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Analysis of Field Data for Risk Assessment of Vapor Intrusion at a Trichloroethylene-Contaminated Site – A Case Study in Taiwan

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ABSTRACT

The potential risks of vapor intrusion (VI) can arise from low bulk soil contaminant concentration existing in shallow soils beneath a building foundation. To assess VI risks for such a contamination scenario, a comprehensive study was conducted on a factory building located at a trichloroethylene (TCE)-contaminated site. This study involved the integration of various types of field data, including groundwater, bulk soil, soil gas and indoor air data, along with the utilization of the Vapor Intrusion Screening Level (VISL) calculator. Previously observed high TCE concentrations in soil gas are attributed to accumulation of TCE vapor within the unsaturated soil beneath the building floor, since ground surface is extensively paved at this site. These soil gas data do not directly correlate with the magnitudes of bulk soil and/or groundwater TCE concentration with the linear adsorption model. Soil gas TCE concentration exceeding 10^7 μg/m^3 (or bulk soil concentration exceeding 18.9 mg/kg) observed in shallow soils (at a depth of less than 1 m) may pose health risk to the workers inside the building due to VI, as we have detected TCE vapor concentrations exceeding indoor air screening level several times in the past. This bulk soil TCE concentration, however, falls below soil pollution control standards for TCE, i.e., 60 mg/kg, in Taiwan. As a result, soil remediation is not considered at this site. Soil gas TCE concentrations have reduced to less than 10^6 μg/m^3 after two years of groundwater remediation work at this site. However, we have observed significantly higher soil gas TCE levels at a depth of 0.5 m compared to other depths. This discrepancy raises suspicions that an amount of TCE may still be trapped within the shallow soils that are not reached by groundwater table.

Keywords: soil gas; indoor air; vapor intrusion; health risk assessment.

INTRODUCTION

Trichloroethylene (TCE) is a widely-used industrial solvent and has been frequently detected in soils and groundwater (Lin et al. 2018; Bahrami et al. 2018). Long-term or short-term TCE exposure has been recognized to result in human health effects, including neurotoxicity, immunotoxicity, developmental toxicity, liver toxicity, kidney toxicity, endocrine effects, and several forms of cancer (http://www.clu-in.org/contaminantfocus/default.focus/sec/trichloroethylene_(tce)/cat/overview/). Especially, TCE vapor arising from underground or nearby contaminated soil and/or groundwater may migrate into buildings, which is termed as vapor intrusion (VI). In the past ten years, several countries drafted VI screening levels for volatile organic compounds (VOCs) to prevent the impact of soil and groundwater contamination on the indoor air quality of dwelling houses nearby contaminated sites. For example, long-term risk-based remediation goal and short-term removal action levels of TCE in indoor air drawn up by the United States Environmental Protection Agency (USEPA) in USEPA (2014a, 2016).

Indoor air VOC level can be predicted with sampling and testing bulk soil, groundwater or soil gas and compared to the screening targets through risk-based approaches, e.g., USEPA (2017). USEPA (2015) pointed that soil gas concentration if not measured but calculated based

on contaminant concentration in bulk soil with different conversion models may vary by orders of magnitude, which may result in a great difference for risk assessment and follow-up actions. Zhang et al. (2019) explored the applicability of bulk soil concentration for VOC-contaminated site assessments using in-situ bulk soil-soil gas data pairs of benzene and two conversion models. They concluded that collection of sol gases for high permeability soil would be more reasonable for screening the VI pathway due to large porosity in coarse soil particles. Ma and Lahvis (2020) provided rationale and recommended methods for soil gas sampling to improve VI risk assessment. However, due to sampling simplicity and cost effectiveness, sampling and testing bulk soil and/or groundwater are popular in most of the site investigation activities and thereby are usually used for predicting soil gas concentration (Zhang et al., 2019; Ma and Lahvis, 2020).

Environmental Protection Administration of Executive Yuan (EPAEY) in Taiwan has not yet started to regulate indoor air quality regarding potential inhalation risk caused by soil and groundwater contamination at sites, as well as to draw up standard methods in regulation for soil gas sampling. TCE has been prevalent in lots of the sites contaminated by chlorinated solvents in the past and is not easily removed completely from soil and groundwater system. Remediation work on some TCE-contaminated sites is being undertaken during the past decade in Taiwan, e.g., the Taoyuan site of Radio Company of America (RCA), the Taofen site of Taiwan VCM corporation. Sites located in industrial regions and/or enclosed by factory buildings are usual due to improper use or treatment of TCE solvent in a factory building. Thus, soil and groundwater beneath the floor of the factory building are contaminated due to the liquid leakage to the building floor and penetration through the cracks of the floor. For on-site remediation, it is difficult to accurately determine the location and extent of contamination and implement direct dipping methods while the factory remains operational. Besides, the remediation work may be carried out for only focusing on recovering groundwater quality, if the detected bulk soil TCE in unsaturated soils does not exceed soil pollution control standards (SPCS), i.e., 60 mg/kg for TCE (SPCS, 2011) in Taiwan.

This study aims to explore the relevance of soil gas and indoor air TCE concentration and bulk soil/groundwater contamination and assessing the potential hazard of VI in a factory building typically with contaminated soils in the unsaturated zone beneath its floor. We collaborated with an investigation and remediation teams, i.e., Yuh Shan Environmental Engineering corporation, LTD. (YSEE) and Taiwan VCM corporation (TVCM), for bulk soil and groundwater data of a TCE-contaminated site at which a factory is located and is the origin of the contamination. Soil gas and indoor air samplings and analyses were conducted and integrated with groundwater and bulk soil data for comprehensive assessment of VI potential for the workers in the factory building. Vapor Intrusion Screening Level (VISL) Calculator released by USEPA (USEPA, 2017) was applied for the risk assessment.

MATERIALS AND METHODS

Study area

The site located in the middle of Taiwan in rural area has been assessed for soil and groundwater contamination that originated from a factory. The factory works for polishing and cleansing plumbing hardware, belt buckle and metal parts for centuries. Liquid TCE was first used as a solvent between 1992 and 2011 and then replaced by 1-bromopropane after all. The factory is in a one-floor tin-sheeted building which encompasses approximately 650 m^2 with a height of 6 m. An ultrasonic cleansing machine occupying about one-tenth of the building area is located at the middle to the southwestern corner of the building for metal polishing work. Liquid TCE was loaded in a big stainless steel tub as cleansing fluid. The tub and cleansing machine are enclosed by thin wooden wall in the building. Layout of the building and the nearby area are shown in Figure 1. Unknown volume amounts of TCE have leaked to the floor from the tub and penetrated through the cracks of the floor to subsurface soils in the past. Besides, used solvent has been recycled and purified by heating and condensation. Filter clothes were used for purification of the used solvent and then washed in a tub located at the eastern corner of the building, so that wastewater containing dissolved TCE was occasionally produced and drained to ditches in which wastewater flows from the eastern corner of the building to the northwestern direction along the drainage line nearby the building. The factory discontinued

the use of liquid TCE since December 2011. The purchased and recorded mass amounts of TCE solvent were 111.42 tons during the years from 2003 to 2011. However, no record was left for the amounts of solvent used before 2003.

The factory building has a 30-cm thick concrete floor which is also the foundation of the building. The building was surrounded with traffic roads and several paved parcels of land for more than 10 m wide as shown in Figure 1. Beyond the roads and land are parcels of farmland. Across a road along the northwestern side of the building is a paved parcel of land and another factory building which was built few years ago. The building is ventilated by two industrial three-blade fans installed on the upper wall above the ultrasonic cleansing machine. The diameter and rotating speed of the fans are 56 in (142 cm) and 600 rpm, respectively. Besides, air conditioning is operated in the building during warm and hot seasons.

Since October 2020, a project focusing on remediating TCE-contaminated groundwater at this site has been carried out by TVCM (TVCM, 2022). TVCM conducted in Situ chemical oxidation (ISCO) for groundwater remediation at this site. Several injection wells screened from 1 to 7m and 4 to 7 m deep were installed inside and outside the building, respectively. After then, a certain volume amount of $KMnO_4$ solution was injected into one of the injection wells located at the northeastern side of the ultrasonic cleansing machine in November 2020 to test the performance of the remedial efficiency. Periodical injections of $KMnO_4$ solution into the wells inside the building are being conducted for every 3 months later.

Field data

Subsurface soil and groundwater table characteristics

The geology condition at the site was investigated by YSEE in February 2018. Soil cores to 10 m deep below ground surface level (bgsl) were obtained at locations G1, G2 and G3 (outside the building) (YSEE, 2019). Their locations are indicated in Figure 1. The lithology of each soil core was visually judged by experienced site investigators. Three primary soil layers were identified: a silt or clay layer at depths of 0.2–3 m bgsl, a fine sand layer at depths of 3–5m bgsl and a coarse sand layer at depths of 5–10 m bgsl. Besides, a thin clay layer within coarse sand was detected from the G3 soil core obtained at depths of 7–8 m bgsl. Soil samplings to a depth of 5 m below the building foundation near the ultrasonic cleansing machine at locations S5 and S6 were requested by our team in March 2018. Soil cores obtained from these locations were also visually judged for lithology. Soil cores with different lithologies were selected and sent to the laboratory of YSEE for physical examination which includes soil particle size distribution (SPSD), soil moisture content, specific gravity and void ratio. Experimental methods used for obtaining these soil characteristic parameters are CNS 11776–2011, CNS 5091–1986 and CNS 5090–1988. The lithology of each soil core at different depths was classified by standard method (CNS 12387–1988) as follows: SM (Silty sand) at depths of 0–1m and CL (Silt or sandy clay) at depths of 1–3m at both locations; SM at depths of 3–5m for the S5 sample; and ML (Silty clay) at depths of 3–5m for the S6 sample. Results of the soil physical examination show that porosity (converted from void ratio) ranges from 0.36 to 0.46, soil density (converted from specific gravity) ranges from 2.68–2.78 kg/m^3 and soil water saturation is as high as 0.78 near the foundation. Total organic carbon (TOC) of each soil core was also tested by using the wet air oxidation method. Results show TOC of the tested samples is in a range from 0.00371 to 0.00092 (w/w).

We monitored the depth to groundwater table at a well, SW08 (indicated in Figure 1), with a water level logging instrument (Rugged TROLL@100, In-Situ) for a whole-year period from September 2018 to September 2019. The well was constructed by YSEE in 2018 and has a screened interval of 4.5–6 m bgsl. The monitoring result shows that groundwater level fluctuates due to wet (May to August) and dry seasons (September to April) of a year. In August, groundwater level is as high as 1.5 m bgsl; in February, it is as low as 4.5 m bgsl.

Soil and groundwater contamination

Several sets of groundwater samplings were conducted inside and nearby this factory building since 2012 by different investigation teams authorized by EPAEY and local Environmental Protection Bureau. The most recent investigation was conducted by YSEE in March 2018. There are totally 9 monitoring wells screened at a depth of 4.5 to 6 m, 6 to 7.5 m or 8.5 to 9.5 m bgsl.

Sample testing follows the EPAEY method NIEA W785.55B. Results show that TCE concentration exceeded the groundwater pollution control standards (GPCS) of 0.05 mg/L (GPCS, 2013) for the monitoring wells screened between 4.5–6 m bgsl which are located inside and outside the building. Specifically, TCE levels of 25 and 20 mg/L were detected at SW08 located at the northeastern side of the ultrasonic cleansing machine room and at SW06 located at the intercept of the ditch lines, north of the building, respectively. These two locations were regarded as hot spots of the site (YSEE, 2019). Groundwater sampling at SW08 is periodically carried out since the remediation activities were initiated (October 2020). As shown in Figure 2(b), TCE concentration in groundwater varies from 0.97 to 0.004 mg/L after October 2020. The daughter compounds of TCE, *cis-1*,*2*-dichloroethylene (*cis*-DCE) and vinyl chloride (VC), were also detected in groundwater. The *cis*-DCE levels of over 3.0 mg/L which exceeds GPCS of 0.7 mg/L (GPCS, 2013) were detected at several sampling locations surrounding the building. At SW07, VC level is 0.121 mg/L which also exceeds GPCS of 0.02 mg/L (GPCS, 2013) .

Soil was also sampled at depths of 4–7 m below the foundation inside and outside the building for bulk soil contamination testing conducted by YSEE (YSEE, 2019). There are totally 10 soil cores obtained at 5 locations. The testing method is EPAEY method NIEA M711.04C. Results show that all of the soil samples did not exceed the SPCS of 60 mg/kg (SPCS, 2011). The highest TCE concentration of 24.6 mg/kg was detected at a depth of 4–4.5 m at location S5–1 which is close to S5 and the ultrasonic cleansing machine. Soil samples obtained at depths of 0–5 m for S5 and S6 below the foundation were also analyzed for TCE. TCE bulk soil concentration was found to be 31.6 and 18.9 mg/kg at two depths, 4–4.5 m and 0–1 m, respectively, for the S5 samples and 0.236–5.87 mg/kg for S6. The testing method is EPAEY method NIEA M711.04C.

Soil gas and indoor air sampling and analyzing

A 10-in well installed with nested permanent soil vapor sampling probes (D =1 in) was constructed at the northeastern side of the machine room by a well-drilling company in June 2018. Three probes for sampling soil gas at three depths, 0.5 m, 1.5 m and 3 m (below the foundation) were setup and marked as W(0.5 m), W(1.5 m) and W(3 m), respectively, as shown in Figure 1. Equipment setting and installation methods follow those presented in HDOH (2017). After the probes were installed for months, soil gas sampling was conducted according to the procedure presented in HDOH (2017). A gas pump (DOA-P704-AA, GAST, USA) was first used to pump out of the air from a probe (soil vapor probe purging) at a depth. Pumping flow rate was regulated with a float-type flowmeter (PMR1–011426, Supelco, USA) at a rate of 150 ml/min for some minutes (the time of drawing the air from a probe at a depth is determined according to the air flow rate and the volumes of the probe at that depth and tubing). After then, the probe was connected with a 2-L lung box (Pelican™ 1550case, SKC, USA) to collect soil air in a 1-L Tedlar bag (SKC, USA). Two bags of soil gas at each depth were collected. These sample bags were immediately brought back for analyzing TCE vapor concentration. In March 2021, soil gas was also collected from one of the injection well outside the office (inside the building) indicated as SW1 in Figure 1. This well is sealed all the time if $KMnO_4$ solution is not injected. We also sampled indoor air in November 2022 at a location close to the nested probes with a sample bag and the lung box.

Soil gas samplings were occasionally conducted during the past years. Some of the samples were sent to SGS Taiwan Environmental Services Ltd. (SGS) for quantifying TCE vapor concentration and some were detected by our laboratory. SGS used EPAEY method NIEA A722.75B (NIEA A722.76B after March 15, 2020) for the analyzing. Our laboratory applied sorbent tubes to collect TCE mass from a sample bag. We first drew a certain volume amount of gas (0.005 or 0.05ml) from a bag with an air-tight needle and then injected the gas into a sorbent tube (Tenax GR or Carbotrap® 300). The TCE mass collected by the sorbent tube was then analyzed by a solvent desorption (SD) method with an automatic thermal desorber (ATD) (PerkinElmer Corp, USA) and gas chromatography(GC)/electronic capture detection (ECD) methods with a GC-2014 equipped with an ECD-2014 (Shimadzu Corp., Kyoto, Japan) and a capillary column of which two models were used: one is molecular sieve 5A (30 m × 0.53 mm × 0.5 μm, Supelco, USA)) and another one is SPB-624 (30 m × 0.32 mm × 1.80 μm, Supelco, USA). Tube oven temperature of ATD is set to 280 and 240° for conditioning sorbent tubes and detecting field samples, respectively. For detecting field samples with the

SD-GC-ECD system, column temperature of the GC is set up in the following sequence: (1) fixed temperature at 50° for 10 min.; (2) temperature increases to 100° at a rate of 5°/min.; (3) temperature increases to 220°at a rate of 15°/min.; and (4) temperature is hold for 10 min. The SD-GC-ECD system was also used for preparing standard curves. We used TCE vapor at 1500 ppm (Airgas, USA) and TCE liquid solutions at 100 μg/ml (Supelco) and 5000 μg/ml (Sigma-Aldrich) to produce standard curves before and after sample testings. For the 1500 ppm gas solution, different amounts of gas volume (0.005–0.05 ml) corresponding to different amount of TCE mass were injected into sorbent tubes for the SD-GC-ECD analysis. For analyzing the 1500 ppm gas sample, column temperature for GC is set to 50° and hold for 10 min. Breakthrough amount of TCE mass has been checked by connecting two sorbent tubes for the injection and analyzing with the SD-GC-ECD system and was proven to be minimal. The 100 μg/ml and 5000 μg/ml liquid solutions were both diluted to 1 μg/ml first and then injected into different sorbent tubes (Carbotrap® 300) with different amounts of solution volume (0.01–0.12 ml). Then a purge and trap system was used to purge and trap TCE mass into the sorbent materials in a tube.

Indoor air in the building was sampled by using sorbent tubes (Tenax GR or Carbotrap® 300) since July 2020. The dates of indoor air sampling are within a week of the dates of soil gas sampling. Air sampling was conducted by drawing a known volume of air through the sorbent material of a tube at a flow rate of 50–150 ml/min for 1–2 hours using a sampling pump (XR5000 or Pocket Pump TOUCH, SKC Corp, USA). Indoor air at two to four locations in the building was collected. These locations are IA1 (near the ultrasonic cleansing machine), IA2 (near a refrigerator opposite to the machine room), IA3 (in the office) and IA4 (outside the office and near the opened door) as indicated in Figure 1. After the sampling, the tubes were sealed with caps and immediately sent to our laboratory for quantify TCE mass with the SD-GC-ECD analysis. In August 2022, SGS conducted indoor air sampling and analyzing at similar locations with using canisters and EPAEY method NIEA A715.16B.

Risk assessment

We consider VI in this case study as an exposure pathway for the workers in the building. The USEPA's VISL calculator (USEPA, 2017) was used to calculate target screening levels for groundwater and soil gas that are protective of on-site workers exposed to vapors with a user-specified target hazard index (noncarcinogens) (Target_HQ) and target cancer risk for carcinogens (Target_CR). The VISL calculator also calculates attenuation coefficient (α) which is defined as a ratio of vapor concentration in the indoor space (C_{ia}) to that at a contamination source (C_{source}) and based on the Johnson and Ettinger model (Johnson and Ettinger, 1991) (referred to as the J&E Model). The J&E model is a one-dimensional, steady-state analytical solution to vapor transport with diffusion through soil zone and advection through the building floor to indoor spaces. After obtaining an α value, the VISL calculator then computes C_{ia} with C_{source} which is computed from an assigned groundwater or soil gas concentration. Two kinds of source medium, groundwater and exterior soil gas, were implemented in the VISL calculator to compute C_{source}.

There are totally four scenarios with different source media considered in the VI assessment as show in Table 1. Except for the first scenario, source medium is set as exterior soil gas in the VISL calculator. The highest TCE concentrations observed from the groundwater and bulk soil samples in 2018 were individually assigned as a source for VI. They are groundwater TCE concentration of 25 mg/L observed at SW08 and bulk soil TCE concentration of 31.6 and 18.9 mg/kg observed at S5 at a depth of 4.0–4.5 m and 0–1 m, respectively (see Table 2). We also directly adopted a soil gas TCE concentration observed at W(0.5) in February 2020 as a source, i.e., 1780 ppm (=9.56 × 10^6 μg/m^3). Soil gas TCE concentration corresponding to groundwater source is calculated by the VISL calculator through equilibrium assumption between vapor and aqueous phases (shown in Table 1). Soil gas TCE concentration corresponding to bulk soil TCE concentration was computed with a model assuming linear adsorption and equilibrium partitioning of TCE among aqueous, gaseous and solid phases (Feenstra et al, 1991), hereafter called linear adsorption model (shown in Table 1). The derived TCE source concentrations (C_{source}) are also presented in Table 1. Source depth below the foundation (L_T) is determined according to the sampling depth of soil core or soil gas. Annually average groundwater depth at the site is assigned as the source depth for the groundwater source scenario.

Table 1. Source scenarios corresponding to on-site TCE concentrations and the VISL calculation results.

Source scenario[1]		Vapor concentration of the contamination source, C_{source}, µg/m^3	Ts (°C)	Source depth below the foundation, L_T (m)	Ls[5] (m)	Attenuation coefficient, α[6]	Predicted indoor air concentration, C_{ia} (µg/m^3)[7]	Target_IA (µg/m^3)	
On-site groundwater concentration, C_w (µg/L)									Target_GW (µg/L)
1	25000	1.02×10^7[2]	25.3	2.9	3.4	4.2×10^{-8}	0.43	2.05	10500
On-site bulk soil concentration (mg/kg)									Target_SV (µg/m^3)
2	31.6	3.35×10^7[3]	25	4.2	4.5	4.0×10^{-8}	1.5	2.05	4.7×10^7
3	18.9	2×10^7[3]	25	0.5	0.8	1.4×10^{-6}	27[8]	2.05	1.5×10^6
On-site soil gas concentration (µg/m^3)									
4	9560000[4]	9560000	25	0.5	0.8	1.4×10^{-6}	13[8]	2.05	1.5×10^6

[1] All source scenarios are set with an indoor air exchange rate (ach) of 4.1/hr.

[2] $C_{source} = H_s \times C_w \cdot 1000$, in which H_s is Henry's law constant (=0.408, USEPA, 2017) and C_w is the on-site groundwater concentration in µg/L (USEPA, 2017).

[3]
$$C_{source} = \frac{C_T H_s \rho_b}{\theta_w + K_{oc} f_{oc} \rho_b + H_s \theta_{air}} \times 10^6$$

(Feenstra et al., 1991), in which C_T are the bulk soil concentration (mg/kg) of TCE; f_{oc} is the organic carbon fraction; ρ_b is the soil bulk density (g/cm^3); θ_w is the soil moisture content; θ_{air} is the air content; K_{oc} is the organic carbon water partition coefficient (L/kg). The values of f_{oc}, ρ_b, θ_w and θ_{air} are obtained from the field investigation. The value of K_{oc} is obtained from Chiou et al. (1979).

[4] =1780 ppm (observed in February 2020)

[5] $L_s = L_T + L_b + L_{crack}$, in which L_b is the depth below grade to base of foundation (=0 for the building) and L_{crack} is the foundation thickness (m).

[6] The J&E model (USEPA, 2017)

[7] $C_{ia} = \alpha C_{source}$

[8] Exceeding Target_IA

RESULTS

Field data

Table 2 summaries the number of samples, the detected maximum concentration of TCE and the corresponding date, location and depth of sampling for the field investigation of soil, groundwater, soil gas and indoor air conducted from 2018 to 2022. The maximum TCE concentrations detected in soil and groundwater are located at the northeastern side of the machine room. Specifically, at SW08 (see Figure 2(b)), groundwater TCE concentration decreases tremendously from 25 mg/L (March 2018) to 0.17 mg/L (October 2020) and then fluctuates between 0.9 and 0.04 mg/L. Soil gas sampling were occasionally conducted from October 2018 to November 2022 at W(0.5 m), W(1.5 m), W(3 m) and SW1 (an injection well for ISCO). Indoor air sampling at IA1, IA2, IA3 and IA4 started from July 2020. In addition to present the max TCE concentration detected in soil gas and indoor air in Table 2, the measured, temporal variations of TCE concentration in soil gas and indoor air are presented.

Results of the soil gas TCE vapor concentration are presented in Figure 2(a). In the figure, the time span (September-October 2020) for setting the remediation wells inside and outside the building are indicated by a line with an arrow pointed at the time axis. The soil gas measured results are therefore divided into two parts: the ones before and after the remedial activities were initiated. The first three sets of observed soil gas data (two of them were measured by SGS) show that the magnitudes of TCE vapor concentration are over 10^3 ppm at three soil depths and some are over 10^4 ppm. However, soil gas TCE concentration dropped one order of magnitude immediately after the setting of the remediation wells (the November 2020 results) and kept decreasing after then. In March 2021 (a half year after the remedial activities were initiated), TCE level dropped to 177 ppm at the 0.5 m depth and 20–41 ppm at other depths (including the SW1

Table 2. Summary of field investigation results for the studied site

Sample	No. of samples	Max. TCE concentration	Date	Location[(1)]	Depth (m)	Source
Soil core	10[(2)]	24.6 mg/kg	March 2018	S5–1	4–4.5	YSEE, 2019
	10[(3)]	31.6 mg/kg	March 2018	S5	4–4.5	Our study
		18.9 mg/kg	March 2018	S5	0–1	Our study
Groundwater	20[(4)]	25 mg/L	March 2018	SW08	4.5–6	YSEE, 2019 & TVCM, 2022
Soil gas	22	24972 ppm (=1.34×10^8 µg/m^3)	July 2020	W	0.4	Our study
Indoor air	19	377 µg/m^3	November 2020	IA1	-	Our study

[(1)] see Figure 1,
[(2)] 5 locations, 2 depths of each,
[(3)] 2 locations, 5 depths of each,
[(4)] 12 of 20 samples are from SW08.

Table 3. Indoor air sampling and testing results

Date sampled	TCE vapor concentration (µg/m^3) at location			
	IA1	IA2	IA3	IA4
July 20, 2020	3	14		
November 20, 2020	377	ND(<6.7)	62	
March 12, 2021	48	8	15	
	56	9	29	
August 30, 2022[(1)]	6.1			ND(<1.34)
October 27, 2022	1.1	0.5	ND(<0.3)	
	1.0	0.4	ND(<0.3)	

[(1)] Sampling and testing conducted by SGS.

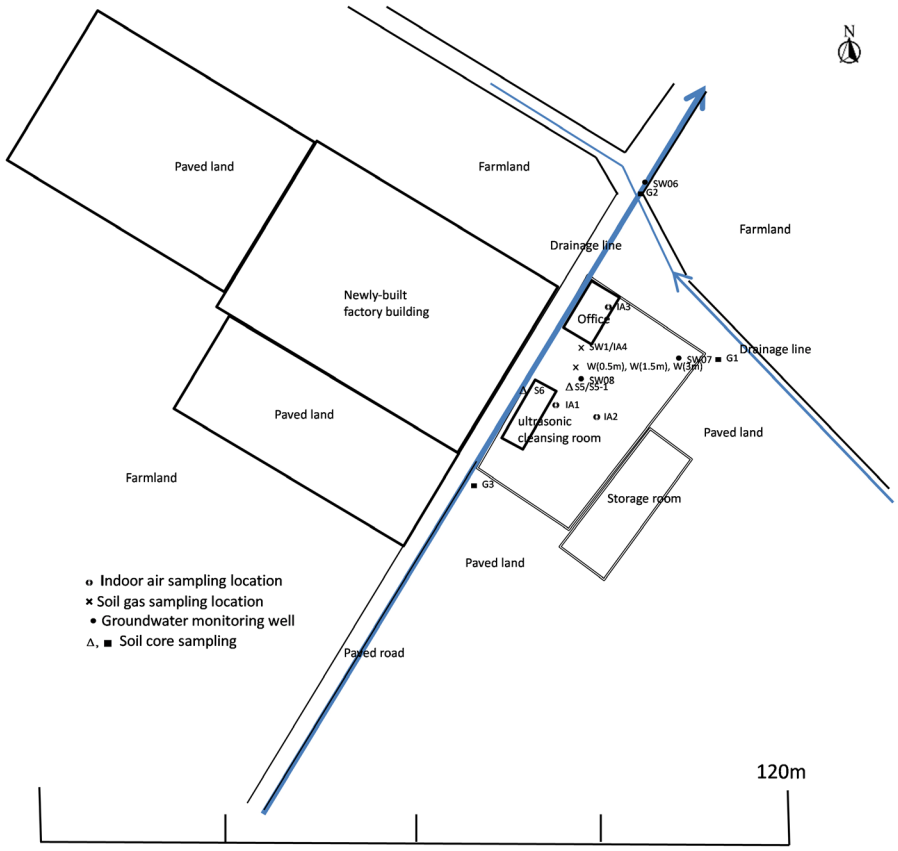

Figure 1. Layout of the investigated building, the nearby area and the sampling locations

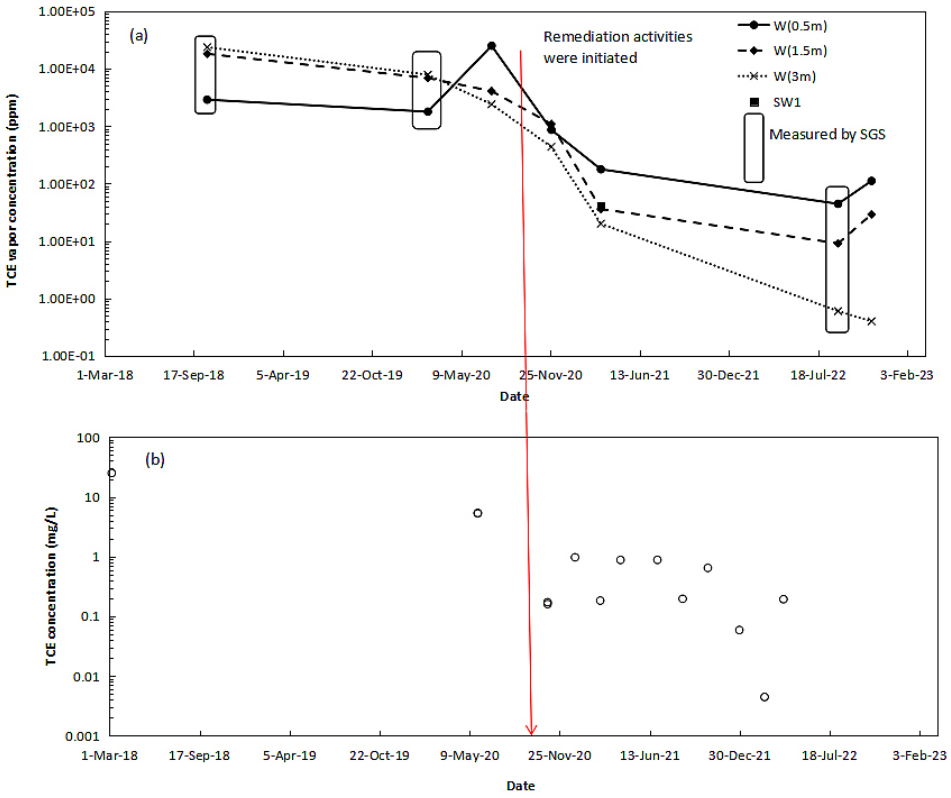

Figure 2. Observed temporal variations of TCE concentration in (a) soil gas at different depths and location; (b) groundwater at SW08 (TVCM, 2022)

respectively). Correspondingly, Figure 2(b) presents the observed, time-varied groundwater TCE concentrations obtained at SW08 which is near the soil gas sampling well.

Measurements for indoor air TCE vapor concentration are presented in Table 3. There is only one set of indoor air data observed before the remediation wells were set up. At that time, TCE vapor concentrations were less than 14 μg/m^3 at IA1 and IA2. However, after the settings of the remediation wells were completed (November 2020), TCE vapor levels were detected as 377 μg/m^3 at IA1 (close to the machine room) and as 62 μg/m^3 at IA3 (in the office). The next set of the measurements (March 2021, 4 months after November 2020) shows that TCE level is more than 15 μg/m^3 at IA1 and IA3, but less than 10 μg/m^3 at IA2 (the opposite side of IA1). In August 2022, SGS detected a TCE level of 6.1 μg/m^3 for the IA1 sample and less than the detection level (<1.34 ug/m^3) for the IA4 sample (outside the office and near the opened door). Two months later, we detected TCE level in indoor air ranging from 0.4 to 1.1 μg/m^3 at IA1 and IA2 and less than detection level (<0.3 μg/m^3) at IA3.

Risk assessment

Table 4 presents the input parameter values and settings for the first and last scenario. An uncertain parameter value shown in Table 4 is the fraction of foundation area with crack for which the VISL calculator suggests with a range from 0.0001 to 0.0019. We found that attenuation coefficient (α) is insensitive to this parameter value in our case study and assigned it as 0.001. All of the source scenarios were set with an indoor air exchange rate (ach) of 4.1/hr, i.e., a max value suggested by the VISL calculator, leading to the ratio of average vapor flow rate into building and building ventilation rate ($Q_{soil}/Q_{building}$) to be 0.00034 (USEPA, 2017). Table 5 shows the assigned soil parameter values for the soil layers beneath the foundation based on the physical examination results of soil cores obtained at S5.

Four source scenarios were assessed by the VISL calculator. As shown in Table 1, source TCE concentrations (C_{source}) derived from groundwater or bulk soil for the first three scenarios and the assigned soil gas TCE concentration for the forth scenario are of about the same orders of magnitude (10^7 μg/m^3). We assessed the effect of these sources

Table 4. Summary of input parameters for the case study

Items	Unit	Value or settings		Data source
1. Source characteristics				
Source medium		Groundwater	Exterior soil gas	
Contaminant concentration (C_{medium})	µg/L	25000		Observed in March 2018
	µg/m^3		9560000	Observed in September 2020
Depth below grade to source medium, L_s	m	3.4	0.8	On site
Average temperature (T_s)	°C	25.3	25	On site
2. Chemical properties				
Chemical name		Trichloroethylene		(1)
Henry's Law constant (H_s)	[–]	0.408		(1)
Unit risk factor (IUR)	(µg/m^3)$^{-1}$	4.1×10^{-6}		(2)
Reference concentration (RfC)	mg/m^3	2×10^{-3}		(2)
Diffusivity in air (D_{air})	cm^2/sec	6.87×10^{-3}		(1)
Diffusivity in water (D_{water})	cm^2/sec	1.02×10^{-5}		(1)
3. Building characteristics				
Building setting		Commercial		On site
Foundation type		Slab on grade		On site
Depth below grade to base of foundation (L_b)	m	0		On site
Foundation thickness (L_{crack})	m	0.3		On site
Fraction of foundation area with crack		0.001		Adopted from the VISL calculator
Enclosed space floor area (A_{bf})	m^2	650		On site
Enclosed space mixing height (H_b)	m	6		On site
Indoor air exchange rate (ach)	1/hr	4.1		Max. value adopted from the VISL calculator
$Q_{soil}/Q_{building}$		0.00034		(3)
4. Exposure parameters				
Target risk for carcinogens (Target_CR)		1×10^{-6}		Default value
Target hazard quotient for non-carcinogens (Target_HQ)		1		Default value
Average time for carcinogens (AT_c)	yrs	70		(2)
Average time for non-carcinogens (AT_{nc})	yrs	25		(2)
Exposure duration (ED)	yrs	25		(2)
Exposure frequency (EF)	days/yrs	250		(2)
Exposure time (ET)	hrs/day	8		(2)
Mutagenic mode-of-action factor (MMOAF)	yrs	72		(2)

(1) Chemical data in the VISL calculator,

(2) ToxSummary data in the VISL calculator based on USEPA (2014b) and USEPA RSLs (2015),

(3) Calculated by $\left(\frac{Q_{soil}}{Q_{building}}\right)_{adj} = 0.003 \times \frac{0.45}{ach}$ as shown in USEPA (2017).

Table 5. Characteristics of soil layers beneath the building foundation

Layer(1)	Classification	Layer thickness, L_i (m)	Porosity, n	Water moisture content, θ_w	Soil bulk density, ρ_b (g/cm^3)
A	Silty sand	1	0.37	0.3	1.71
B	Silt or Sandy clay	2.5	0.41	0.39	1.62

(1) Layer A is immediately beneath the building foundation; layer B is below layer A.

sample). The last measured results in November 2022 show that TCE vapor concentration obtained at depths of 0.5 m and 1.5 m are 100 and 29 ppm, respectively, and are both under the detection limit (<0.4 ppm) at the 3 m depth and from the indoor space (at SW1). SGS conducted the sampling and testing in September 2022 and obtained TCE vapor concentration an order of magnitude less than the November ones at the 0.5 m and 1.5 m depths (44.3 and 9.1 ppm,

located at different depths below the foundation. Results of the attenuation coefficient (α) and the corresponding indoor air concentrations (C_{ia}), indoor air and groundwater or soil vapor screening levels (Target_IA and Target_GW or Target_SV) are also listed in Table 1. The last three levels (Target_IA, Target_GW and Target_SV) are based on the target risk of 10^{-6} for carcinogens (Target_CR) and target hazard quotient of 1 for non-carcinogens (Target_HQ) and the data of toxicity factors and exposure parameters from USEPA (2014b) and the screening level tables of USEPA RSLs (2015) as presented in Table 3. Results show that the magnitudes of the attenuation coefficient range from 10^{-8} to 10^{-6} and the predicted indoor air concentrations exceed the Target_IA for more than 5 times for the last two source scenarios.

DISCUSSION

Soil gas TCE concentration has dropped more than two orders of magnitude after the remediation work was initiated and kept decreasing to less than 180 ppm after the work was conducted for two years. We suspected that the activity of the setting of the remediation wells leaded to the release of contaminated soil air which has been accumulated under the building in the past. Yao et al. (2020) have noticed that high subslab soil gas contaminant concentrations exist under paved surface ground. The following remediation activity (injection of the $KMnO_4$ solution into the underground) also in advance recovered shallow groundwater quality (as shown in Figure 2(b)) which led to less TCE vapor partitioning to soil air. The 2022 soil gas data show that TCE level observed at the 0.5m depth is more than one order of magnitude greater than those found at the 1.5m and 3.0m depths. It implies that a certain amount of liquid TCE that is not reached by groundwater table resides in shallow soils (depth < 1m) beneath the foundation. However, remediation of the shallow soils has not yet been considered. It is also noted that the indoor air TCE concentration detected by SGS at IA1 in August 2022 is greater than Target_IA (=2.05 μg/m^3), although the October data detected by our laboratory is less than 2.05 μg/m^3. It implies indoor air in this factory building still needs to be monitored.

The present input data of toxicity factors and exposure parameters for the VISL calculator are based on USEPA (2014b) and USEPA RSLs (2015) as shown in Table 4. If using the recent USEPA RSLs (May, 2023) for carcinogenic and non-carcinogenic screening levels of TCE for composite worker air at Target_CR of 10^{-6} and Target_HQ of 1, i.e., 3.0 and 8.8 μg/m^3, respectively, the combined risk-based indoor air screening level will be calculated as 2.23 μg/m^3. There are only a little bit of differences between these target screening levels for indoor air, i.e., 2.05 v.s. 2.23 μg/m^3. The present risk assessment results were obtained with an indoor air exchange rate of 4.1/hr. According to the ventilation setting in the building, an air exchange rate can be estimated as high as 15/hr leading to a $Q_{soil}/Q_{building}$ value as low as 0.00009 for which indoor air concentrations predicted by the VISL calculator for the last two source scenario cases still exceed Target_IA.

Differences of the attenuation coefficient (α) values predicted by the VISL calculator are great due to different source depth below the foundation (L_T) assigned in each case, i.e., α is 10^{-6} with L_T of 0.8m and 10^{-8} with L_T of >3.4m. We further calculated the α value for screening VI (=Target_IA/C_{source}) and found its range is between 6×10^{-8} and 2×10^{-7} for these source scenarios. However, they are all far less than the USEPA recommendation, i.e., 0.03 for soil gas to indoor air and 0.001 for groundwater to indoor air (USEPA, 2015b, Ma et al., 2020) and also less than 0.0008 for soil gas to indoor air provided in the work of Lahvis and Ettinger (2021). It means these suggested α values for screening VI are fairly conservative for our case.

TCE concentration of 10^7 μg/m^3 assigned for soil gas in these scenario cases are about the lower limit of the soil gas TCE concentrations observed before November 2020. After November 2020, the soil gas TCE concentration observed at W(0.5 m) was dropped to 177 ppm (=9.5×10^5 μg/m^3) and further reduced to 111 ppm (=6.0×10^5 μg/m^3) on November 2022. If the recent observed soil gas results are relevant to bulk soil TCE concentration with the linear adsorption model, we may guess that bulk soil TCE concentration in shallow soils beneath the foundation is decreased to be less than 18.9 mg/kg after two years of groundwater remediation work.

CONCLUSIONS

Conclusions are made below:

1. Previously observed high TCE soil gas concentrations are attributed to accumulation of

TCE vapor in the unsaturated soil beneath the building floor, since ground surface at the site is extensively paved. These soil gas data do not correlate with the magnitudes of bulk soil TCE concentration with the linear sorption model.

2. Soil gas TCE concentration of greater than 10^7 μg/m^3 observed in shallow soils at a depth of less than 1 m may pose health risk to the workers inside the building due to VI, even at an high air exchange rate of 15/hr, as we have detected TCE concentrations in indoor air exceeding Target_IA several times in the past.
3. Indoor air (or soil gas) needs to be monitored because an amount of TCE is still trapped within the shallow soils that are not reached by groundwater table, as we have observed a significant higher soil gas TCE levels at a depth of 0.5 m compared to other depths after the groundwater remediation work was initiated for two years.
4. It is necessary to use soil gas data as a source medium and the VISL calculator for initial VI screening. The ratio, $Q_{soil}/Q_{building}$, corresponding to indoor air exchange rate greater than 4.1/hr, however, needs to be explored further since high ventilation rates and air conditioning in factory buildings are usual in Taiwan.

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