Field vapor extraction test and long-term monitoring at a PCE contaminated site

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Abstract

The results of a field investigation, vapor extraction tests, and long-term monitoring at a PCE-contaminated site in Saga, Japan, are reported. The field investigation indicated that PCE likely was trapped in a surface clayey sand layer (vadose zone), and soil vapor extraction (SVE) was adopted as the remediation approach. The field test results the effectiveness of SVE in removing volatile organic compounds (VOCs) from contaminated sites. For the case where the radius of influence for an extraction well was 15–20 m, the blower capacity had no obvious effect on the radius of influence possibly due to the short circuiting of air from the ground surface. However, the maximum negative pressure (difference between vapor pressure and ambient pressure) in the extraction well was approximately proportional to blower capacity for the range of blower capacities tested. The long-term monitoring results indicate that PCE concentration varied seasonally, and temperature and rainfall are two of the influencing factors.
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1. Introduction

Contamination of soil and groundwater by volatile organic compounds (VOCs) is a significant environmental problem, as there are numerous reported sites contaminated by VOCs. For example, number of sites is about 1000 in Japan and about 20 000 in the United States [1]. Therefore, the effective and economical cleanup of VOC-contaminated sites is an important task of geoenvironmental engineering.

One of the methods for cleanup of VOC-contaminated sites is soil vapor extraction (SVE). Because the method is safe and economical, it is widely used in practice. However, due to the limitation in field performance data, the design methodology for SVE is not well established, and its long-term effect is not fully understood. A field SVE test and long-term monitoring were carried out at a PCE-contaminated site in Saga, Japan, to investigate the effect of the SVE in treating the PCE-contaminated sites.

This paper first reports the field conditions and the results of the soil vapor and groundwater surveys. Then, the field test arrangement and test results as well as long-term monitoring results are presented with analysis and discussion. Suggestions for the design and effective operation of SVE systems are made based on the results of this study.

2. Description of the site

2.1. Soil profile

The site is located in a diluvial deposit, and the elevation at the site is 4–5 m. The Sea of Genkai is northwest, about 300 m away from the site, and the Tamashima River is on the east side, about 370 m away from the site. The soil profile at the site up to 5 m deep is shown in Fig. 1. A clayey sand surface soil about 0.8 m thick is underlain by a sand deposit mixed with gravel. Groundwater was 3.2 m below the ground surface at the time of boring. In this area, the bedrock is Mesozoic granite. Since the borehole did not reach the bedrock, the exact thickness of the diluvial deposit is not known. Fig. 2 shows the grain-size distribution curves of the subsoil. D_{50} of the subsoil is 0.3–0.8 mm. For the soil within a 2 m depth, the fines content ($<75 \mu m$) ranges from

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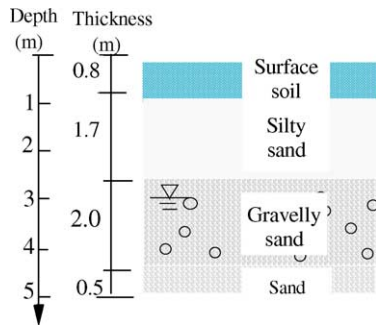*E-mail address:* chai@cc.saga-u.ac.jp (J.-C. Chai).

Fig. 1. Cross-section of subsoil.

Fig. 3. PCE concentration variations in groundwater.

18 to 35%, and for the soil below a 2 m depth, the fines contant is almost 0.

2.2. Field contamination condition

In 1993, the 'Basic Law for Environment' was mandated in Japan. The PCE contamination at the site was first discovered in 1993 when the 'Basic Law for Environment' requiring monitoring of groundwater quality was mandated. Since then, some selected well points at the site have been monitored semi-annually. Up to June 1997, there was no clear tendency in reduction of the PCE concentration in the groundwater. In contrast, a rapid increase of PCE concentration in groundwater was observed in 1996. Fig. 3 shows the results of one monitoring point (W-3 in Fig. 5). An investigation revealed that the possible source of contamination was from a dry cleaner, which used PCE as a solvent. A groundwater survey and a soil vapor survey were conducted around the cleaner in August 1997 and October 1997, respectively. Fig. 4 shows the survey results at existing well points. The PCE concentration in four wells exceeded the Japanese environmental standard of 0.01 ppm, with a maximum concentration of 0.912 ppm. The PCE appeared to be migrating toward the southeast. Although there are no measurements on the direction of groundwater flow, most possibly the local groundwater flows toward the southeast and the Tamashima River.

Fig. 5 shows the surface soil vapor survey results. It can be seen that within the cleaner, the PCE concentration was
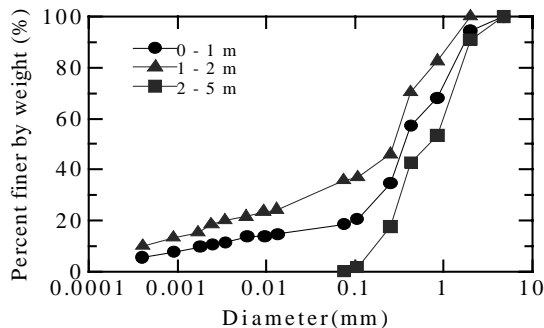
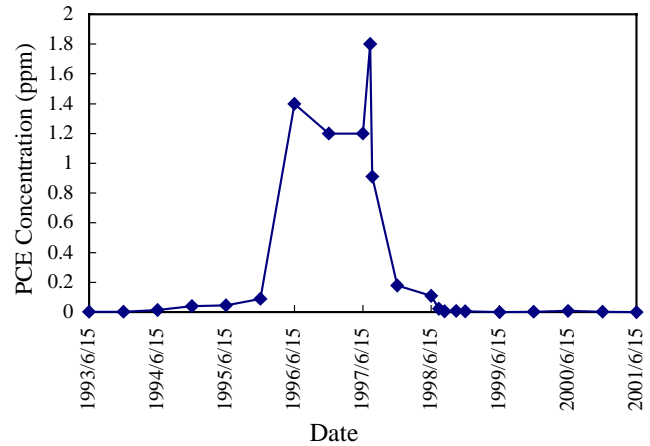higher than 100 ppm vol. over most of the area, and at two locations, the PCE concentration was 500 ppm vol. These two locations are related to a PCE dry machine. Before October 1995, the PCE dry machine was located inside the cleaner and very close to the 500 ppm. vol contour. After that the machine was discarded and put to the 500 ppm. vol contour place outside the cleaner. Some of the PCE probably remained in the old machine and subsequently was transported to the ground by rainfall. In 1998, the old machine was finally disposed and, since then, the PCE concentration in groundwater generally showed a tendency towards reduction (Fig. 3). The maximum recorded PCE concentration in soil vapor was 1500 ppm vol., which was measured at point EW-2 (see Fig. 5) during a preliminary investigation (September 1997).

To investigate the distribution of contaminant with depth, a borehole (EW-2 in Fig. 5) was made. The depth of the borehole was 5 m and the groundwater level was 3.2 m below the ground surface (see Fig. 1). This borehole subsequently was used as an extraction well. The total PCE content in the soil (soil vapor, soil particles, and pore water) was measured and the results are depicted in Fig. 6. The highest
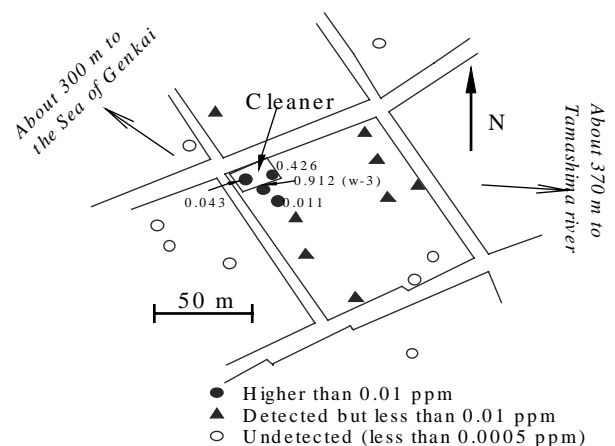

Fig. 2. Grain size distributions.

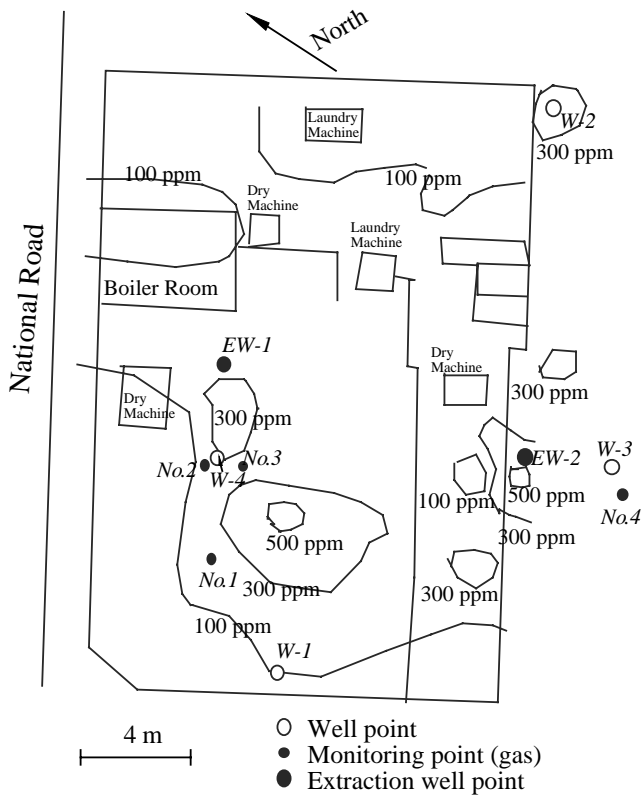Fig. 4. Survey results on existing well points.

Fig. 5. Surface soil vapor survey results.

Table 1
PCE concentration from borehole investigation

Depth (m)	Content of PCE in soil (mg/kg)	PCE concentration in soil gas (ppm vol.)[a]	PCE concentration in groundwater (mg/l)[a]
0.5	1.14	641	–
0.95	7.76	4381	–
1.5	3.48	1964	–
1.95	4.13	2329	–
2.5	2.6	1469	–
3	0		
3.6	0.54	–	2.9
3.95	0.21	–	1.1
4.2	0.01	–	0.1
4.5	0	–	0.0
4.95	0	–	0.0

[a] Calculated.

PCE content was in the vadose zone at a depth around 1 m. In this investigation, the PCE concentration in groundwater and soil vapor was not measured separately. Assuming that (i) the porosity of the soil is 0.4 and (ii) PCE located above the groundwater level was in the soil vapor and PCE located below the groundwater level was in groundwater, the PCE concentrations in soil vapor and groundwater listed in Table 1 were estimated. The estimated maximum PCE concentration in the groundwater of 2.91 mg/l is about 1.5 times the maximum value measured in W-3 (Fig. 3). The estimated maximum concentration in soil vapor is much higher than the measured maximum value of about 1500 ppm vol.. A portion of the PCE in the vadose zone may have possibly existed in the liquid form or been adsorbed to the soil particles.
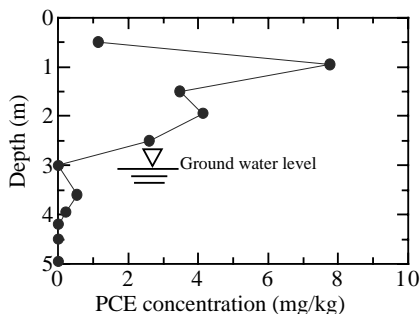

Fig. 6. Variation of PCE content with depth.

Since the unit weight of PCE is 16.22 kN/m^3 (at 20 °C), another possible scenario is that some of the PCE sunk to the bedrock and gradually dissolved and/or diffused into the groundwater. To check the possibility of this mechanism, a two-dimensional (2D) advective–diffusive contaminant transport analysis was conducted. The 2D advection–dispersion equation for contaminant transport is as follows:

$$R_d \frac{\partial C}{\partial t} = D_{hx} \frac{\partial^2 C}{\partial x^2} + D_{hz} \frac{\partial^2 C}{\partial z^2} - v_x \frac{\partial C}{\partial x} - v_z \frac{\partial C}{\partial z} \tag{1}$$

where D_{hx} and D_{hz} are the coefficients of hydrodynamic dispersion (incorporating the effects of molecular diffusion and mechanical dispersion) in the x- and z-directions, respectively, v_x and v_z are the horizontal and vertical components of seepage velocities, C is concentration, t is time, and R_d is retardation factor, which can be expressed as

$$R_d = 1 + \frac{\rho_b K_d}{n} \tag{2}$$

where n is porosity, K_d is distribution coefficient, and ρ_b is the dry density of soil. The finite layer technique developed by Rowe and Booker [2] was adopted to solve the partial differential equation (Eq. (1)). The computer program MIGRATE [3] was used to conduct the analysis. The thickness of the diluvial deposit was assumed as 10 m, and the analysis model is shown in Fig. 7. The assumed conditions were: a width of source of 5 m, a source concentration of 100 mg/l, 200 g/m^2 of PCE, which is equivalent to a 2-m-thick solution with a concentration of 100 mg/l. A D_{hx} of 600 m^2/year (mainly due to the mechanical dispersion) and D_{hz} of 0.013 m^2/year (in soil effective molecular diffusion) were also assumed, the Darcy's horizontal flow velocity of 30 m/year (a value measured at another site in Saga, Japan) and the vertical flow velocity of 0, and a porosity for the ground of 0.4. For distribution coefficient of K_d, a measured value of about 1 ml/g (batch contact test) was used. The test was conducted following ASTM standard D5285 [4]. The simulated results are depicted in Fig. 8 and show that, under the assumed conditions, the contaminant can only
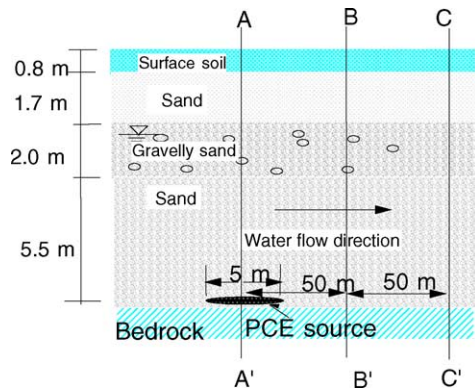
Fig. 7. Proposed model for 2D advection–diffusion analysis.

Fig. 9. Profiles of extraction wells and monitoring points.

air-flow rate of about 1.25 m^3/min. At that time, only the air-flow rate and PCE concentration in the extracted air were measured. Fig. 10 shows the variation in PCE concentration in the extracted air. The concentration was reduced from about 150 to about 5 ppm vol. At the end of the extraction, a maximum concentration of 35 ppm vol. was measured at EW-2 (see Fig. 5). After that time, PCE concentration in soil vapor was not continuously monitored. In October 1999, a concentration of about 80 ppm vol. was measured at EW-2.

3.3. Soil vapor extraction test conducted in 1999

To investigate the area of influence for an extraction well, a SVE test was conducted again from October to December 1999. From October 1 to November 4, 1999, the extraction was conducted from EW-1 and from November 5 to 18, 1999, the extraction was carried out from EW-2 (see Fig. 5). During most of the time, a blower with a capacity of 4.5 m^3/min was used. However, prior to termination of the test, a blower with a capacity of 9.0 m^3/min was used to investigate the effect of blower capacity on the negative pressure distribution. Monitoring for all the points was taken until December 25, 1999. After then, only selected points were monitored. In the following discussion, the difference
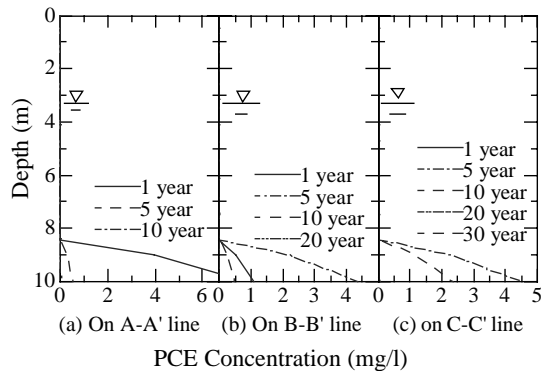

Fig. 8. Analyzed PCE concentration variation on certain selected lines.

diffuse to a 2-m-thick zone from the assumed source location. At least this analysis indicates that the measured PCE in the shallow depth of groundwater as well as in the vadose zone was not from the bedrock.

Combining the field investigation with the 2D analysis results, the primary source of the PCE was located in the vadose zone, and SVE was selected as the remediation approach.

3. Field soil vapor extraction test

3.1. Field test arrangement

Considering the location of the higher PCE concentration areas and the availability of space, two extraction wells, one inside the cleaner and another outside the cleaner were set up in 1998 as indicated in Fig. 5 (EW-1 and EW-2). To investigate the influence area of an extraction well, five monitoring points (no. 1–4 and W-4) were established in September 1999. The profiles of the wells and monitoring points are illustrated in Fig. 9.

3.2. Soil vapor extraction conducted in 1998

From February 26 to May 24, 1998, extraction was conducted from EW-1 for about 9 h/day, 5 days/week, at an
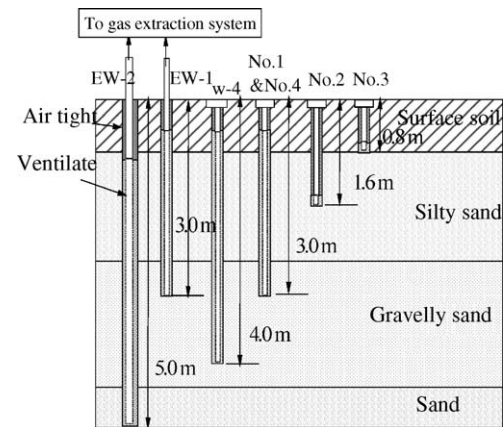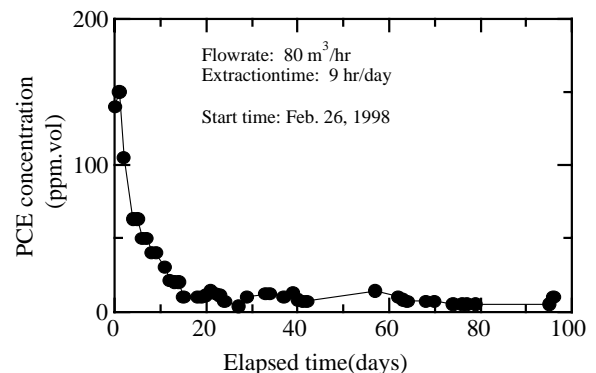

Fig. 10. PCE concentrations in extracted air during 1998 extraction period.
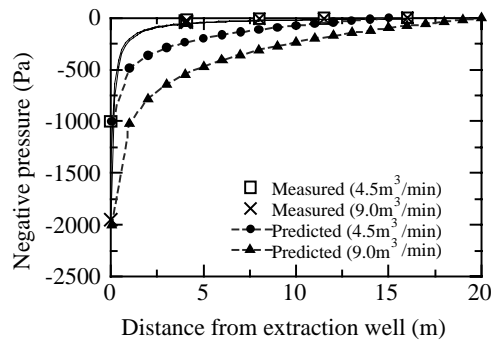
Fig. 11. Negative pressure variations.

Fig. 12. Negative pressure variations with depth.

between the pressure at measuring point and ambient pressure is defined as negative pressure. During the test, the negative pressure and PCE concentration in the soil vapor were monitored in the extraction wells and the monitoring points. Also, PCE concentrations in groundwater were measured at the well points W-1, W-4, and EW-2.

3.3.1. Negative pressure distribution

Under the condition of a steady-state radial flow (flow direction is horizontal and no air from the ground surface enters the ground), the relationship between radius and absolute pressure is given as follows [6]:

$$P(r) = P_{\mathrm{w}} \left[1 + \left(1 - \frac{P_{\mathrm{atm}}}{P_{\mathrm{w}}} \right)^2 \frac{\ln(r/R_{\mathrm{w}})}{\ln(R_{\mathrm{w}}/R_{\mathrm{I}})} \right]^{1/2} \qquad (3)$$

where r is the radius from extraction well, $P(r)$ is the absolute pressure at radius r, $P_{\mathrm{atm}} = 101$ kPa, absolute ambient pressure, P_{w} is the absolute pressure at extraction well, R_{w} is the radius of vapor extraction well, and R_{I} is the radius of influence for a vapor extraction well. Fig. 11 shows the measured and calculated (Eq. (3)) negative pressures versus the radius from the extraction well EW-1. For the calculations, the parameters used were: $R_{\mathrm{w}} = 57$ mm, and $P_{\mathrm{w}} \approx 100$ kPa (flow rate of 4.5 m^3/min) and 99 kPa (flow rate of 9.0 m^3/min). It was assumed that $R_{\mathrm{I}} = 15$ m and 20 m for flow rates of 4.5 and 9.0 m^3/min, respectively. From the figure, the following observations can be made:

(i) The radius of influence (R_{I}) was about 15–20 m. At a radius r of 16 m, the measured negative pressure was about 1 Pa. The negative pressure reduced very fast with radius, and the value at $r = 4$ m was 2–3% of that in the extraction well. Therefore, a practical effective radius may be less than the radius of influence, and based on the results from this site, a value of 5 m is suggested for sandy ground. Values for the radius of influence reported in the literature range from 9 to 30 m [5]. The calculated negative pressures are greater than the measured pressures, which indicates that there was some circulation of air from the ground surface, even though asphalt pavement or a thin concrete layer covered most of the surface area around the test site. However, due
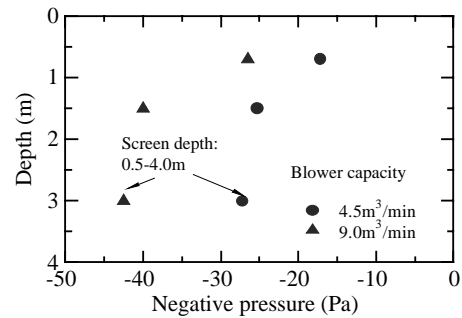
to the cracks in the surface layer and possible gaps between the pipe systems of the cleaner and the surface layer, air leakage was possible. This result indicates that for most practical cases, a simple radial air-flow condition is not applicable.

(ii) The negative pressure in the extraction well was almost proportional to the blower capacity for the range investigated. However, the effect of the blower capacity on the radius of influence was not clearly demonstrated possibly due to the short circuiting of air from the ground surface.

The distribution of the negative pressure with depth at 4 m away from the extraction well is shown in Fig. 12. In the figure, the 3 m depth is the depth of the well point with a ventilation depth from 0.5 to 4.0 m. Generally, the negative pressure is smaller near the ground surface, which provides direct evidence that air had entered the ground from the ground surface during the test.

3.3.2. Soil permeability to air flow

Under the condition of a steady-state radial flow, the relationship between the air permeability and the flow rate is as follows [6]:

$$k = \frac{\mu Q}{\pi P_{\mathrm{w}} H} \times \frac{\ln(R_{\mathrm{W}}/R_{\mathrm{I}})}{1 - (P_{\mathrm{atm}}/P_{\mathrm{w}})^2} \qquad (4)$$

where k is the soil permeability to air flow, Q is air flow rate, H is the thickness of ventilate layer, and μ is the viscosity of air ($= 1.8 \times 10^{-4}$ g/cm s). With the conditions of this site and using $R_{\mathrm{I}} = 15$ and 20 m for flow rates of 4.5 and 9.0 m^3/min, respectively, a soil permeability to air flow of about 0.45 cm/s can be back-estimated. Since short circulation of air from the ground surface was likely, the actual permeability to air flow might be higher than this value. Furthermore, for a flow rate of 4.5 m^3/min, the relationship between R_{I} and k can be calculated as in Fig. 13, which shows that under the ideal radial flow, the R_{I} exponentially increases with the increase of k.

3.3.3. PCE concentration variation in soil vapor

Fig. 14a and b shows the PCE concentration variation up to December 25, 1999. At the beginning, the distribution
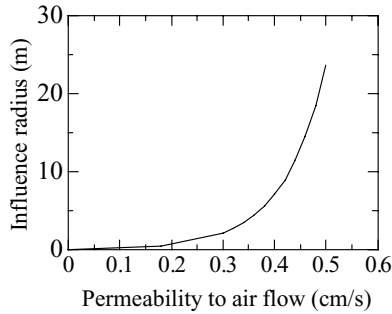
Fig. 13. Relationship between soil permeability to air flow and influence radius.

Fig. 15. PCE concentration variations in groundwater during extraction period.

in PCE concentration in the subsoil was not uniform and, therefore, a comparison with the absolute value is difficult. The location of the maximum PCE concentration was EW-2, which is 11.5 m (indicated in the legend) away from the extraction well EW-1. When extracted from EW-1, the concentration in EW-2 was reduced from 75 to 13 ppm vol. (Fig. 14a). During the extraction from EW-2, the PCE concentration varied from 13 to 1.3 ppm vol. (Fig. 14b). As a general tendency, the following two points are recognized:

 (i) The closer to the extraction well, the greater the relative reduction of PCE concentration in soil vapor.
(ii) At 16 m away from EW-1 (no. 4 in Fig. 5), when extracted from EW-1, the PCE concentration did not significantly change. This supports the suggested radius of influence of 15–20 m based on the negative pressure distribution.
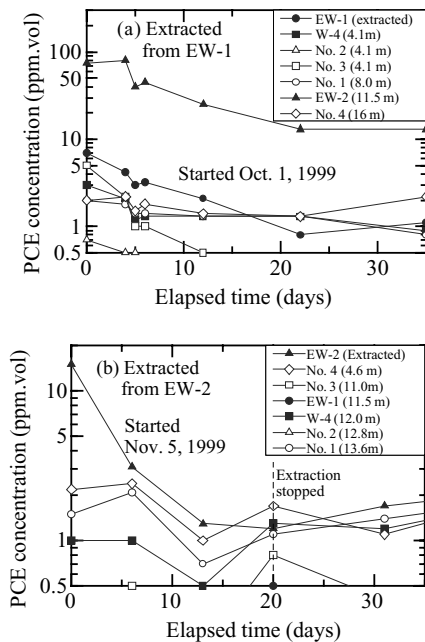
3.3.4. PCE concentration in groundwater

Variations in the PCE concentration in the groundwater at three monitoring points are given in Fig. 15. Although the reduction of PCE concentration can be clearly recognized during the extraction period, it might not be entirely due to the SVE because groundwater is moving. During the test period, the groundwater level varied from 3.5 to 4.0 m below the ground surface. As a result, at point W-4 (see Fig. 5), sampling the groundwater after November 18, 1999 was not possible.

3.3.5. Ratio of PCE concentration in soil vapor to that in groundwater

At steady state, the ratio between the concentration in the soil vapor (C_G) and the concentration in the liquid (aqueous) phase (C_L) is given by Henry's constant (K_H). Thibodeaux [7] expresses K_H as follows

$$K_H = \frac{C_G}{C_L} = \frac{16.04pM}{TC_L} \tag{5}$$

where p is the vapor pressure of VOC (mmHg), M is gram molecular weight of VOC, and T is temperature (K). In Eq. (5), C_L is in ppm. For PCE at 20 °C, $p = 13.7$ mmHg, $C_L = 130$ ppm [6], and from Eq. (5), $K_H = 0.95$. At 25 °C, $p = 18.6$ mmHg, $C_L = 140$ ppm, and $K_H = 1.2$ [8]. The PCE concentrations were measured in both the soil vapor and the groundwater at only two monitoring points (W-4 and EW-2 in Fig. 5), and their ratios are depicted in Fig. 16. Although true steady-state conditions cannot be achieved in the field, comparing the measured ratio of C_G/C_L with the theoretical value is useful for identifying the source of the contaminant. In the field, assuming an average temperature of 20 °C, it can be seen from Fig. 16 for EW-2, that almost all measured C_G/C_L values were higher than the theoretical Henry's constant of 0.95. During extraction from EW-2 (November 5 to 18, 1999), the value for C_G/C_L value decreased from about 16 to 0.83 at EW-2, and the ratio increased again after stopping the extraction. This indicates that PCE likely existed in the vadose zone at EW-2. Actually, as mentioned previously, the discarded PCE dry machine was placed at the location of EW-2. Also, this result

Fig. 14. PCE concentration variations in soil vapor. (a) Elapsed time (days). (b) Elapsed time (days).

Fig. 16. Estimated Henry's constants.
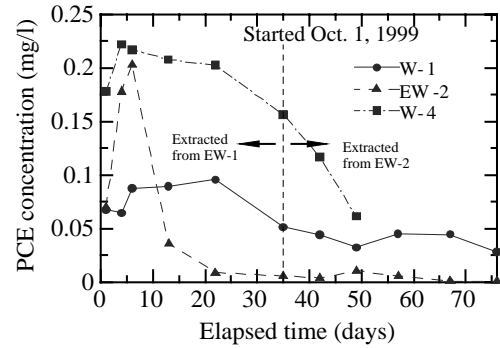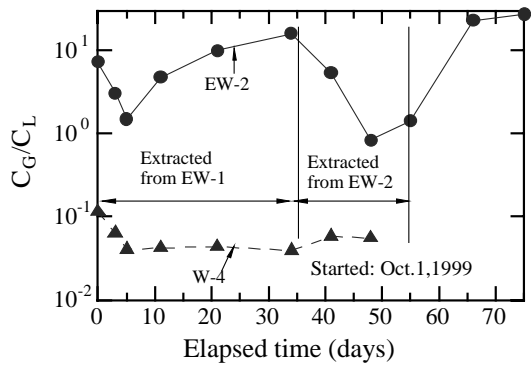
indirectly indicates that the reduction in PCE concentration in the groundwater (Fig. 15) at EW-2 might not be solely due to the SVE, where there was a tendency for PCE to dissolve into groundwater from soil vapor. For W-4, the ratio of C_G/C_L was much less than 0.95, which indicates that there was a possibility that PCE in the soil vapor was from the evaporation of PCE in groundwater.

4. Long-term field-monitoring results

After stopping the extraction, the site was left without monitoring for about half a year. Since June 2000, monthly monitoring was conducted at EW-2 for soil vapor and at W-1 as well as W-2 for groundwater, and the results are shown in Fig. 17a and b, respectively. It can be seen that up to
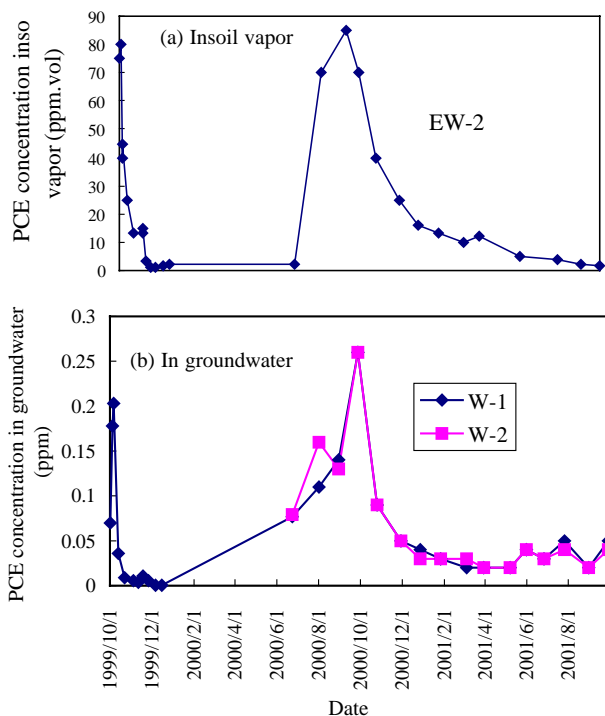
June 2000, the PCE concentration only gradually increased. After then, the PCE concentration increased rapidly with a peak value in the soil vapor at the beginning of September 2000 and in the groundwater at the end of September 2000. After then, the PCE concentration decreased again, although there was no further remediation action. The reason for this decrease in PCE concentration is not clear yet, but it is considered that PCE concentration variation might relate to temperature variation and the amount of rainfall. In 2001, the absolute values were reduced, but there also was an increase of concentration in groundwater during summer period.

For PCE, the relationship between volatilization vapor pressure (p) and temperature can be expressed by Antoine's equation [9]:

$$\log p = A - \frac{B}{t + C} \tag{6}$$

where t is temperature (°C), $A = 6.1017$, $B = 1386.9$, and $C = 217.52$. The vapor pressure p is in kPa. The rainfall and the average temperature variation at the site are shown in Fig. 18a and b, respectively (date from Saga Meteorological Observatory). Although the temperature in the soil is different from that in air, as a rough estimation, when temperature varies from 0 to 25 °C (Fig. 18b), from Eq. (6), the vapor pressure of PCE at 25 °C will be about five times of that at 0 °C. Therefore, the temperature variation is certainly one of the reasons for a change in PCE concentration in the soil vapor. However, the increase in measured PCE concentration was greater than five times in 2000. Other reasons might be

Fig. 17. PCE concentration variations (a) in soil vapor (b) in groundwater.
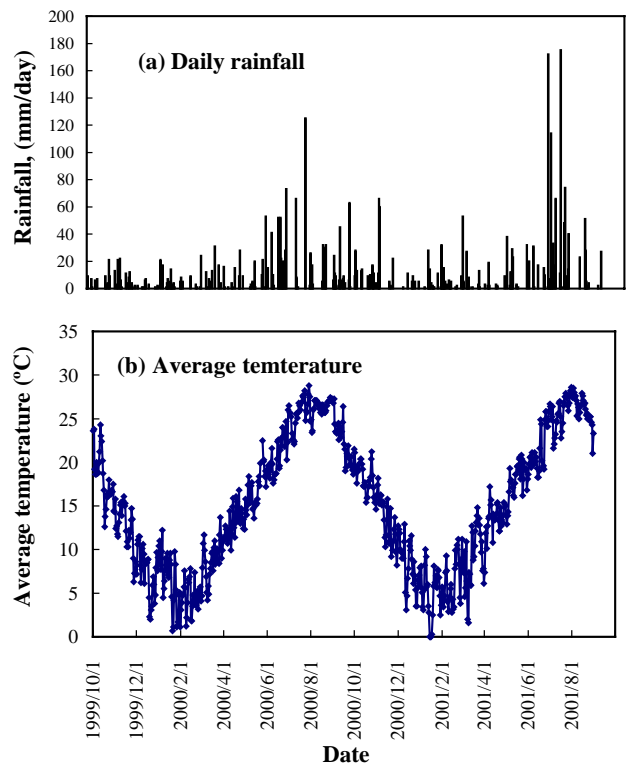

Fig. 18. (a) Daily rainfall and (b) average temperature variation.

the diffusion of PCE from neighboring area and the effect of rainfall. It is possible that the infiltration of rainfall dissolved or transported out the PCE remaining in the vadose zone. Volatilization of PCE initially increases the PCE concentration in the soil vapor, but with rainfall, PCE was transported or dissolved into groundwater. As described in the previous paragraph, the time of peak concentration of PCE in the soil vapor was earlier than that in the groundwater (Fig. 17a and b), which indirectly supports this reasoning.

The long-term monitoring results have two practical impacts. (i) The concentration of VOCs in the ground varies seasonably. To confirm the remediation results or judge whether a site needs to be continually treated, long-term monitoring is required. (ii) In areas with significant seasonable variation in temperature and rainfall, SVE may be more effective when conducted during the higher temperature period.

5. Conclusions

A PCE-contaminated site in Saga, Japan, is described, and the field investigation and SVE tests as well as the long-term field-monitoring results are reported. The investigation revealed the following conclusions:

(1) The analysis of the results of the soil vapor survey, groundwater monitoring, and borehole investigation indicates that PCE from a dry cleaner was likely trapped in the surface clayey sand layer (part of the vadose zone), and gradually diffused into the soil vapor and dissolved into rainfall and then the groundwater, which caused the long-term contamination of the site.

(2) For VOC-contaminated sites, SVE is a safe, economic, and effective remediation method. However, to completely clean up a site, long-term extraction may be required.

(3) For the site tested (sandy subsoil), the radius of influence of an extraction well was 15–20 m. A practical effective radius of 5 m is suggested.

(4) The maximum negative pressure in the extraction well was almost proportional to the blower capacity for the range tested. However, the effect of blower capacity on the radius of influence was not clearly demonstrated.

This is likely due to the short circuiting of air from the ground surface. It is suggested that for most practical cases, a simple radial air-flow condition is not applicable.

(5) The long-term monitoring results indicate that PCE concentration varies seasonally. Temperature and rainfall are two of the factors influencing the variation in PCE concentration. The practical impact of this result is that, to confirm the remediation result or judge whether the site needs to be continually treated, selecting correct monitoring periods is important.

Acknowledgements

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