For the SVE test, there was no noticeable variation in TCE vapor concentration between three different test runs: 1. 8 hours daily for 5 days, 2. 24 hours together with air blowing at another well (BH1), 3. five consecutive days. Even for five-day consecutive test, total amount of removed TCE was estimated only to be as low as 46.5 g.

Key words : Unsaturated zone, DNAPL, Pneumatic test, Air flow connectivity, SVE

1. Introduction

Groundwater contamination by Dense Non-Aqueous Phase Liquid (DNAPL), such as trichloroethylene (TCE), has been found in many industrial complexes in Korea. DNAPL forms a long term source of contamination due to its low solubility in water (Susan and Dunja, 1991). Under the influence of gravity force of DNAPL, it migrates downward through unsaturated zone. DNAPL must have sufficient mass to overcome the capillary forces of smaller pores holding water (Amundsen et al., 1999; Ji et al., 2008). Therefore, DNAPL tends to remain behind while it is migrating to water table, trapped in unsaturated zone. Residual DNAPL blobs in unsaturated zone partition into the vapor phase, the degree of which depends on the relative volatility of DNAPL (Fetter, 1999).

The study area, located in an industrial complex, Wonju, Republic of Korea, is contaminated by TCE, which was used as solvent from 1988 to 1997. Contaminated-top soil dug out up to 3 m deep in 2004 to 2005. However, a high concentration (15 mg/L) of TCE in groundwater exceeding drinking water standard (0.03 mg/L in Korea) is still detected in the source zone area. Recent studies showed that the rise in water table led to an increase in TCE concentration, indicating that TCE sources exist in unsaturated zone above the water table (Yang, 2011).

This study aims at characterizing unsaturated zone in terms of permeability and air flow connectivity and investigating feasibility of soil vapor extraction (SVE). Lee et al. (2007) reported that in-situ technology occupied 83.3% of domestic remediation market from 2000 to 2006 in Korea, while ex-situ technology did 16.7%. SVE was most selected by as much as 35.5% among many in-situ technologies because of its advantage of high economic feasibility and convenience in use at operating business places. SVE is

*Corresponding author : iwyeo@chonnam.ac.kr
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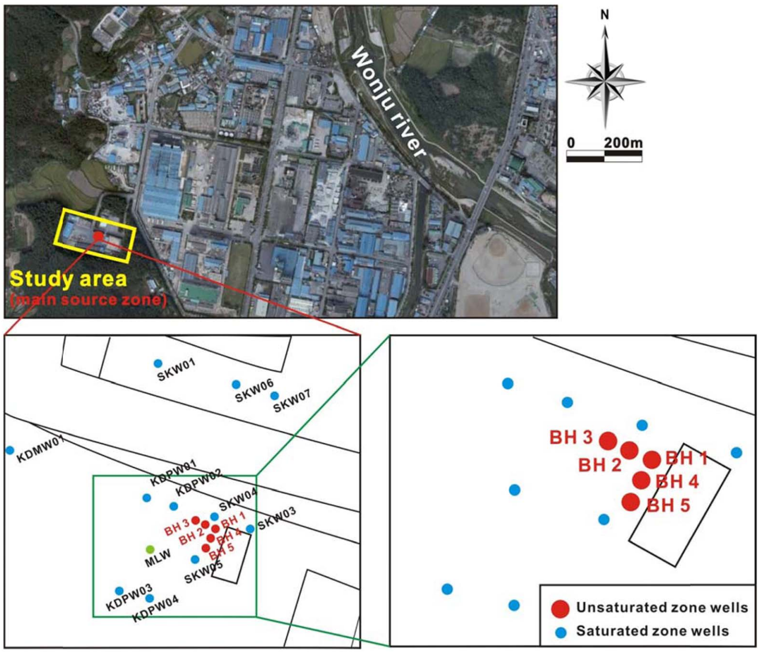

Fig. 1. Location of the study area in the industrial complex in Wonju and schematic diagram of the wells (BH1 to BH5) used for this study.

often considered as one of the feasible remediation methods for removal of VOCs in unsaturated zone. The SVE system can remove DNAPL trapped in unsaturated zone. As air is drawn through the soil, contaminants that volatilize into the vapor phase are carried along with the bulk movement of air in a process known as advection (USACE, 2002). Air flow patterns in subsurface are affected by hydraulic conductivity, soil permeability and soil structure (Johnson et al., 1994). Less permeable sediments such as silt and clay are not considered appropriate for SVE because they inhibit air flow, thus lowering the removal efficiencies (Mayer and Hassanizadeh, 2005). Therefore, it is important to characterize the unsaturated zone.

Pneumatic test was conducted to determine air permeability of porous medium in unsaturated zone. Air flow tests were also carried out to investigate air flow connectivity between multi-level screens of the wells, which is essential to the design of the SVE system. The pilot scale SVE test system was constructed, and three different test runs were carried out to optimize test procedure. TCE vapor concentration was monitored with time. The SVE removal efficiency of DNAPL trapped in the unsaturated zone was evaluated for its feasibility.

2. Hydrogeological Setting

The study area, revealed as DNAPL source area, is set on a developed flatland (EL. 136 m) of the mountain (EL. 205 m) in the west side of an industrial complex in Wonju, Korea, located about 120 km east of Seoul (Fig. 1). The Wonju river on the east side of the study area runs toward the north. Consequentially, the ground water flows from DNAPL source zone to the river. There are a number of small-sized factories on alluvium between the study area and the river. Average annual precipitation measured in the Wonju meteorological station was 1480 mm for 2009-2012 (KMA, 2013).

Of DNAPL source zone, the unsaturated zone mainly consists of weathered soil (about 3 to 6 m deep below the surface) with reclaimed soil (about 0 to 3 m deep) on the top of it, below which the weathered rocks (approximately 6 to 29 m deep) and the fresh two-mica granite (below 29 m deep) are sequentially seated as schematically drawn in Fig. 2. From October, 2010 to February, 2012, the water level measured in the source zone fluctuated between 8 m and 13 m deep below the ground surface. TCE concentration was closely connected to water level fluctuation (Yang, 2011), which was is 13.15 ppm when the water table rose to 8 m

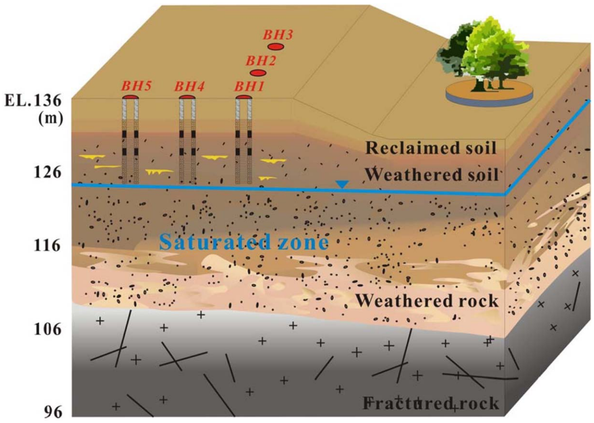

Fig. 2. Schematic diagram showing vertical cross section and hydrogeological setting in DNAPL source zone area.

deep below surface and 0.55 ppm when it dropped to 13 m deep, respectively. The rise in water table led to an increase in TCE concentration. This observation strongly suggested that residual DNAPL blobs exist in the unsaturated zone between the reclaimed soil and the water table.

A high TCE concentration in groundwater sample was detected at SKW4, SKW5 and KDPW2 (Fig. 1). The multi-level SVE test appears suitable for variety of geologic environment and has advantage over other field-test methods (Widdowson et al., 1997). Therefore, five boreholes (BH1 to BH5) with three multi-level screens at the depth of 3.0~4.5 m, 5.5~7.0, and 8.0~12.0 m were constructed to characterize the unsaturated zone. The details on the wells are schematically drawn in in Fig. 3. Five boreholes are 1 m distant from each other.

3. Field Tests

3.1. Pneumatic Test

Pneumatic tests were carried out for the whole screen of BH1 to BH5 in turn. Air was blown or extracted into/from one of five wells for three hours using air blower and vacuum pump, and air pressure change was monitored at the neighboring two wells. During the tests, the wells were all capped. Air injection and extraction rates were 140 L/min and 45 L/min, respectively.

Permeability was calculated using the following equation, which was modified from the Theis equation for air permeability (Johnson et al., 1990):

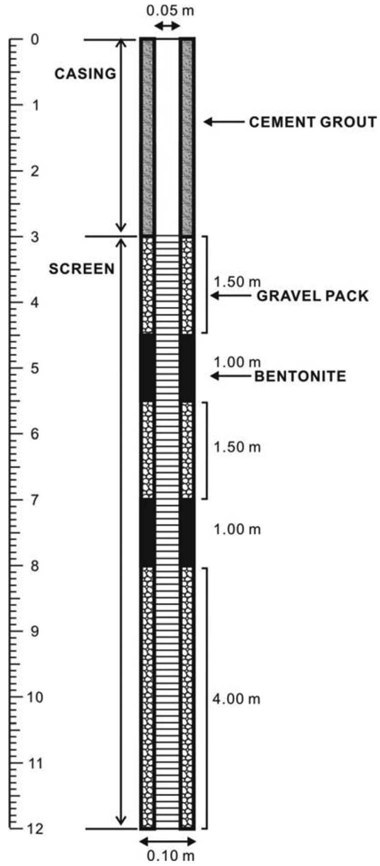

Fig. 3. Details of the well with multi-level screens.

$$k = \frac{Q_v \mu}{4\pi b(P - P_{atm})} W(u) \tag{1}$$

where k is air permeability [L^2], Q_v is volumetric flow rate [L^3/T], μ is air viscosity [M/LT], b is thickness of unsaturated zone [L], $(P - P_{atm})$ is pressure-drawdown [M/LT^2], $W(u)$ is the well function.

For the same pressure-drawdown data, gas conductivity (K) can be estimated using the Theis solution:

$$h_0 - h = \frac{Q}{4\pi Kb} W(u) \tag{2}$$

where Q is flow rate [L^3/T], $(h_0 - h)$ is drawdown in mm H_2O [L], and $W(u)$ is well function.

The Hantush leaky solution can be also used for gas conductivity (Hanstush, 1960):

$$h_0 - h = \frac{Q}{4\pi Kb} W\left(u, \frac{r}{B}\right) \tag{3}$$

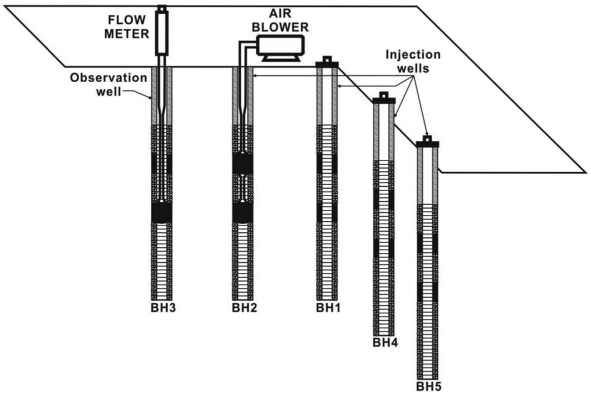

Fig. 4. Set-up for air flow connectivity tests between BH3 and every screen of the other wells.

where $W(u,r/B)$ is the Hantush leaky well function defined by

$$B = \left(\frac{Tb'}{K'}\right)^{1/2} \quad (4)$$

where b' is the confining layer thickness, and K' is gas conductivity of confining layer.

Soil samples at the depth of 4 m, 6 m and 9 m were taken from the recovered cores. Grain size analysis was carried out to find effective grain size, finally obtaining an estimate of the permeability using the following approximation (Massmann, 1989):

$$k = 1,250D_{15}^2 \quad (5)$$

where k is in darcy and D_{15} is grain size in mm for which 15 percent of particles are smaller.

3.2. Air Flow Test

BH3 was selected for the pilot scale SVE test because the highest TCE vapor concentration was found in the lower screen of BH3 and BH5, and TCE was detected in soil core sample at the depth of 4 m of BH3. Air flow in the subsurface, which the success of SVE depends on, can be influenced by geological structure, well condition, or water content. For this reason, Air flow tests were carried out to investigate air flow connectivity between BH3 and the other wells. Air was injected at BH3, and air flow was observed at three screens of each monitoring well (BH1, BH2, BH4, BH5).

While air was being injected into a selected screen sealed by double packer, air flow was first measured at the lower screen (8.0~12.0 m) of the BH3 packed by a single packer (Fig. 4). Then, the single packer was moved up to the middle section to measure total air flow through the middle and lower screens (note that the use of single packer at BH3 was simply due to shortage of packers), and total air flow rate was deducted from that of the lower screen, yielding the air flow only through the middle section. The single packer was again moved up to estimate air flow at the upper screen of BH3. This procedure was repeated for all the screens of four wells (BH1, BH2, BH4, BH5) to complete the air flow measurement between BH3 and the other four wells.

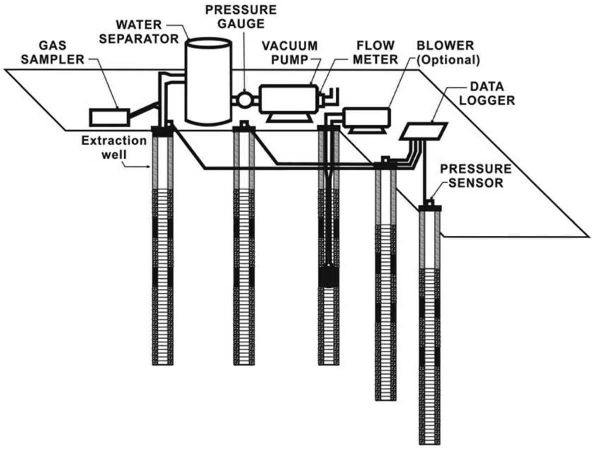

Fig. 5. Set-up for the SVE tests. Air was extracted from BH3 with/without air blow into the lower screen of BH1.

3.3. SVE Test

SVE system was designed based on pneumatic tests and air flow tests. According to the results of the initial gas sampling and soil core analysis as mentioned above, BH3 was targeted for SVE test. Air flow tests also indicated that the horizontal air flow was relatively well developed between the lower screens of the wells compared with the shallow depth. Therefore, air extraction from the isolated lower screen of BH3 was carried out at 270 L/min, but the deep unsaturated zone could not match the vacuum capacity. The SVE test was inevitably performed for the entire screens of BH3. Three different operating strategies were undertaken to optimize the SVE test and evaluate the feasibility: 1. for 8 hours daily for five days, 2. for 24 hours together with air blowing at the lower screen of BH1, and 3. for five consecutive days. Soil gas extracted from the BH3 was periodically sampled, and TCE vapor concentration was analyzed.

4. Results

4.1. Pneumatic Test

Pressure-drawdown data obtained from pneumatic tests for BH1 to BH5 were plotted with time. Typical drawdown data from the injection well of BH2 showed a flattening in slope in tens of seconds (Fig. 6). After reaching the flattening, the pressure steadily decreased at BH2, which indicated a leakage to the ground after the early stage of pneumatic test. The same phenomenon was observed at the monitoring well of BH3. The drawdown data were fitted to determine air permeability using Eq. (1), which was listed in Table 1. The average permeability was measured to be 2.01×10^{-6} cm^2, which was equivalent to 203.7 darcy. Gas conductivity was also estimated using the Theis and Hantush solutions and was converted into permeability in darcy (Table 1). Average permeability was estimated to be 81.6 by the Hantush method and 120.8 darcy by the Theis method, respectively. Permeability estimated by the Hantush method was smaller due to the leakage to the ground than that by the Theis (Massmann and Madden, 1994). Permebailty in hundreds of darcy corresponded to clean sand or gravel that was the same as materials used for the gravel pack placed around the screen in the well, which indicated that during pneumatic test, major pressure-drawdown was affected by air leakage.

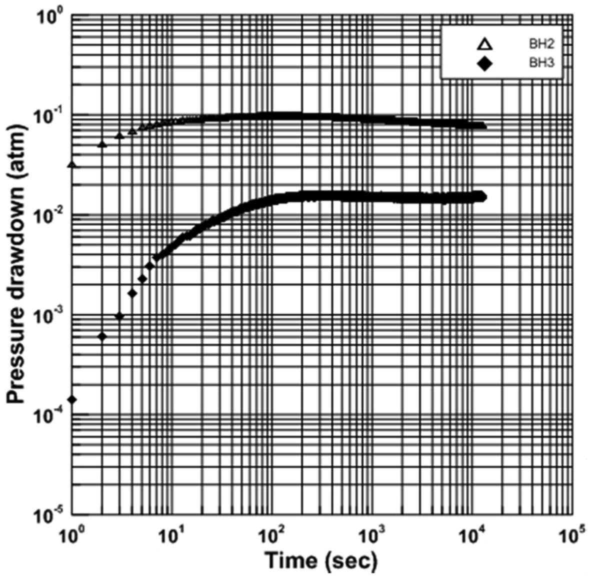

Fig. 6. Pressure-drawdown plot of the injection well of BH2 (triangle) and the monitoring well (diamond) of BH3 with time by pneumatic test.

Permeability was estimated from the grain size analysis. No noticeable variation in effective grain size with depth was found: 0.053 mm at 4 m, 0.053 mm at 6 m and 0.052 mm at 9 m deep. Grain size analysis showed that porous media in the unsaturated zone consisted mainly of silty sand. Estimated permeability using Eq. (5) was 3.51 darcy at 4 m, 3.51 darcy at 6 m, and 3.38 darcy at 9 m, average permeability of which was 3.5 darcy in geometric mean. This grain size analysis confirmed that permeability estimation by pneumatic test in the study area was obscured by the effect of the gravel pack.

4.2. Air Flow Connectivity

Air blowing tests were carried out to characterize air flow connectivity between BH3 and the other four BH wells. Air flow measured at BH3 was summarized in Table 2. When air was blown into the upper screens of the four wells, no air flow was observed at BH3 except that relatively small flow

Table 1. Permeability and conductivity obtained from pneumatic tests

Well	Permeability (cm^2)		Gas Conductivity (m/sec)			
	Theis (Eq. 1)		Theis (Eq. 2)		Hantush (Eq. 3)	
	Extraction	Injection	Extraction	Injection	Extraction	Injection
BH1	2.78×10^{-6}	2.04×10^{-6}	1.52×10^{-3}	7.26×10^{-4}	1.54×10^{-3}	5.08×10^{-4}
BH2	1.28×10^{-6}	1.49×10^{-6}	1.24×10^{-3}	7.16×10^{-4}	8.98×10^{-4}	5.06×10^{-4}
BH3	1.85×10^{-6}	1.07×10^{-6}	1.18×10^{-4}	5.31×10^{-4}	7.68×10^{-4}	3.42×10^{-4}
BH4	2.81×10^{-6}	2.05×10^{-6}	2.77×10^{-3}	1.54×10^{-3}	1.55×10^{-3}	1.01×10^{-3}
BH5	2.25×10^{-6}	2.60×10^{-6}	1.51×10^{-3}	7.15×10^{-4}	7.68×10^{-4}	3.77×10^{-4}
Geometric mean	2.01×10^{-6} cm^2 (203.7 darcy)		1.16×10^{-3} m/sec (120.8 darcy)		7.84×10^{-4} m/sec (81.6 darcy)	

Table 2. Air flow rate measured at BH3 for air blowing at the other wells at 85 L/min

Injection		Observed air flow at BH3 (L/min)		
Well	Screen	3.0 ~ 12.0 m	5.5 ~ 12.0 m	8.0 ~ 12.0 m
BH2 (1.0 m from BH3)	3.0 ~ 4.5 m	4.3	0.0	0.0
	5.5 ~ 7.0 m	1.0	2.0	0.0
	8.0 ~ 12.0 m	17.0	33.0	33.0
BH1 (2.0 m from BH3)	3.0 ~ 4.5 m	0.0	0.0	0.0
	5.5 ~ 7.0 m	0.0	0.0	0.0
	8.0 ~ 12.0 m	5.0	8.8	9.0
BH4 (2.2 m from BH3)	3.0 ~ 4.5 m	0.0	0.0	0.0
	5.5 ~ 7.0 m	0.0	0.0	0.0
	8.0 ~ 12.0 m	3.6	6.5	6.8
BH5 (2.8 m from BH3)	3.0 ~ 4.5 m	0.0	0.0	0.0
	5.5 ~ 7.0 m	0.0	0.0	0.0
	8.0 ~ 12.0 m	2.3	4.3	4.5

(4.3 L/min) was measured compared with 85 L/min of air injection at the upper screen of BH2. The same air flow phenomenon was observed when air was injected into the middle screens of the four wells, which indicated that the air injected at the shallow depth tended to leak to the ground. This result implicates for the SVE test that when air injection or extraction at the shallow depths (i.e., upper and middle screens) is done, it is highly possible that little air flow will be formed between the BH wells due to air leakage to the ground.

Air injection into the lower screen of neighboring wells developed a better air flow with BH3 than that at the shallow depth did. The largest air flow was measured at BH3 when air was injected into the bottom screen of BH2. However, accumulated total air flow became smaller for the whole screen observation at BH3 than that of the lower screen only. The decrease in accumulated air flow indicated that air, entered through the lower screen of BH3, was not all collected through BH3 to flow meter on the ground surface, part of which leaked to the ground.

Air flow tests indicated that the horizontal air flow was relatively well developed between the lower screens (i.e., deep unsaturated zone) of the wells compared with the upper levels. The extraction/injection well configuration of utilizing the lower screen intervals can be suggested for an efficient SVE to avoid air leakage to the ground.

4.3. SVE Test

As suggested by pneumatic and air flow tests, air extraction from the isolated lower screen (8.0~12.0 m) of BH3 was first conducted at 270 L/min, only for the vacuum pump to come to halt during the test due to insufficient air supply of silty sand enough to match the vacuum capacity. Therefore, the SVE test was inevitably carried out from the whole screens of BH3.

When air was extracted at 270 L/min for 8 hours daily for five days, TCE vapor concentration was constant at approximately 5 ppmv (parts per million by volume). For 8 hours of extraction, there was no discernible change in TCE vapor concentration except that TCE vapor concentration at day 4 and 5 was half of that of day 1 to 3, which might be due to rate-limited volatilization of TCE into soil air (Fig. 7a).

The well configuration with air blowing into the lower screen of BH1 was tested while air was being extracted for 24 hours from BH3. TCE vapor concentration and its variation were similar to the test for 8 hours (Fig. 7b). Air blowing with the extraction was found not to be of help to the SVE in this study area.

The five day consecutive SVE test was carried out at the same extraction rate of 270 L/min from BH3 as before. TCE vapor concentration reached 4.5 ppm at the early stage of the test, and kept almost same throughout the test period (Fig. 7c), not showing any rate-limited process. Furthermore, the amount of removed TCE was estimated to be as

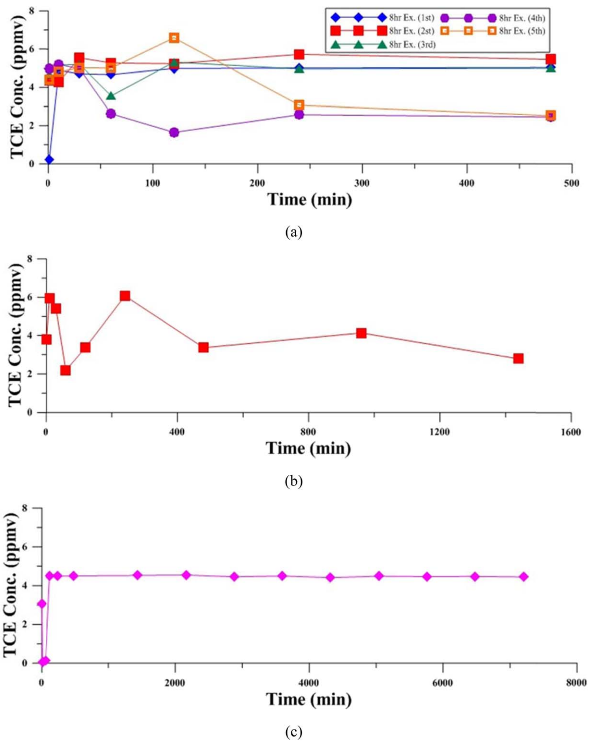

Fig. 7. Variation of TCE vapor concentration with time for the SVE tests of BH3 (a) for 8 hours daily for five days, (b) for 24 hours with air blowing at BH1 and (c) for five consecutive days.

low as 46.5 g even for five consecutive day run. The low efficiency of the SVE is due to air leakage to the ground at the shallow depth, relatively fine-grained silty sand and possibly the BH wells not hitting residual TCE blobs.

5. Conclusions

This study aims to characterize the unsaturated zone at which residual DNAPL (TCE) existed above/around the water table and to evaluate SVE. First, pneumatic tests were carried out to determine permeability of porous media for five wells with three multi-level screens penetrating unsaturated zone. A flattening in slope in tens of seconds in the pressure-drawdown curve indicated a leakage to the ground at late stage of pneumatic test. The permeability was estimated from the early time of pressure-drawdown, ranging from 81.6 by the Hantush leaky solution to 203.7 darcy by the modified Theis solution for air permerability.

This high permeability corresponded to clean sand. However, grain size analysis showed that porous media in the unsaturated zone consisted mainly of silty sand. Pneumatic tests were found to be severely affected by the gravel pack and leaking in early and late stages, respectively.

Air flow tests were also carried out to investigate air flow connectivity between multi-level wells. When air was injected into the shallow (3.0~4.5 and 5.5~7.0 m) depth screens, meaningful air flow was not detected. This is thought that injected air leaked to the surface. On the other hand, when the air was injected into the deeper screen (8.0~12.0 m), the horizontal air flow was well developed through unsaturated zone to the neighboring wells. The extraction/injection well configuration of utilizing the lower screen intervals can be suggested for an efficient SVE to avoid air leakage to the ground.

As suggested by pneumatic and air flow tests, air was extracted at 270 L/min from the lower screen isolated by a single packer for SVE test. However, air extracted from the unsaturated zone was short of the capacity of the vacuum pump, which came to a halt. Therefore, the SVE test was inevitably carried out for the entire screens of BH3. TCE vapor concentration was constant at 4 to 5 ppmv for three different tests: 8 hours daily for five days, 24 hours test together with air blowing, and five consecutive days. Even for 5-day consecutive test, the amount of removed TCE was estimated to be only 46.5 g. The SVE was found to be inefficient, which may be due to relatively fine-grained silty sand blocking appropriate air flow for SVE, air leakage to the ground at the shallow depth, or the wells not hitting residual TCE blobs.

Acknowledgments

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