

ABSTRACT

Exposure to contaminants in outdoor air, resulting from migration of volatile chemicals from soil matrix, soil gas or groundwater, can present a significant human health risk. Vapor intrusion into indoor air usually results in greater exposure and risks than migration into outdoor air. This is because wind disperses contaminants into a large volume of outdoor air, plus advective sources of HVAC systems create negative pressure and draw subsurface air into buildings. At contaminated sites with no existing or potential future buildings, exposure to volatile chemicals in outdoor air should be considered. In the absence of existing State or Federal guidance for estimating outdoor air inhalation risks using soil gas data, we present methodology for a screening-level health risk assessment. The effective diffusion through the unsaturated vadose zone is assumed to be the sole mode of emission. Dispersion is based on Q/C values derived from the Industrial Source Complex model. Standard risk assessment methods are used to estimate inhalation exposure and associated risks. Sensitivity analyses were performed, comparing DTSC default soil assumptions to sand, source areas of 0.5 acres to 30 acres, and dispersion models (Q/C versus box model). Soil gas to outdoor air attenuation factors ranged from 10⁻⁵ to 10⁻⁶ for tetrachloroethylene, trichloroethylene and benzene. Case studies demonstrate that potential outdoor air exposures may drive the risk assessment when buildings with indoor air exposures do not exist or are prohibited. If screening-level risks exceed acceptable levels, collecting outdoor air samples and/or conducting site-specific refined estimates of outdoor air concentrations and inhalation risks is recommended.

OBJECTIVES

- Determine whether risk assessment from subsurface volatile emissions to ambient air is warranted at contaminated sites with no existing or potential future buildings.
 - ❖ Develop algorithms to model ambient air concentrations from subsurface soil gas.
 - ❖ Perform sensitivity analyses.
 - ❖ Apply to case studies using standard risk assessment methodology to predict ambient air risks.
- Establish standardized process for assessing ambient air risk from soil gas in the absence of potential indoor air exposures.

METHODS

SOIL GAS TO OUTDOOR AIR MODELING

Assumptions

- No diffusion through the capillary zone
- No advective movement of vapors
- Infinite non-depleting source, linear equilibrium partitioning of contaminant within soil (sorbed to soil matrix, to dissolved phase, and to vapor phase)
- Homogeneous soil type
- Steady-state diffusion of both liquid and vapor phases through the vadose zone to ground surface
- Soil gas sampling depth 5 ft below ground surface

Emissions were modeled utilizing the earlier work of Johnson and Ettinger (1991) (J&E) which employs the Millington and Quirk (1961) model on vapor transport modeling in the subsurface. Chemical-Specific properties and the soil properties physical constants were taken from the VLOOKUP table in the DTSC-Modified J&E Model spreadsheets.

Dispersion was modeled using air dispersion factors (Q/C). The Q/C dispersion model is more defensible than the box model. The Q/C model uses a ground level source, is appropriate for long-term or annual average concentrations, and is applicable to source areas of varying sizes and shapes (i.e., not limited to rectangular as is the box model). The USEPA Q/C values (Exhibit 11; USEPA 1996) were derived using the AREA-ST model incorporated into EPA's Industrial Source Complex Model (ISC2) platform, a full year of meteorological data from 29 locations across the United States, and assuming source areas ranging from 0.5 to 30 acres. Q/C values from the California locations (Fresno, Los Angeles, and San Francisco), were used.

SENSITIVITY ANALYSES

Assumed high soil gas concentrations of 10,000 mg/m³ for selected carcinogenic volatile chemicals (tetrachloroethylene, trichloroethylene, and benzene).

- Emission: Soil type (DTSC default soil assumptions versus sand)

Soil Type	Vadose zone SCS Soil type	Vadose zone soil bulk density (g/cm ³)	Vadose zone soil total porosity (unitless)	Vadose zone soil water-filled porosity (cm ³ /cm ³)
DTSC-Default		1.5	0.43	0.15
Sand	S	1.66	0.375	0.054

- Dispersion (Q/C range for California): Size of soil gas plume (Source areas of 0.5 acres versus 30 acres)
 Fresno, 30 acres (121406 m²) source area Q/C = 31.90 g/m²-s per kg/m³
 San Francisco, 0.5 (2023 m²) acres source area Q/C = 89.51 g/m²-s per kg/m³
- Dispersion models (Q/C versus box model)
 Source areas: 0.1, 0.5, 1, 5, 10, 20 and 30 acres.
 Dispersion factors (Q/C) were calculated using USEPA (2002) Equation D-1 and Exhibit D-3 parameters for Zone 2 San Francisco, g/m²-s per kg/m³
 Box model assumed a square-shape source, thus LS was calculated as the square root of the source area.

SOIL GAS TO OUTDOOR AIR ALGORITHMS

Emission

$$Q_{calc} = C_v \times \frac{D^{eff}}{d} \times CF$$

Q_{calc} = Emission flux calculated, mg/m²-s
 C_v = Concentration in soil vapor measured from soil gas sampling and analysis, mg/m³
 d = depth of soil gas sample from ground surface, m
 CF = Conversion factor, 10⁻⁴ m²/cm²

$$D^{eff} = D_a(\theta_a^{3.33}/n^2) + (D_w/H'_{TS})(\theta_w^{3.33}/n^2)$$

(Equation 11, US EPA 2004; J&E Model User's Guide)

D^{eff} = Effective diffusion coefficient across soil unsaturated vadose zone, cm²/s

D_a = Diffusivity in air, cm²/s
 θ_a = Soil air-filled porosity, cm³/cm³
 n = Total soil porosity, cm³/cm³
 D_w = Diffusivity in water, cm²/s
 θ_w = Soil water-filled porosity, cm³/cm³
 H'_{TS} = Henry's law constant at the system temperature, dimensionless

Dispersion

Q/C Model:

$$Q_{calc}/C_{OA} = Q/C$$

Select Q/C value, substitute calculated Q (Q_{calc}) and solve for C_{OA}

$$C_{OA} = Q_{calc} \times CF_{g-kg} / (Q/C)$$

Q/C = Air dispersion factor, g/m²-s per kg/m³
 C_{OA} = Concentration in outdoor air, mg/m³
 Q_{calc} = Emission flux calculated above, mg/m²-s
 CF_{g-kg} = Conversion factor, 1000 g/kg

Box Model:

$$C_{OA} = Q_{calc} \times A / (LS \times V \times MH)$$

A = Area, m²
 LS = Length, m
 V = Average wind velocity, 2.25 m/s (default)
 MH = Mixing height, 2 m (default)

Attenuation Factor

$$\alpha = C_v/C_{OA}$$

RISK EVALUATION / CASE STUDIES

Conducted screening level risk evaluation for the inhalation route from exposures to volatiles emanating from subsurface soil gas to ambient air for a standard commercial/industrial worker scenario. Risks from chronic exposures were evaluated as per USEPA Guidance (USEPA, 2009).

RISK ASSESSMENT

$$Risk = EC \times IUR \times CF_{\mu g-mg}$$

IUR = Inhalation Unit Risk, (μg/m³)⁻¹
 CF_{μg-mg} = 1000 μg/mg
 EC = Exposure Concentration, mg/m³

$$EC = (C_{OA} \times ET \times EF \times ED) / AT$$

ET = Exposure time, 8 hrs/d
 EF = Exposure frequency, 250 d/yr
 ED = Exposure duration, 25 yr
 AT_c = Averaging time for carcinogenic effects (70 y x 365d/y x 24 hr/d), 613,200 hrs

Chemical	IUR (μg/m ³) ⁻¹	Source
PCE	5.9E-06	CalEPA
TCE	4.1E-06	IRIS
Benzene	2.9E-05	CalEPA
DBCP	2.0E-03	CalEPA

CASE STUDIES

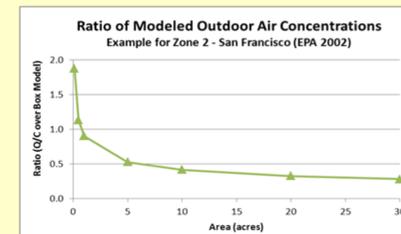
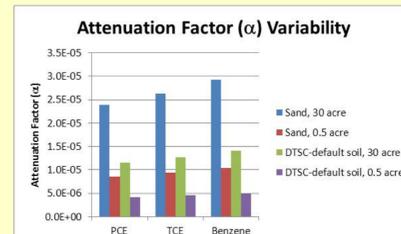
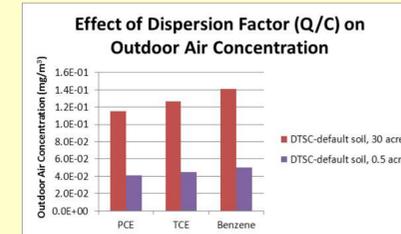
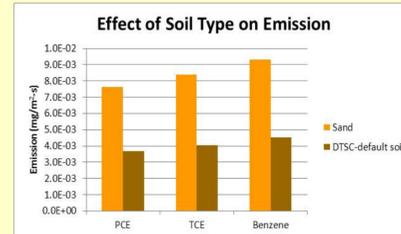
Case A: Former rail yard that was a major railroad operations facility from 1865 until the 1990's. It served as the primary locomotive maintenance and rebuilding facility. Main industrial operations area volatile subsurface contamination of chlorinated solvents and their breakdown products. Evaluated risks from tetrachloroethylene (PCE), trichloroethylene (TCE) and vinyl chloride (VC) using maximum soil gas concentrations, DTSC-default soil properties, and Q/C for 30 acre source with Fresno climatology.

Case B: Current operating rail yard site active since the 1920's. Operations include historical repair and maintenance of railcars and refueling activities. Volatile subsurface contamination of fuel products and chlorinated solvents. Evaluated risks from PCE, TCE and benzene using maximum soil gas concentrations, DTSC-default soil properties, and Q/C for 30 acre source with Fresno climatology.

Case C: Current liquid products formulation and packaging facility for agricultural chemicals, used historically as a chemical warehouse. Surface and subsurface releases included 1,2-dibromo-3-chloropropane (DBCP) and petroleum hydrocarbons. Evaluated risks from DBCP and benzene maximum soil gas concentrations; site-specific soil properties, Q/C approach with the size of 0.1 acre (site-specific) with Los Angeles climatology.

RESULTS

SENSITIVITY ANALYSES



- Emission from sand was approximately 2 times higher than DTSC-default soil.
- Dispersion Factors (Q/C) for California produced outdoor air concentrations from 30 acres that were almost 3 times higher than from 0.5 acres (the smallest and largest Q/C values for California).
- Attenuation factors from soil gas to outdoor air were in the 10⁻⁵ to 10⁻⁶ range and varied by less than an order of magnitude using Q/C modeled dispersions for 0.5 to 30 acre sources in California from sand or DTSC-default soil.
- Dispersion models (Q/C versus box model) predicted up to 2 to 3 fold differences in outdoor air concentrations, depending on the size of source area: the Q/C model predicts higher C_{OA} for smaller sizes, while the box model predicts higher C_{OA} for larger sizes (> 1 acre in this example).

CASE STUDIES

	Chemical	C _v (mg/m ³)	Qcalc (mg/m ² -s)	C _{OA} mg/m ³	α	EC _c (mg/m ³)	Risk
Case A	PCE	7560	2.79E-03	8.73E-02	1.2E-05	7.12E-03	4.2E-05
	TCE	33,000	1.29E-01	4.06E+00	1.3E-05	3.31E-01	6.6E-04
	VC	12,400	6.73E-03	2.11E-01	1.7E-05	1.72E-02	1.3E-03
Case B	PCE	820	3.02E-04	9.47E-03	1.2E-05	7.72E-04	4.6E-06
	TCE	10	4.04E-06	1.27E-04	1.3E-05	1.03E-05	2.1E-08
Case C	Benzene	170	7.66E-05	2.40E-03	1.4E-05	1.96E-04	5.7E-06
	DBCP	2940	9.01E-05	1.11E-03	3.8E-07	9.08E-05	1.8E-04
	Benzene	0.058	1.71E-08	2.12E-07	3.6E-06	1.73E-08	5.0E-10

Yellow highlighted cells denote risks in excess of 1E-06, the point of departure for regulatory levels of concern.

DISCLAIMER

Professional affiliations are listed for contact purposes only. Analyses and conclusions contained herein are solely those of the authors and do not represent guidance or official policy of the California Department of Toxic Substances Control or California Environmental Protection Agency.

DISCUSSION

Soil Gas to Outdoor Air Modeling

The maximum attenuation factor for soil gas to outdoor air (α_{SG-OA}) was 5 x 10⁻⁵. In the one case study with site-specific soil properties evaluated here (Case C), α_{SG-OA} values were 1 to 2 orders of magnitude less than the screening level model. DTSC's Vapor Intrusion Guidance (CalEPA, 2011) recommends using soil gas to indoor air attenuation factors for future residential and commercial land uses of 1 x 10⁻³ and 5 x 10⁻⁴, respectively. The screening-level model presented here consisting of diffusion only emissions and Q/C dispersion modeling is a conservative approach for initial evaluation of sites with subsurface contamination of volatile chemicals when no buildings exist and land use controls prevent future buildings.

Case Studies Key Findings/Recommendations

Predicted risks at levels of concern for the standard commercial/industrial outdoor worker (non-soil invasive). Cumulative risks for each case study exceeded 1E-6, the regulatory level of concern.

Case A:

- PCE and TCE screening level outdoor air risks were predicted at > 4E-5 and 6E-4, respectively, and VC risk was 1E-3.
- A soil vapor extraction system is in place and groundwater is being pumped and treated.
- Post-remediation soil gas sampling and a site-specific risk assessment are recommended.

Case B:

- PCE and benzene screening level outdoor air risks both were predicted to exceed the regulatory point of departure of 1E-6.
- No soil gas samples have been collected from a major potential source area.
- A work plan for additional soil gas sampling and risk assessment are under preparation.

Case C:

- DBCP is the main risk driver, with the cancer risk > 1E-4 estimated from the outdoor air model.
- Outdoor air samples were collected as a follow-up. The maximum detected DBCP concentration (0.018 μg/m³) is approximately two orders less than the modeled outdoor air concentration, i.e., **outdoor air risks predicted by the model are conservative.**
- Benzene was detected in all outdoor air samples with estimated cancer risk > 1E-6. It likely reflects ambient air background as benzene concentrations in soil gas samples were very low with model-estimated cancer risk < 1E-9.

CONCLUSIONS

- At contaminated sites with no existing or potential future buildings, exposure to volatile chemicals in outdoor air should be evaluated in the human health risk assessment.
- A conservative methodology for screening-level inhalation human health risk assessment is presented as a tool to evaluate potential ambient air risks to outdoor workers from subsurface soil gas emissions.
- Sensitivity analyses demonstrated
 - Emissions vary 2-fold for DTSC-default soil vs sand
 - Dispersion varies 3-fold for source areas of 0.5 vs 30 acres (Maximum and minimum Q/C for California Zones)
 - Dispersion varies 2-3-fold between Q/C and box models
- Soil gas to outdoor air attenuation factors (α) ranged from 10⁻⁵ to 10⁻⁶ for PCE, TCE, and benzene.
- Case studies demonstrated that potential outdoor air exposures may drive the risk assessment when buildings with indoor air exposures do not exist and land use controls prevent future buildings.
- If predicted screening-level risks exceed acceptable levels, collecting outdoor air samples and/or conducting site-specific refined estimates of outdoor air concentrations and inhalation risks is recommended.

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