Sustainable Approaches for Soil Gas Mitigation Systems

Ian Hers[1] and Eric Hood[2]

[1] Golder Associates Ltd., #500-4260 Still Creek Drive, Burnaby, BC V5C 6C6
[2] Golder Associates Ltd., 100 Scotia Court, Whitby, ON L1N 8Y6

Principal Contact: Ian Hers, Golder Associates Ltd., #500-4260 Still Creek Drive, Burnaby, BC V5C 6C6 ph: 604-298-6623 fax: 604-298-5253 ihers@golder.com

ABSTRACT

Soil gas mitigation is increasingly considered as a pre-emptive strategy at sites impacted with volatile contaminants, radon or naturally-occurring biogenic gases (*e.g.*, methane). For new building construction, there is a range of possible mitigation solutions, which often involve modification of the building envelope in contact with soil to incorporate soil gas venting and/or barrier systems. New approaches are emerging; however, there is limited knowledge and guidance on the design and effectiveness of such measures. This paper focuses on sustainable approaches for soil gas mitigation where aerated sub-floors are used in conjunction with semi-passive (wind turbine) or low-power fans. Aerated sub-floors are much more permeable than gravel layers, and thus are more efficient in term of venting characteristics.

Scoping calculations based on civil engineering principles are presented for evaluating the influence of wind forces and the stack effect on venting performance and show that even small frictional losses significantly reduce airflow rates. Because the frictional losses in aerated sub-floors are small, there is significant benefit in use of such systems. To illustrate the effect of venting on vapour intrusion, results are presented for a modified version of the Johnson and Ettinger model that uses semi-analytical mass balance calculations to quantify the reduction in the vapour attenuation factor achieved by venting of a sub-building layer. The air flow calculations, frictional loss calculations, and modified Johnson and Ettinger model represent an improved framework for quantitative analysis of sustainable mitigation options.

The paper concludes describing three case study sites where soil gas mitigation systems utilizing aerated sub-floors were installed where volatile organic compounds (*e.g.*, chlorinated solvents or petroleum hydrocarbons) were of potential concern. Building sizes varied from 18,800 to 95,600 sq ft. Performance testing was completed at each site for the purpose of determining the number and size of fans required to provide effective ventilation and to confirm that subslab depressurization was sufficient to overcome variations in building depressurization resulting from changes in weather and building operation. The performance testing indicated that the aerated sub-floors at all three sites could be ventilated using low-power radon fans. For wind turbines, the model calculations and limited testing indicated limited venting efficiency, although

the efficiency may be improved through the use of aerated sub-floors and the adoption of design practices to minimize pipes frictional losses.

INTRODUCTION

Soil gas mitigation is increasingly considered as a pre-emptive strategy at sites impacted with volatile contaminants, radon or naturally-occurring biogenic gases[1]. This study addresses new building construction, for which there are a range of possible mitigation solutions, including modification of the subsurface building envelope to include passive or active venting systems and more efficient venting layers such as aerated sub-floors. New more sustainable approaches for mitigation such as the use of passive (*e.g.*, wind turbines) forces or low-power fans in conjunction with aerated sub-floors are emerging. There is limited knowledge and guidance on the design and effectiveness of such measures, although Folkes[1] presents data that showed aerated sub-floors can be efficiently ventilated using relatively small fans (10-20 Watts (W)) for residential or small commercial buildings. Lanzon *et al.*[2] present field testing of wind turbines for a site with a conventional gravel venting layer where measured air flows were low (0.13 to 0.65 L/min at a wind speed of 4.8 km/hr), consistent with the low specific capacitance of a gravel/piping system.

While the use of completely wind-driven systems was considered, the variability in their performance resulting from variable wind speed and the additional construction cost of such a passive system (*i.e.*, through the additional risers necessary to create sufficient vacuum), led to a focus on the use of low-power electric radon fans that are associated with a negligible cost through electrical consumption. This paper therefore focuses on sustainable approaches for soil mitigation where aerated sub-floors are used in conjunction with low-power fans.

DESIGN CONCEPTS

Two approaches to the design of soil vapour venting systems are subslab depressurization (SSD) and subslab ventilation (SSV). Both approaches are similar, but there are differences that may be exploited to improve mitigation performance depending on objectives and site conditions. SSD involves the construction of a permeable sub-floor layer that is placed under vacuum by drawing air from vent piping. Ambient air from beside the building moves laterally (and possibly also vertically through the foundation slab) and enters the subslab layer in an uncontrolled manner. SSV involves supply of air through inlet ports typically positioned to encourage uniform air flow throughout the venting layer in response to small pressure differences. Depending on the permeability of the sub-floor layer, SSV may achieve significant dilution of vapours migrating toward the building. While the subsoil vacuum will be lower for a SSV compared to SSD system, the SSV system may nonetheless be effective to prevent vapour intrusion or reduce soil

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[1] The methods in this paper are only applicable to sites with low methane generation rates and do not apply to landfills.

gas advection into the building to acceptable levels. A possible added design feature is to control inlet air flow to optimize the venting performance. In addition to depressurization and venting, the mitigation system design may also include the installation of a vapour barrier, although a barrier may not be necessary where relatively high ventilation rates can be achieved (*e.g.*, aerated sub-floors).

The sustainability or optimization of soil vapour mitigation systems can be approached in several ways[1]:

- Optimize design criteria for vacuum and/or air flow rate;
- Reduce friction losses; and
- Employ passive forces or low-power fans.

Optimize Design Criteria for Vacuum and/or Air Flow Rate

For design of radon mitigation systems, a subslab depressurization of 5 to 9 pascals (Pa) (0.02 to 0.035 inches water column (wc)) has been recommended[3,4]. However, earlier guidance states that when SSD systems are installed under worst case conditions (*i.e.*, fans on, winter heating season) any measurable subslab depressurization should be sufficient (*i.e.*, 0.001 to 0.002 in. [wc])[5]. McAlary *et al.*[6] emphasize that achieving the ASTM threshold for SSD systems constructed below large buildings requires very large air flows particularly when floors are leaky and concluded that a minimum depressurization of 1 Pa was sufficient for reducing subslab vapour concentrations to acceptable levels for the building they evaluated. They also describe an approach for optimizing the air flow rate by balancing the estimated upward diffusive chemical flux by the measured extracted mass removal rate by the venting system. Lutz *et al.* (2011)[7] indicate, based on field experience, that reductions in indoor vapour concentrations can be achieved with subslab vacuums as low as 1 Pa. These mass flux and pressure concepts are further explored through a modified version of the Johnson and Ettinger model[8] that was developed to evaluate subslab venting, as described below.

Reduce Friction Losses

The use of aerated sub-floor forming systems (*e.g.*, Ventform, Cupolex) provide significant advantages over subslab venting layers constructed of sand or gravel material due to the reduced frictional pressure losses. There has been only limited quantitative evaluation of aerated sub-floor pressure losses, but some data is available describing material air permeabilities for aerated sub-floor systems. For example, OveArup[8] used computational fluid dynamics modeling to determine an air permeability of 1×10^8 darcies for Ventform (1 darcy = 1×10^{-12} m^2). This compares to soil-air permeabilities of 5×10^4 darcies for gravel and 1×10^1 darcies for sand (permeabilities selected based on the mid-point of the range of values reported in Freeze and Cherry[9]. Based on this data, the permeability of an aerated sub-floor is 10^3-10^7 times greater than that of a conventional venting media.

The pressure drop due to frictional loss through an aerated sub-floor can be estimated using Darcy's Law, assuming 1-D horizontal laminar air flow through a rectangular area, where there is a vacuum at one end of the floor and atmospheric pressure at the other end, as follows:

$$\Delta P_l = \frac{Q\ \theta_a\ u\ L_C}{W_c H_C k_c}$$

Where Q is air flow (m^3/s), W_c and L_c are aerated sub-floor width (perpendicular to flow) and length, respectively (m), H_c is height (m), θ_a is air-filled porosity, μ is dynamic viscosity of air (Ns/m^2) and k_c is the material air permeability (m^2).

An example pressure drop is calculated for a 186 m^2 (2,000 ft^2) aerated sub-floor and an air flow rate of 10 cfm. Based on the field testing presented subsequently in this paper, a flow rate of 10 cfm is a reasonably conservative estimate of flow needed to achieve a vacuum of 0.02 inches wc for a 2,000 ft^2 Cupolex aerated sub-floor. Assuming an air-filled porosity of 0.8, a W_c, L_c and H_c equal to 10 m, 18 m and 0.15 m, respectively, and k_c of 1×10^{-4} m^2, a pressure loss of 0.01 Pa is calculated (note that if the area and flow rate is scaled up 10 times to represent a commercial building, the pressure remains the same). For a gravel layer of identical dimension (porosity of 0.3), the comparable pressure loss is 20 Pa, which appears to be a relatively small value, but based on the analysis presented below would preclude the use of passive forces to aerate a gravel venting layer.

Employ Passive Forces or Low-Power Fans

Passive forces that may be utilized for soil gas venting include wind turbines, differences in sub-floor and outdoor temperatures, and radiant heating of a venting stack. Solar-powered or low-power radon fans are another option and require operational oversight, but for which maintenance requirements are generally minimal and power consumption costs are small. The methods that employ passive forces are described below.

Wind Turbines

Wind turbines are potentially an effective means of sub-slab venting but little quantitative analysis of their performance has been conducted. It is possible to estimate the wind turbine air flow rate from the calculated wind siphoning pressure from estimated flow and discharge coefficients based on Australian Standard AS4740, and some manufacturers publish flow rates for turbines (*e.g.*, Edmonds Hurricane Ventilator)[10]. The wind siphoning pressure may be estimated from:

$$P_w = \frac{q}{2} (C_f V_t)^{2}$$

Where q is the density of air (kg/m^3), C_f is a flow coefficient (dimensionless) and V_t is wind speed (km/hr). The effective aerodynamic area of the ventilator (F) can be calculated from:

$$F = C_d A$$

Where C_d is a discharge coefficient (dimensionless) and A is the throat area of the ventilator (m^2). The wind siphoning air flow may be estimated from:

$$Q_w = \left(F \frac{2 P_w}{q} \right)^{0.5}$$

Calculations of ventilator air flow rates indicate wind turbines can provide for relatively high air flow rates. For example, assuming an air density of 1.2 kg/m^3, and reasonable range of values for C_f (0.17-0.3), C_d (0.4-0.6) and F (0.04 to 0.06 m^2)[10], an air flow rate of 1362 to 3607 L/min (48 to 127 cfm) is calculated for a wind speed of 12 km/hr (moderate sustained wind speed). However, it is critical to recognize that the calculated flow rates assume that there is no frictional resistance to air flow in the plenum being ventilated (*i.e.*, the sub-slab void). While there has been little work evaluating the performance of wind turbines under vacuum, available data suggests that the air flow decreases rapidly to zero for vacuums as low as a few pascals. Revell and Huynh[11] present test data for wind turbine air flow versus vacuum for different wind speeds. For a wind speed of 12 km/hr, a turbine with a 250 mm diameter throat has a reported air flow of 2000 L/min (71 cfm), that decreased to zero flow at 3 Pa vacuum, while a ventilator with a 300 mm throat had a reported flow rate of 2800 L/min (99 cfm) that decreased to zero flow at 2 Pa.

Stack Effect

Similar scoping level calculations can be performed to evaluate the venting flow rate induced by the stack effect. The stack pressure can be estimated from:

$$P_S = q\ g\ h\ \frac{\Delta T}{T}$$

Where g is the gravitational constant (9.81 m/s^2), h is the stack height (m), ΔT is the temperature difference between air below the building in the aerated sub-floor (assumed to be higher) and outdoor air temperature (K), and T is the outdoor air temperature (K). The stack air flow rate may be estimated as follows:

$$Qs = F\ (2\ g\ h\ \frac{\Delta T}{T})^{0.5}$$

When estimating the temperature below the building it is important to recognize that because of the airflow, subslab air during winter (in cooler climates) will be warmer than outdoor air but cooler than indoor air. Assuming a temperature difference of 2°C, a stack height of 10 m and effective aerodynamic area (F) of 0.05 m^2, the estimated stack pressure is 2 Pa, and estimated flow rate is 3470 L/min (123 cfm). However, this calculation does not account for frictional pressure losses, which are modeled through an iterative solution that accounts for pressure losses through friction and temperature, with example calculation as follows. Using the D'Arcy-Weisbach friction coefficient and relative roughness for galvanized steel (0.00075) and assuming a 10 m long, 200 mm diameter duct (straight-run), the pressure losses result in a significant reduction in the unimpeded flow rate (approximately 55% decrease to 1,500 L/min (53 cfm)).

It is assumed that geothermal warming is sufficient to avoid subslab thermal effects in systems operated in SSD mode. However, the introduction of cold air below the building for systems operated in SSV mode is a separate design issue that may be a concern in cold climates, necessitating lower air flow rates to avoid freezing conditions below the building and/or the insulation of subslab services vulnerable to frost damage.

Radiant Heating

Radiant heating of the vent stack (*i.e.*, “solar chimney”) is another passive force that may be utilized through locating the vent stack in a southerly direction and through coatings that absorb heat. Radiant heating and ventilation of buildings is increasingly being employed as part of sustainable building designs.

Summary

Passive forces such as wind turbines and temperature differences (stack effect) can potentially result in significant venting air flow rates; however, they are constrained by frictional pressure losses. Depending on temperature differences, the air flow from the stack effect may be greater than those generated by a wind turbine. The scoping calculations presented indicate for conventional gravel venting layers, these forces are insufficient to create substantive air flow rates. With the use of aerated sub-floors, passive forces may be more effective, but their effect is dependent on environmental conditions (requisite wind and temperature conditions) and therefore the period of effective operation is intermittent.

MODELING STUDY

A preliminary vapour intrusion modeling study was completed to predict indoor vapour concentrations for a commercial slab-at-grade building with a SSV system, constructed above a trichloroethylene (TCE) plume in groundwater. Given the uncertainty for prediction of vapour migration processes and the potential range in input parameters, the modeling is approximate (*i.e.*, order of magnitude accuracy).

A proprietary modified version of the Johnson and Ettinger[12] model developed by Golder has been used for screening level predictions of the attenuation between soil vapour and indoor air. The model utilizes a semi-analytical model (SOLVER in MS Excel) to calculate the chemical mass flux in the unsaturated soil zone, the mass flux removed through venting of the aerated sub-floor, the mass flux through the building envelope and the mixing of vapours in the building air space. The model has been benchmarked to the USEPA Superfund Johnson and Ettinger model for the case where there is no mass removed through venting of the aerated sub-floor (*i.e.*, model collapses to Johnson and Ettinger[12] solution).

Model Processes and Input Parameters

The modeling assumes that there is a laterally continuous, constant-in-time, non-depleting groundwater source located below the building. The processes modeled are as follows:

- Partitioning of TCE from groundwater to soil vapour;
- Upward one-dimensional vapour- and aqueous-phase diffusion within the unsaturated soil zone;
- Instantaneous mixing of vapours within the aerated sub-floor and dilution through venting, and removal of mass based on the ventilation rate within the aerated sub-floor;
- Vapour- and aqueous-phase diffusion through dust-filled cracks in the concrete floor of the building; and
- Instantaneous mixing of vapours in the air space of the building through ventilation.

Soil gas advection into the building was only simulated for the base case (without aerated sub-floor). For the aerated sub-floor case, the air space in the aerated sub-floor is assumed to be at the same pressure as the indoor air space (*i.e.*, no advective flow). This is a conservative assumption because under active venting the pressure in the aerated sub-floor will be lower than in the building and therefore air could be drawn from the building into the aerated sub-floor.

For purposes of estimation of soil properties, the soil is assumed to be coarse-grained and have the same properties as those assumed by U.S. EPA[13], as follows:

- Water-filled porosity soil and dust-filled cracks (dimensionless) = 0.055
- Total porosity soil and dust-filled cracks (dimensionless) = 0.375
- Soil bulk density = 1.7 g/cm^3
- Soil temperature = 15^{o}C
- Depth to groundwater below aerated floor = 3 m

The building parameters were as follows:

- Building width and length = 43 m by 43 m (141 ft by 141 ft)
- Building area = 1,858 m^2 (20,000 sq ft)
- Building vapour mixing height = 3 m
- Depth to base of foundation = 0.3 m (slab-on-grade building design)
- Crack width and ratio = 1 mm and $2x10^{-4}$
- Foundation concrete slab thickness = 0.15 m
- Soil gas advection rate = 10 L/min
- Building air change rate = 1 hr^{-1}

Model Processes and Input Parameters

Limited model simulations for a commercial building illustrate how eliminating of building depressurization and subslab venting potentially reduce the vapour attenuation factor.

The modeling simulations were conducted for a range of ventilation rates for the aerated sub-floor with the results presented in Table 1. The model-predicted vapour attenuation factor for the base case is $2.6x10^{-4}$, which assumes no venting and soil gas advection due to building depressurization. For Case 1, there is no soil gas advection, but no mass removal through venting, and the attenuation factor is $2x10^{-6}$, or two orders-of-magnitude lower than the base case. This case approximates a SSD system where there are negative pressures below the building but very low air flow rates. Cases 2 to 4 simulate progressively increasing ventilation rates, and corresponding approximately order-of-magnitude reductions in the attenuation factors. Although the modeling study only addresses a limited number of scenarios and input parameters, it demonstrates how SSV can potentially have a significant influence on the attenuation factor. Subslab ventilation provides for an added factor of safety against vapour intrusion and particularly at sites with elevated soil vapour concentrations is one approach to reduce the potential for vapour intrusion (use of vapour barriers is another approach). This modeling approach, together with scoping calculations of air flow and pressure, provides a quantitative basis for venting system design.

Table 1: Modified J&E Model Predictions for Commercial Building Scenario.

Conditions	Base Case – J&E model	Case 1 – Negligible Subslab Ventilation	Case 2 – 0.01 ACH of Venting Layer	Case 3 – 0.1 ACH of Venting Layer	Case 3 – 1 ACH of Venting Layer
Soil gas advection rate into building (cfm)	10	0	0	0	0
Ventilation rate	0	0	49.2	492	4923

Conditions	Base Case – J&E model	Case 1 – Negligible Subslab Ventilation	Case 2 – 0.01 ACH of Venting Layer	Case 3 – 0.1 ACH of Venting Layer	Case 3 – 1 ACH of Venting Layer
(L/min)					
Ventilation rate (cfm)	0	0	1.74	17.4	174
Vapour Attenuation Factor	$2.6x10^{-4}$	$2.0x10^{-6}$	$3.6x10^{-7}$	$4.36x10^{-8}$	$4.4x10^{-9}$

CASE STUDIES

Site Descriptions

Site F is a single-storey slab-at-grade building without a basement, with an area of 95,600 sq. ft. (approximate exterior dimension of 85 m x 105 m) and a 5.8 m high ceiling, constructed for a commercial occupant. The building floor was constructed with an aerated sub-floor consisting of a minimum of 80 mm thickness of concrete poured over interlocking plastic forms (95 mm high Cupolex, Pontarolo Engineering) to create a continuous void space below the concrete slab. The forms were placed over a continuous woven polyethylene with sealed seams and edges placed over the entire building footprint. The polyethylene was placed as an additional mitigation measure. The Cupolex was connected to eight perimeter inlet ports with threaded caps, which could be optionally removed to increase air flow to the aerated floor. At the time of testing the inlet ports were closed and fitted with 1/4 inch sampling ports for the measurement of subslab differential pressure. The building was only partially constructed (building envelope was completed, and interior finishing was in progress). The mitigation system included two exhaust risers that were terminated at grade at the time testing was conducted and the construction joints (including the perimeter foundation joints and sawcuts) in the floor slab were unsealed. There were numerous plumbing and service penetrations, including water mains, floor and plumbing drains, monitoring wells, columns, refrigeration pits, and sumps. Ground cover next to the building was a sidewalk and asphalt parking lot on two sides, a 5-metre wide landscaped strip on the third side, and landscaping to the property line on the fourth side.

Site N is a single-storey slab-at-grade building with a partial basement, with an area of 23,600 sq ft (approximate exterior dimensions of 45 m x 40 m) and a 8.99 m high ceiling, constructed for multiple commercial occupants. The building floor over the subgrade was constructed with a minimum 75 mm thickness of concrete poured over Cupolex forms (254 mm high). Where the subslab void space was discontinuous as a result of elevation differences of separations by structural members, the voids were interconnected with PVC pipe to allow air flow between the separated voids. The system included seven risers, with at least one riser in each discontinuous void space. Each riser was fitted with a sampling port for differential pressure measurement. All risers extended to the roof and were completed with wind-powered turbine ventilators (Edmonds Hurricane). At the time of testing, the main tenant spaces were occupied and the floor (including tile) was sealed. The ground cover on all sides of the building was impervious (sidewalks with asphalt parking lot surrounding).

Site C is a single-storey slab-at-grade building without a basement, with an area of 18,800 sq ft (approximate exterior dimension of 34 m x 55 m), constructed for a commercial occupant. The building floor was constructed with a minimum thickness of 75 mm of concrete over Cupolex form (254 mm high). The venting system included four perimeter inlet ports (sealed and used for differential pressure monitoring) and four risers equipped with wind-powered turbine ventilators (Edmonds Hurricane). At the time of testing, building construction was essentially complete although the heating, ventilation and air conditioning (HVAC) system was not in operation. A landscaped area was present on the west side of the building, and was surrounded by concrete sidewalks and an asphalt parking lot on the remaining sides.

Testing Protocol

At each site, leak testing was conducted with the venting system operated as an active subslab depressurization system to determine if the induced differential pressure in the subslab void was sufficient to overcome typical variability in building depressurization related to HVAC system operation, climatic conditions, and opening/closing of building doors. The venting system was presumed effective if a minimum depressurization target of 0.02 inches water column (wc) was inferred to be present throughout at least 90% of the building footprint, an approach consistent with available guidance for radon mitigation[3].

At Site F, airflow versus vacuum testing (*i.e.*, leakage of system to outdoor and indoor air) of the venting system was completed with the HVAC system in day-time operation (outdoor temperature 37 ˚C, occasional breezes). All building and bay doors were closed with the exception of one man-door. The two exhaust risers were temporarily fitted with low-power radon mitigation fans (AMG-Legend 150 W, 353 cfm at static pressure; AMG-Fury 175 W, 541 cfm at static pressure). The higher capacity fan was equipped with an inline damper to allow air flow adjustment, while the second fan operated at a constant rate (25 cfm) throughout the leak test. The initial total air flow rate was 268 cfm, which was decreased in four steps to 82 cfm. Each exhaust riser was fitted with temporary measurement ports (1/4 inch threaded John Guest valves) to allow measurement of differential pressure (Fluke 922). Flow measurements were made using a pitot tube installed through 14 mm diameter drilled holes. For this test and all subsequent tests described, there was a straight pipe run length upstream of the pilot tube of at least eight pipe diameters. When testing was conducted, the system was operated in SSD mode with the inlet ports sealed.

At Site N, leak testing was performed with the HVAC system in evening operation (outdoor temperature 21˚C, still wind conditions). All building doors were closed. All the risers were temporarily sealed with the exception of the exhaust riser (E3), where the turbine ventilator was replaced with a temporary fan (AMG-Fury) with measurement ports for air flow and differential pressure. The initial total air flow rate was 277 cfm, which was decreased in four steps to 52 cfm. When testing was conducted, the system was operated in SSD mode so the inlet ports were sealed.

At Sites F and N, leak testing was completed using an identical protocol. An initial round of baseline differential pressure measurements was made, and then the fans were installed and placed in operation at the maximum possible flow rate. The fan flow rates were then decreased in steps and the differential pressure measurements were repeated, continuing until the differential pressures were less than the minimum depressurization criteria of 0.02 inches water column (vacuum relative to ambient atmospheric pressure (*i.e.*, gauge pressure)).

At Site C, leak testing was performed prior to building occupancy and its HVAC system was not in operation. The outdoor temperature was approximately 2˚C with light winds. Building heat was provided by a portable construction heater placed by the loading dock equipped with a duct through a bay door that directed heated air to the interior spaces of the building. All four risers were temporarily sealed with the exception of the exhaust riser (C6), which was fitted with a temporary fan (AMG-Legend). The operating air flow rate was 172 cfm. Each riser was fitted with a monitoring port for differential pressure measurement. Differential pressure measurements were made at a single operating flow rate, following an initial round of baseline differential pressure measurements.

For monitoring points located on the building exterior, differential pressure measurements varied by up to 0.005 inches wc as a result of wind forces on the building. A similar effect was not observed for interior monitoring ports.

Testing Results

For Site F, the differential pressure measurements at five different venting rates (268 to 82 cfm) plus a baseline round with no fans active (0 cfm) are shown in Figure 1. The baseline measurements at all but one monitoring location indicated that the building was slightly depressurized with respect to the subslab void by up to 0.005 inches wc. Under active operating conditions, differential pressures increased linearly with increases in venting rate over the range of venting rates tested. The target differential pressure of 0.02 inches wc was achieved at all monitoring locations at a total venting flow rate above 82 cfm (corresponding to 0.9 cfm per 1000 sq ft), excluding location H1 where no measurable differential pressure was noted. A subsequent camera inspection of H1 revealed that it had been inadvertently sealed with concrete during floor construction. Inspection of the differential pressure data indicates that the distribution of subslab pressure was uniform over the building footprint at all venting rates, suggesting that frictional pressure losses within the subslab void were negligible. The differential pressures at the two risers with fans (data not shown) were of greater magnitude than those measured in the subslab void, indicating that there were air flow frictional losses at the riser entrance.

As previously mentioned, the Site F building included a continuous woven polyethylene below the subslab void. Accordingly, the only known significant leakage pathway for air entry into the void space was through construction joints and penetrations in the floor slab. Using performance data from the testing, an equivalent orifice area for the floor slab was calculated using:

$$Q = C_d A \left(\frac{2\Delta P}{\rho}\right)^{0.5}$$

Based on the maximum flow rate (268 cfm), the average differential pressure (-0.118 inches wc), a typical orifice coefficient (0.61) and the reported density of air (1.225 kg/m^3), the calculated orifice area is 299 cm^2. Note that this corresponds to one 1 mm crack that is about 300 m in length, which is much less than the total length of construction joints that are present in the building. Further leak testing is planned following sealing of the construction joints and penetrations for comparison purposes.

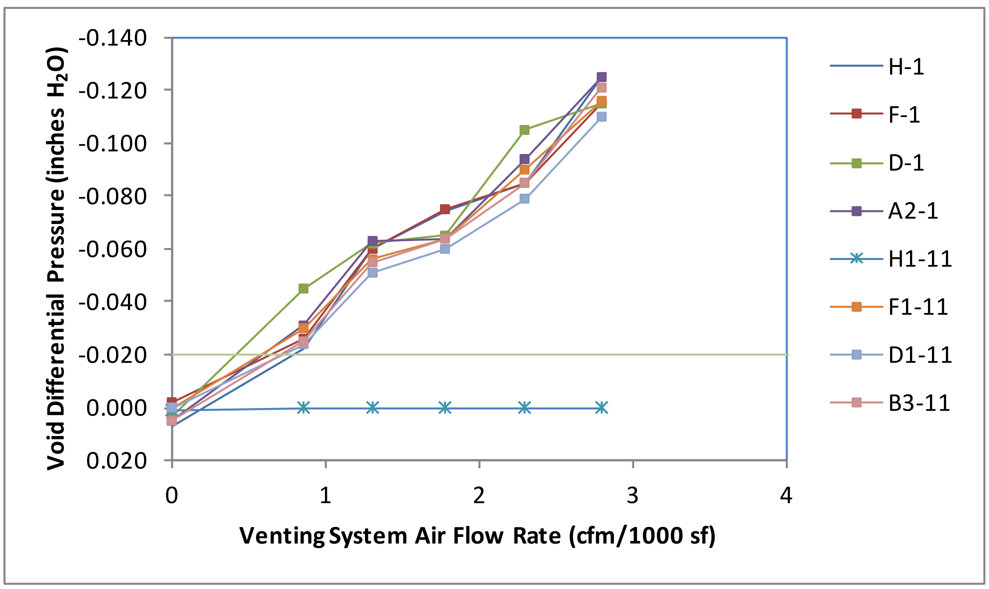

Figure 1: Site F (95,600 sq ft) Venting Flow Rate vs. Void Pressure (negative value indicates vacuum)

For Site N, the differential pressure measurements completed at five different venting rates (277 to 52 cfm) plus a baseline round with no fans active (0 cfm) are shown in Figure 2. The baseline measurements indicated that the building was slightly depressurized with respect to the subslab void (0.001 to 0.002 inches wc). Under active conditions, differential pressures increased non-linearly with increases in venting rate (Figure 2). The target differential pressure was achieved at all monitoring locations at total venting flow rates greater than 118 cfm (corresponding to a minimum venting rate of 5 cfm per 1,000 sq ft of building footprint)

Inspection of the differential pressure data indicates that it varied at some locations, apparently resulting from the absence of continuity through the subslab void space. The fan was mounted on riser E3, which had the highest differential pressure. The next highest differential pressure was at measurement location E5, which was tied into the same continuous subslab void space as the exhaust fan. Approximately half of the pressure differential loss between E3 and E5 appears to have resulted from air flow entrance losses to riser E3. Monitoring locations B4, B5, C4, and C5 are all tied into a void space that was not continuous to the entrance void space. This second continuous void space was tied into the entrance void through six transfer pipes along an approximately 30 m boundary between the two voids. Each of these monitoring locations have identical pressure differentials, indicating that there is minimal head losses in a continuous void and that the losses are likely attributable to the six transfer pipes. The exhaust fan had the least influence on monitoring location D2, which was separated from the fan by two sets of transfer pipes (*i.e.*, in a third void space).

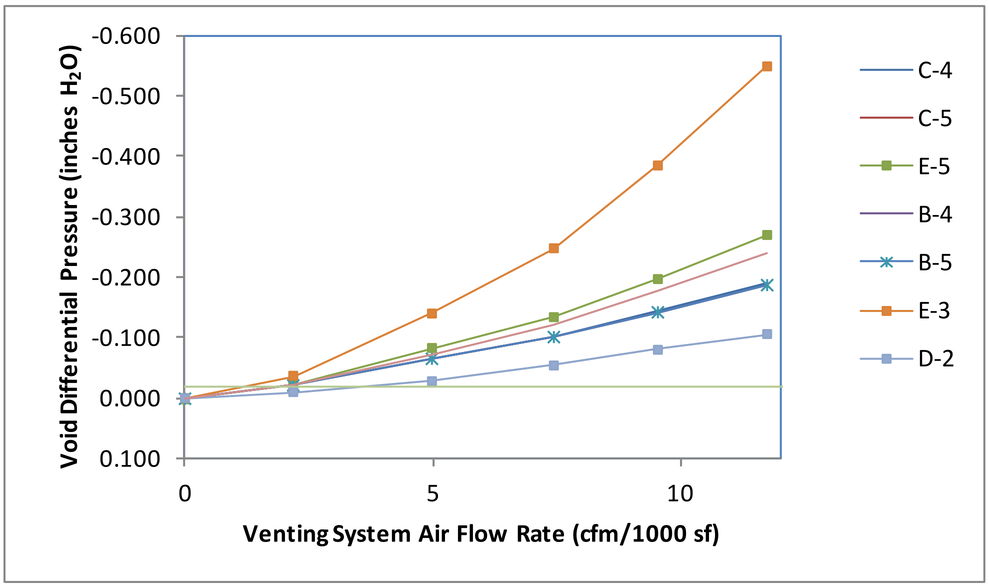

Figure 1: Site N (23,600 sq ft) Venting Flow Rate vs. Void Pressure (negative value indicates vacuum)

At Site C, the system was operated under active conditions (175 cfm at -0.85 inches water column at riser C6, corresponding to 9.3 cfm per 1,000 sq ft). Baseline differential pressure data were not collected. The differential pressure was uniform at each of the three of the remaining monitoring locations at -0.02 inches wc (average of four measurements at each location).

One trial of turbine ventilator performance was also conducted at Site C using a high capacity fan directed at the wind turbine to simulate a strong wind (wind speed of 55 km/hr). At this wind speed, the turbine induced a differential pressure of -0.15 inches wc (37 Pa) at an exhaust air flow rate of 72 cfm.

Discussion

At all three sites, there were larger differential pressures at exhaust risers equipped with a fan (relative to ambient air) but lower and uniform differential pressures at the other monitoring locations in the same void space. This suggests that there were negligible frictional losses in the aerated sub-floor (< 0.001 inches wc) but larger exit losses immediately surrounding the suction point in the subslab. At Site N, the use of transfer pipes to interconnect discontinuous sections of the subslab void appeared to result in measurable friction losses. If these losses had been sufficiently large to prevent the achievement of the depressurization target, a second fan connected to this separate void space may have been necessary.

The results of performance tests at Site F, N and C, with air flows scaled for a 40,000 sq ft building (to enable comparison to the results in Folkes[1]), is presented in Figure 3. The maximum measured vacuums are plotted since this is a conservative approach for design; however, frictional losses through risers are not shown. If, for example, the design criteria was 200 cfm air flow at 0.02 inches wc, a 150 W radon fan would be sufficient assuming a 20 m long, 150 mm diameter duct (and other assumptions described above) because additional estimated frictional losses are only 0.27 inches wc. The calculations illustrate how a relatively small fan can ventilate a large aerated sub-floor. However, multiple risers and fans are recommended for redundancy and to provide for more even distribution of air flow, particularly when the aerated sub-floor is not a single continuous void space. The permeability of the surface cover adjacent to the building and engineered methods of supplying air to the sub-floor may also influence venting design.

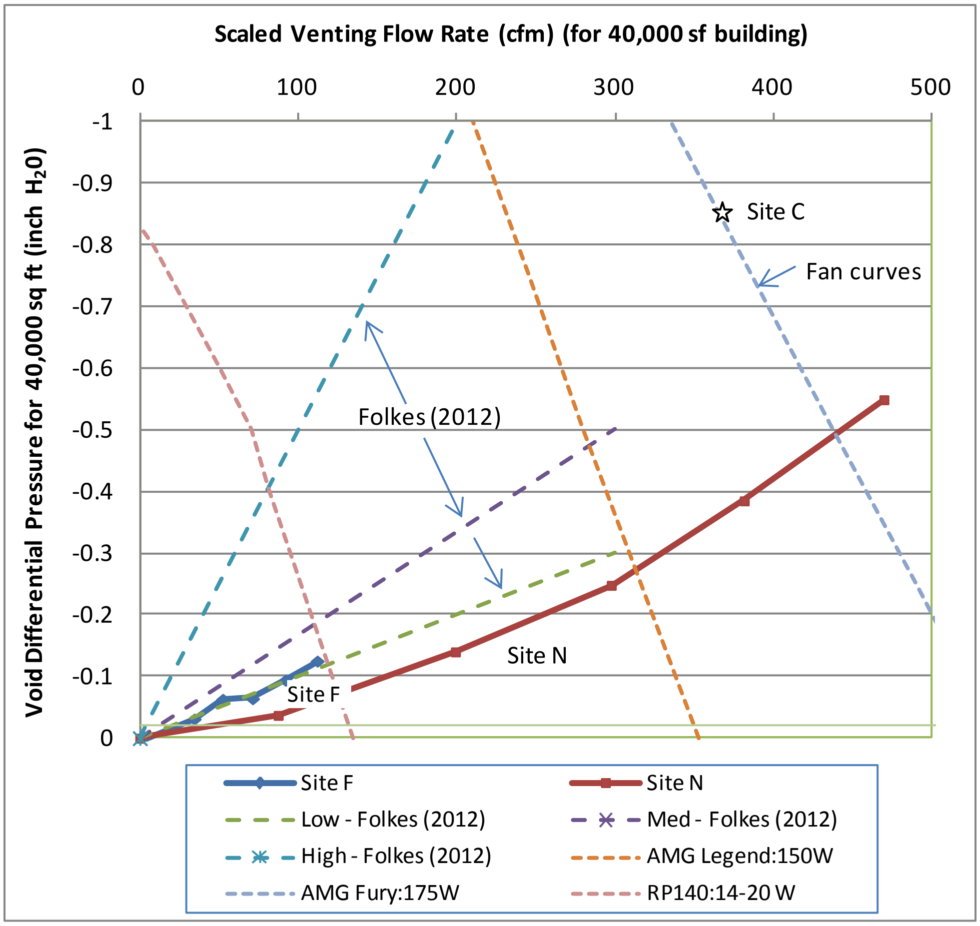

Figure 3: Venting Flow Rate vs. Void Pressure for 40,000 sq ft Building

A conceptual framework for selection of fan for aerated sub-floor design is provided in Figure 4. The fan curve should be outside of both the minimum criteria for air flow and vacuum, as shown.

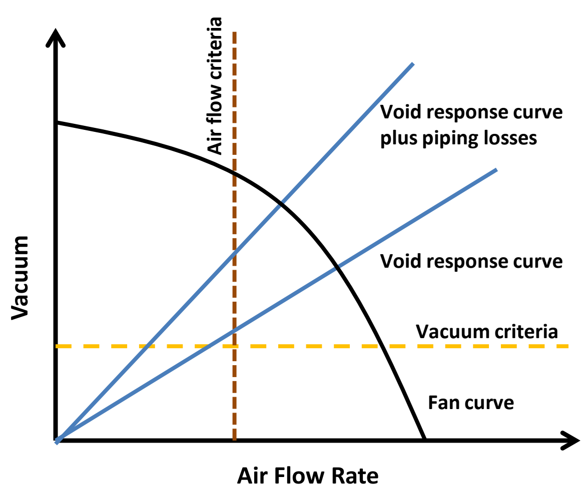

Figure 4: Conceptual Framework for Venting Design

Limited testing of the wind turbine (Site C) indicated that the air flow generated at very high wind speed (55 km/hr) was about 40% of that generated by a 150 W radon fan. Applying a linear scaling factor, at moderate wind speed (12 km/hr), approximately eleven wind turbines would provide comparable air flow to that of a single radon fan. Further testing would be required to determine whether wind turbines could provide for adequate depressurization, but it is clear that frictional losses in piping systems would need to be minimized (*i.e.*, through large diameter pipes, long-radius turns, *etc.*) to achieve satisfactory performance. A practical observation was that fouling of the turbine by a piece of waste was noted during testing, suggesting that turbines may require relatively frequent inspections to ensure their operation.

SUMMARY

The sustainability or optimization of soil vapour mitigation systems can be approached in several ways, including optimizing design criteria for vacuum and/or air flow rate, reducing friction losses (primarily through use of aerated floors), and use of passive forces or low-power fans. Passive forces such as wind turbines and temperature differences (stack effect) can potentially result in significant venting air flow rates; however, they are constrained by frictional pressure losses. The use of aerated sub-floors presents advantages over conventional gravel venting layers through significantly reduced frictional losses.

A preliminary vapour intrusion modeling study, conducted using a version of the Johnson and Ettinger model modified by Golder to include venting of a subslab layer, was completed to predict indoor vapour concentrations for a commercial building with a SSV system, constructed above a TCE plume in groundwater. Modeling results indicate elimination of building depressurization and thus soil gas advection reduced the vapour attenuation factor by two orders-of-magnitude, and that there were further order-of-magnitude decreases in the attenuation factor when the aerated sub-floor was ventilated. This modeling approach, together with scoping calculations of air flow and pressures, provide an approximate quantitative basis for venting system design.

The results of performance testing are summarized as follows:

- The minimum vacuum criteria of 0.02 inches wc was achieved at 0.9 cfm/1,000 sq ft for Site F and 5 cfm/1,000 sq ft for Site N. The void specific capacitance for the three sites ranged from approximately 206 to 2140 cfm/inches wc. Comparison of the void response curves to fan curves indicates a relatively small low-power fan is capable of venting an aerated sub-floor for a relatively large building footprint.
- The systems included passive inlets that were sealed during testing. Given the systems were run in SSD mode, the vacuums measured were relatively small and suggest significant leakage from the ground beside the building and through the foundation.
- There were no measureable pressure losses in the aerated sub-floor, with the exception of losses associated with air transfer pipes and exhaust riser entrance losses.

- Limited testing of a wind turbine indicated moderate flows (78 cfm) at a high wind speed (55 km/hr). Scaling of results to a moderate air flow (12 km/hr) suggests that eleven wind turbines would provide comparable air flow to that of a single 150 W radon fan.

Given the low capital costs and minimal power requirements for small fans capable of depressurizing and venting an aerated sub-floor, the use of wind-driven turbines is considered best suited as a low-maintenance measure in the absence of a demonstrated necessity for a venting system. An active system provides the added certainty of effective performance. Although it may be possible to adequately ventilate aerated sub-floor for certain larger commercial buildings using a single relatively small fan, multiple risers and fans may be needed for redundancy and to improve distribution of air flow, particularly when the aerated sub-floor is not continuous below ground due to grade beams. Where possible, the void space should be continuous. Where this is not possible, closely spaced air transfer pipes (one pipe per 3 metre separation between voids) should be used to minimize frictional losses. The exhaust riser entrance and riser pipe system should be designed to minimize losses.

REFERENCES

1. Folkes, D. *Performance of Aerated Floor VI Mitigation Systems.* AEHS 22nd Annual International Conference on Soil, Water, Energy, & Air, **2012**, March 19-22, Mission Valley Marriott, San Diego, CA.

2. Lanzon, J., D. Bertrand, H. Groenevelt, P. Nicholson, B. Bingham and T. McAlary. *Passive (wind-driven) Systems for Subslab Venting to Mitigate Potential Vapour Intrusion*. Univ. of Mass. Int. Conf. on Green Remediation, **2010**, June 16, Amherst, MA.

3. FDCA. *Department of Community Affairs Radon Program, Florida Standard for Radon-Resistant New Commercial Building Construction*, **1996,** January 23.

4. American Society for Testing and Materials (ASTM). *Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings*. E2121. **2001.** March.

5. U.S. Environmental Protection Agency (EPA). *Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (Third Edition) for Active Soil Depressurization System*, Air and Energy Engineering Research Laboratory, Office of Environmental Engineering and Technology Demonstration, Office of Research and Development, Research Triangle Park, NC, **1993**, EPA/625/R-93/011.

6. McAlary, T. D. Bertrand, P. Nicholson, S. Wadley, D. Rowlands, G. Thrupp and R. Ettinger. *Pneumatic Testing, Mathematical Modeling and Flux Monitoring to Assess and Optimize the Performance and Establish Termination Criteria for Sub-Slab Depressurization Systems*. Presentation at US EPA Workshop on Vapour Intrusion AEHS Soil and Sediment Conference, **2011**, San Diego, CA., March.

7. Lutes, C., R. Studebaker and N. Weinberg. *Optimal Design of Sub-slab Depressurization Systems for Volatile Organic Compound Vapour Intrusion (VI) Mitigation*. Vapour Intrusion 2010, **2010**, September 29-30, Chicago, IL.

8. OveArup. *Passive Venting of Soil Gases Beneath Buildings Research Report*. Prepared for UK Department of the Environment, Transport and the Regions. **1997**, September.

9. Freeze, R.A. and J.A.Cherry. *Groundwater.* Prentice-Hall , Inc. Englewood Cliffs, NJ. **1979**, 604 pg.

10. CSR Building Products. *Performance Tests on Series of Hurricane 450-600 Ventilators*. Test Report Report No. 25-02-10. **2010.** February 25.

11. Revell, A. and B.P. Huynh. *Characterizing Roof Ventilators*. 15th Australasian Fluid Mechanics Conference, The University of Sydney, Sydney, Australia, **2004**, December 13-17.

12. Johnson, P.C. and R. Ettinger. *Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapours into Buildings.* Environ. Sci. Technol. **1991**, 25, no. 8, 1445-1452.

13. U.S. EPA. *User's Guide for Evaluating Subsurface Vapour Intrusion into Buildings*. Prepared by Environmental Quality Management, Inc. for U.S. EPA Superfund. **2004**. February 22.