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Passive Vapour Barrier Feasibility Study: Redevelopment of an Industrial Site to a Residential Site

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1. Introduction

Impact on air quality inside buildings due to intrusion of vapours of volatile organic compounds ("VOCs") is a source of concern for most sites affected by groundwater or soil contamination by VOCs. In case of redevelopment of industrial sites for residential uses it is necessary to achieve a high reduction rate in vapour intrusion to avoid inacceptable exposure levels of residents.

The case study presented is related to a formerly industrial site located in a residential area in a town in Italy. Soil and groundwater at the site are impacted by chlorinated aliphatic hydrocarbons (VOCs). The site redevelopment project consists in the creation of a residential complex by keeping the existing building structure (industrial sheds) but constructing new floors. Presence of VOCs has been detected in the sub-slab soil vapour and in the indoor air of the site. The current indoor air VOC concentrations do not exceed occupational standards, therefore no abatement measures have been required so far. On the contrary, abatement measures will be needed to mitigate soil vapour intrusion into the future residential dwellings. A reduction of 8 orders of magnitude ($1*10^8$) in VOC vapour concentrations in soil is required to meet the applicable indoor air standards for residential use.

An evaluation of the feasibility of a passive soil vapour mitigation system was carried out. The evaluation included:

- the development of a conceptual model for vapour intrusion;
- the conceptual design of the mitigation system;
- a research of geomembranes available on the market;
- the modelling of the required passive venting rate of the sub-slab void system;
- the prediction of the resulting vapour intrusion attenuation factor and of the expected indoor air VOC concentrations in future building lofts using a modified form of the Johnson and Ettinger model.

2. Summary of contamination data

The site (28,000 m^2) is located in a residential area close to the centre of the town. The building currently present at the site is a one-storey industrial building with isolated plinth foundation. The building covers most of the site, with paved parking areas around the building. The redevelopment of the site will consist in the construction of a residential complex, keeping the existing building structure (roof, pillars, basement, underground parking lot, foundations and external walls) but constructing new

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floors. The architectural design is based on the division of the current building into apartment lofts separated by green areas. The architectural design and building physics were considered for the modelling of the required passive venting rate of the sub-slab void system and the prediction of the resulting vapour intrusion attenuation factor and of the expected indoor air VOC concentrations.

Soil and groundwater contamination exceeding the applicable Italian standards is present at the site. Chlorinated solvents have also been detected in the sub-slab soil vapour and in the indoor air of the site, the latter not exceeding occupational standards.

The main contaminants detected in the indoor sub-slab vapours are trichloroethylene ("TCE"), with maximum concentrations of 5,000 mg/m^3, tetrachloroethylene ("PCE") and 1,1-dichloroethylene ("1,1-DCE") (max. conc. exceeding 1,000 mg/m^3) and 1,2-dichloroethylene ("1,2-DCE") and 1,1,1-trichloroethane ("1,1,1-TCA") (max. conc. exceeding 100 mg/m^3). All the measured indoor air concentrations were below the Threshold Limit Value for the Time Weighted Average (TLV-TWA), as established by the American Conference of Industrial Hygienists ("ACGIH"), and below the occupational standards set up by Italian Legislative Decree ("D.Lgs.") 81/08. TLV – TWA is the time weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect. In case of residential use of the current building the concentrations detected would exceed the standards indicated by the Italian Environmental Protection Agency ("ISPRA") in the Vapour Intrusion VI Guidance for intense physical activity. The maximum indoor air concentrations are reported in the following Table 1.

Table 1: Comparison Indoor air Concentrations and Standards (µg/m^3)

	D.Lgs. 81/08	*ACGIH 2010 TLV - TWA*	*ISPRA Residential Standards (intense physical activity)*	*Indoor air concentrations (maximum value detected)*
Chloromethane	-	-	0.31	2.3
Trichloromethane	10,000.00	48826.18	0.024	1.3
Vinyl chloride	7,770.00	2556.24	0.063	<0.5
1,2-Dichloroethane	-	40474.44	0.021	<0.5
1,1-Dichloroethylene	-	19826.18	0.011	$1.14*10^1$
Trichloroethylene	-	53742.33	0.32	$4.42*10^1$
Tetrachloroethylene	-	169529.65	0.096	$2.39*10^1$
Hexachlorobutadiene	-	213.30	0.025	1
1,1-Dichloroethane	412,000.00	404785.28	-	7.4
1,2-Dichloroethylene	-	793047.03	-	<0.5
1,2-Dichloropropane	-	-	0.028	3.7
1,1,1-Trichloroethane	550,000.00	1909897.75	-	$1.41*10^1$
1,1,2-Trichloroethane	-	54564.42	0.034	<0.5
1,2,3-Trichloropropane	-	60298.57	0.00028	<0.5
1,1,2,2-Tetrachloroethane	-	6865.44	0.0096	1.5

Abatement measures are needed to mitigate soil vapour intrusion into the future residential dwellings. A reduction of 8 orders of magnitude ($1*10^8$) in vapour concentrations in soil is required to meet the residential standards. Normally the installation of active systems is required to obtain such a high reduction. However, for strategic and commercial reasons, technical discussions had led to the choice of a solely passive soil vapour mitigation system over an active system. No literature data has been found on the installation of passive soil vapour mitigation systems for residential redevelopment at sites requiring such a high reduction rate in the vapour intrusion attenuation factor. Consequently, a system composed of geomembranes and of a new sub-slab void system connected to stacks equipped with wind rotating caps has been taken into consideration.

3. Selection of a passive soil vapour mitigation system

The system has been assumed to include, as the main elements, an aerated floor (i.e. a structure allowing circulation of air) sandwiched between two geomembrane barriers. In particular, in sequence from the future native ground surface, the system is assumed to include:

- a bottom barrier composed of a gravel layer with venting piping and of a primary geomembrane above the gravel layer;
- a sub-slab void system sandwiched between two lean concrete layers;
- an upper barrier composed of a secondary geomembrane and of a thick concrete layer, below the new floor.

The installation of a single barrier is considered not sufficient to achieve the standards, even if multiple geomembranes are taken in account (i.e. double geomembrane, geomembrane with concrete).

A preliminary evaluation of different geomembranes was completed. Two primary types of geomembrane barriers available on the market are sheet membranes and spray-applied membranes. Sheet membranes, durable and chemically resistant to chlorinated solvents (for certain types of membranes), are difficult to connect and seal to foundations with sharp corners. Spray-applied membranes are easier to seal to foundations and spray-applied membranes that are composites consisting of a spray-applied core (e.g., chloroprene and latex) and a geomembrane sheet have good chemical resistance and low diffusivity to chlorinated solvent vapours. At this preliminary evaluation stage, both types of geomembranes, which consist of similar cores, are considered to be acceptable barriers. The potential limitation of geomembranes is that there is little data on diffusion coefficients or permeation coefficients for situations where chlorinated solvent vapour concentrations are high, and also no long-term performance data exists.

Among the available sub-slab void systems, the Pontarolo's Cupolex^{TM} ("Cupolex") system is considered appropriate to meet the technical requirements for the subject case. Cupolex is a concrete forming system for floors made from recycled plastic. Concrete is poured over the modular dome forms to create floating or structural slabs with a sub-slab void to be passively ventilated to remove vapours. Figure 1 shows a typical cross-section of the mitigation system described above.

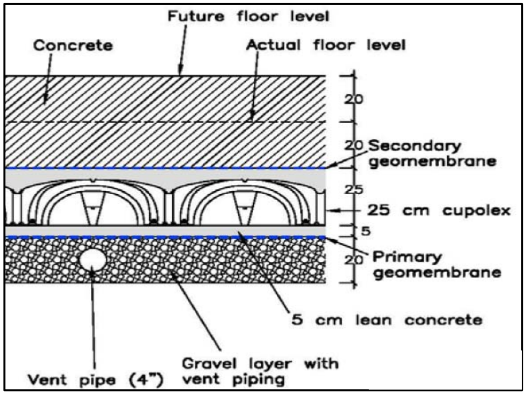

Figure 1: Cross-section of the Mitigation System

The purpose of the bottom barrier is to minimise the upward migration of the volatile contaminants towards the primary geomembrane. The processes through which this will occur are lateral diffusion and advection, anticipated to occur primarily through natural mechanisms such as atmospheric pressure changes and temperature gradients. The purpose of the geomembranes is to reduce the migration of volatile chemicals. The purpose of the Cupolex layer is to provide a highly efficient under-slab void network to facilitate the dilution and dispersion of vapours of chlorinated solvents from beneath buildings.

4. Modelling of air flow in the sub-slab void system

Preliminary modelling of air flow was conducted using a Computational Flow Dynamics ("CFD") numerical model to simulate the air flow in the Cupolex layer and to determine the air flow rate as a function of the local atmospheric conditions (i.e., solar irradiation, external temperature and wind conditions). Preliminary modeling of venting efficiency was also conducted according to civil engineering principles. A difference of pressure generated by a commercial rotating cap for stacks was used in the modelling.

The available difference of pressure induced by the wind and stack effect was determined on a monthly basis. Considering the sum of the contributions of wind and stack effect, a monthly average available difference of pressure was calculated (1.7 Pa in winter and 0.65 Pa in summer). Depending on the available difference of pressure, the average air flow rate through the Cupolex system was determined from the fluid dynamic curve representing the monthly average passive air flow rate through the Cupolex system as a combined effect of the difference of pressure induced by the wind and the stack.

Preliminary modelling of venting efficiency was also conducted according to civil engineering principles.

5. Assessment of passive venting effectiveness

A preliminary vapour intrusion modelling study was then completed to evaluate passive venting efficiency. Given the uncertainty for prediction of vapour migration processes and the potential range in input parameters for the properties of the soil, geomembranes, building and ventilation rate, the modelling is highly approximate (i.e., orders of magnitude accuracy). A proprietary modified version of the Johnson and Ettinger (1991) model was used for predictions of the attenuation factor between soil vapour and indoor air. A semi-analytical model was used to calculate the chemical mass flux in the unsaturated soil zone below the bottom barrier, mass flux removed through the passive venting Cupolex system, mass flux through the building envelope and mixing of vapours in the building air space. The model has been benchmarked to the USEPA Superfund Johnson and Ettinger spreadsheet for the case where there is no mass removed through passive venting of the Cupolex system (i.e., model collapses to Johnson and Ettinger (1991) solution).

The modified model of Johnson and Ettinger does not simulate the possible mass flux that is removed through passive venting or soil gas advection through cracks in the bottom barrier (if there is a positive pressure gradient across the barrier). With respect to the first process, the model is conservative; for the second process, the model is non-conservative. It is considered that these processes are likely minor (and possibly counter-acting) and therefore are unlikely to significantly influence the study findings. The model assumes that the building could be depressurized relative to the underlying soil due to the stack effect or other processes (e.g., ventilation).

The soil vapour data used in model simulations presented in this paper is based on the maximum sub-slab vapour concentration measured in several relevant monitoring events.

The modelling assumes that there is a laterally continuous, constant-in-time, non-depleting soil vapour source located directly below the 0.2 m thick base venting layer. The modified Johnson and Ettinger model is a one-dimensional model for chemical transport. The fluxes modelled are as follows:

- upward chemical diffusion (vapour- and aqueous-phase) within the base venting layer;
- chemical diffusion through the primary bottom geomembrane liner and through dust-filled cracks or openings in the primary geomembrane liner (when present);
- instantaneous mixing of TCE vapours within the aerated floor and dilution through venting;
- chemical diffusion through the second upper geomembrane liner and through dust-filled cracks or openings in the secondary liner (when present);

- chemical diffusion through concrete (only assumed for certain model runs) and dust-filled cracks in the concrete floor of the building;
- soil gas advection through cracks in the concrete floor of the building; and
- instantaneous mixing of vapours in the air space of the building through ventilation.

The model assumes that the building could be depressurized relative to underlying soil due to the stack effect or other processes (e.g., ventilation).

For estimation of the venting volume flow rate in the Cupolex layer, the summer and winter rates estimated for CFD modelling were used (27 to 42 m^3/h for an area of 280 m^2), but were scaled to the building size (9 to 14 m^3/h for an apartment loft of 7 x 10 m). The soil gas advection rates were chosen based on consideration of empirical data for the ratio of the soil gas advection rate and building ventilation rate (Q_{soil}/Q_{build}), and ratio of Q_{soil} to building subsurface foundation area (Q_{soil}/A). The Q_{soil}/Q_{build} ratio values (ranging between about $1.90*10^4$ and $3.81*10^4$) are considered reasonable because of the slab at grade construction, building foundation construction, and climate.

The properties of the geomembranes are critical for modelling. As mentioned above, there is little data on the diffusion coefficient (defined here as the overall mass transport rate through the geomembrane, or permeation rate as defined in McWatters and Rowe, 2010). Given the uncertainty in diffusion rates, for modelling purposes, a base case diffusion coefficient value of 10^{-10} m^2/s, and range of 10^{-10} to 10^{-15} m^2/s were selected.

6. Modelling and Results

Using the source soil vapour concentration estimated, the indoor air concentration of TCE is predicted from the attenuation factor and compared to indoor air standard. For 1,1-DCE, a single model simulation was completed. The 1,1-DCE attenuation factor was $1.95*10^{-4}$, compared to the TCE attenuation factor of $1.87*10^{-4}$. Given that there was little difference between both attenuation factors, for all the scenarios considered, the attenuation factor for TCE was used to estimate the indoor 1,1-DCE concentration.

The model simulations were completed for 5 summer scenarios and for 5 winter scenarios. The base case scenario for summer conditions, consisting on diffusion in the soil, advection and diffusion through cracks in concrete foundation, indicated an approximate 1.5-time increase in the predicted attenuation factor when diffusion through the concrete foundation was included (an increase is not desirable but is taken into account given that there will be some diffusion through concrete). The addition of passive venting resulted in an approximate 5-time reduction in the attenuation factor. A single geomembrane reduced the attenuation factor by approximately three orders-of-magnitude, and the addition of second geomembrane further reduced the attenuation factor by another order-of-magnitude and a half. The results of modelling for winter conditions indicated similar trends as for summer conditions with a slightly greater reduction (8 times) in attenuation factor for the passive venting compared to non-venting condition – simulation of no wind condition.

The predicted indoor air concentrations were compared to the residential standards. The model predicted that indoor air concentrations will be below the residential standards for a conceptual design scenario that includes a passive venting Cupolex system sandwiched between two good quality geomembrane barriers with low chemical diffusion rates (less than or equal to $1*10^{-12}$ m^2/s and crack ratio base liner of $3*10^{-6}$).

Sensitivity analysis on poorer quality geomembranes (chemical diffusion rate of $1*10^{-6}$ m^2/s and crack ratio base liner of $7*10^{-6}$) showed predicted indoor air concentrations exceeding the residential standards. Therefore, significant attention should be given to the design of the geomembrane barriers to achieve targets including possibly modifications to the composite geomembrane design. Consideration should be given to the bench scale testing of geomembrane materials under the approximate conditions to be encountered at the site. The bottom geomembrane should be considered carefully as modelling suggests it has greater influence on vapour intrusion. It may also be more vulnerable to damage than the upper geomembrane because it is based on the gravel below and thin concrete slab above (which is subject to point loading by the Cupolex layer).

Only 20-years limited warranties are provided by the geomembrane manufacturers. No information is available on the resistance to seismic activity of these liners, with the connection between pillars and liners the most delicate point. The monitoring plan will need to account for increased monitoring following seismic activity and more generally also of liner and vent system performance in time.

7. Conclusions

In order to reduce by 8 orders of magnitude the VOC vapour concentrations in the soil under the floor of a decommissioned industrial building and to meet the applicable indoor air standards for residential use in view of the site redevelopment, an evaluation of the feasibility of a passive soil vapour mitigation system was carried out. The conceptual design of the selected mitigation system consists of a bottom barrier (gravel layer with venting piping and geomembrane), an aerated Cupolex layer sandwiched between two lean concrete layers and an upper barrier (geomembrane and concrete layer).

A preliminary evaluation of different geomembranes was completed; the sheet membranes and the spray-applied membranes, were both considered as acceptable.

A CFD numerical model was used for the preliminary simulation of the air flow in the Cupolex layer as a function of the local atmospheric and climate conditions.

A preliminary vapour intrusion modelling study was completed to evaluate passive venting efficiency. A modified version of the Johnson and Ettinger (1991) model was used for predictions of the attenuation factor between soil vapour and indoor air.

The model simulations were completed in summer and winter conditions. The predicted indoor air concentrations were compared to the residential standards. The model predicted that indoor air concentrations will be below the residential standards if the conceptual design described above is implemented at the site.

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