Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy

Volume 11 | Article 18

January 2010

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Chapter 17

OVERVIEW OF TWO LARGE-SCALE RESIDENTIAL SUB-SLAB DEPRESSURIZATION SYSTEM INSTALLATION PROGRAMS

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Abstract: Sub-slab depressurization (SSD) systems, commonly used to mitigate radon, create a vacuum beneath a building to prevent soil gas from entering the building as a result of pressure gradients that naturally exist between the building and the sub-slab region; the extracted soil gas is then vented directly to the atmosphere. This paper describes two large-scale residential SSD system installation case studies. The SSD systems were designed and installed to mitigate intrusion of soil gas, which contained low levels of volatile organic compounds, into (1) 100+ individual houses and (2) several buildings in a multi-structure condominium complex.

The SSD installation methodology consisted of the following components: stakeholder involvement, site assessment, feasibility study, pilot testing/design, installation, performance testing, and operations & maintenance. Public meetings were held and homeowner feedback was elicited to achieve an end product that not only mitigated vapor intrusion, but also was acceptable to the homeowner. The system design process incorporated the results of site-specific assessments and field pilot testing. These systems were installed in a design-build fashion using a variety of construction techniques. Following installation, the SSD systems were performance tested to ensure that the resulting suction field encompassed the entire sub-slab area.

Examples of the SSD system installations are presented. SSD system designs/components and construction techniques, issues, and challenges specific to the two case studies are discussed. System performance data and lessons learned from the SSD installations also are presented. In addition, a comparison of the operation of the engineered SSD systems to several radon mitigation systems previously installed using typical radon industry techniques is conducted to reveal some interesting results.

Key words: vapor intrusion; mitigation; sub-slab depressurization; SSD; volatile organic compounds

1. INTRODUCTION

During the past several years, the issue of vapor intrusion of gas-phase contaminants from soil gas systems into indoor air of buildings has gained much attention in the scientific community and environmental industry (Renner, July 2002). Recent advances in assessing the potential for contaminated vapor intrusion are resulting in more mitigation efforts to address vapor intrusion. A pollution issue in Denver, Colorado received national attention in 2001, when data revealed that indoor air in numerous homes was being impacted from a long-studied groundwater plume, previously thought to pose no risk (Obmascik, April 29, 2001). For most people, especially those with a public water supply, exposure to the indoor air is typically significantly higher than exposure to other environmental media. If this indoor air becomes contaminated with harmful constituents, there is a risk of potential consequences from this exposure. There exists a natural pressure gradient between buildings (lower) and soil gas beneath the buildings (higher). This pressure gradient facilitates the entry of soil gas and potentially any associated gas-phase contaminants such as radon and volatile organic contaminants (VOCs) into buildings, thus contaminating indoor air. Modern buildings are generally built to minimize natural exchange of indoor air with outdoor air, thereby exacerbating the impact of vapor intrusion.

The development and application of mitigation measures to address vapor intrusion have become integral components of this issue. Mitigation measures to minimize the levels of contaminants in indoor air include increasing the exchange (replacement) of indoor air with outdoor air using conventional air exchange systems. However, a more efficient technique of reducing contaminant concentrations in indoor air is to prevent the intrusion of the contaminants into indoor air (USEPA, 1991 & 1993). This can be achieved by: (1) sealing entry points for soil gas (e.g. crawlspaces, cracks, penetrations, and porous walls); and (2) installing a passive or active system to circumvent contaminated soil gas around the building by creating a vacuum below the building and venting soil gas directly to the atmosphere. An active system is referred to as a sub-slab depressurization (SSD) system (USEPA, 1991 & 1993). SSD systems are typically more cost effective than interior air exchange based systems (USEPA, 1993).

This paper presents two large-scale SSD system installation programs that were undertaken in Connecticut to address vapor intrusion issues affecting residential structures. To protect the confidentiality of homeowners, the locations of buildings where the SSD systems were installed are not provided in this paper. The first SSD system installation program involved the installation of systems in a residential neighborhood located downgradient (groundwater flow) of a former industrial complex. Environmental sampling conducted by the United States Environmental Protection Agency (USEPA) indicated the presence of low levels of VOCs in samples of soil gas and indoor air collected within the residential area. The VOCs trichloroethene (TCE) and 1,1-dichloroethene (1,1-DCE) were of primary concern based on risk assessment by the USEPA and the Connecticut Department of Public Health. In response to the detections of these VOCs, SSD systems were installed in 2001 and 2002 to mitigate vapor intrusion at nine buildings, consisting of seven single-family homes and two commercial buildings. Rather than proceeding with additional sampling and data evaluation within the residential neighborhood, a programmatic decision was made by USEPA to install SSD systems in up to 114 residential structures, commencing in Fall 2003. The systems were installed as a preventative measure against potential future vapor intrusion issues in the neighborhood. The USEPA enlisted the Connecticut Department of Environmental Protection (CTDEP) and its environmental engineering consultant, Metcalf & Eddy, Inc. (M&E), to implement the SSD system installation program to protect human health. M&E teamed with two environmental contractors to install the SSD systems.

The second installation program was implemented from February 2004 to May 2005 to address potential vapor intrusion issues at a condominium complex. As part of an area-wide investigation conducted by CTDEP, chlorinated VOCs were detected in groundwater samples that were collected in the vicinity of the condominium complex. CTDEP subsequently conducted sampling of groundwater and soil gas at the complex. Chlorinated VOCs were detected in groundwater and soil gas at concentrations above volatilization criteria specified in the State of Connecticut Remediation Standard Regulations (CTDEP, 1996) and Proposed Revisions, Connecticut's Remediation Standard Regulations, Volatilization Criteria (CTDEP, 2003) in the vicinity of five multi-unit residential buildings. As a result of TCE detections in soil gas in exceedance of CTDEP's proposed revised volatilization criteria, CTDEP contracted

M&E to design & install SSD systems at the five buildings to protect human health. M&E teamed with an environmental contractor to install the SSD systems.

2. SSD INSTALLATION METHODOLOGY

2.1 Overview of an SSD System

An SSD system intercepts the soil gas beneath a floor slab before it migrates into the living/working areas of a building. The system creates a zone of suction immediately beneath the floor slab to capture the soil gas and discharge it to the building exterior/outdoors. Each SSD system consists of the same general set of components as follows:

- Fan/Blower(s)
- Suction Piping
- Exhaust Piping
- Monitoring System and Alarm
- Electrical Service

Figure 1 presents a schematic of a typical SSD system installation. The SSD system fan has both an intake side and an exhaust side. Suction piping connects from the intake side of the fan to a suction hole through the (basement) floor slab. On the exhaust side of the fan, vent piping is connected from the fan to the final vent location. The exhaust piping terminates with a vent cap that prevents intrusion of rain and pests. Multiple fans and/or suction points may be used to create the necessary suction beneath all floor slabs and crawl spaces.

The SSD system also includes a monitoring system to ensure that the system is operating properly. The monitoring system consists of a differential pressure gauge which monitors for the presence of suction in the suction piping at all times. If the monitoring system does not detect any suction, a visual/audible alarm is activated.

2.2 Public Outreach

The USEPA, CTDEP, and M&E participated in public outreach efforts to ensure that the stakeholders understood the objectives and various facets of the SSD installation program. The public outreach consisted of:

- meeting with homeowners, building owners, the condominium association, and various representatives of these groups;
- holding public presentations and workshops; and
- distributing project-related information.

Based on these public outreach efforts, stakeholder concerns were incorporated into the SSD installation program. The public outreach effort facilitated an environment of cooperation and understanding between the residents, regulatory agencies, and environmental contractors.

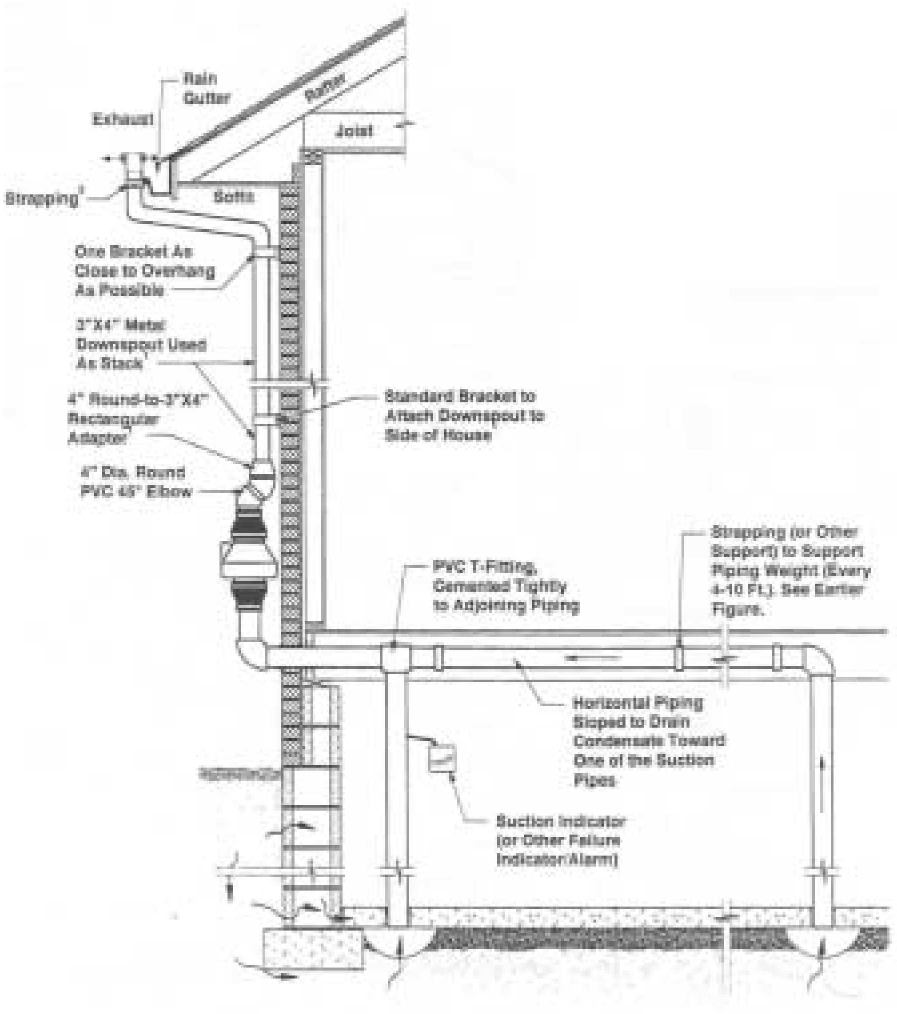

Figure 1. Schematic of Typical SSD System Installation (Source: USEPA, 1993)

2.3 SSD System Installation Program Approach

The approach for installing the SSD systems consisted of a number of steps. Prior to system installation, the property owner signed an access agreement allowing access for SSD system installation work. Once the access agreement was obtained, a site assessment was conducted of each building/property that included an inspection of the foundation walls, basement floors, crawl spaces, and other portions of the house in contact with the ground, and the development of a site plan & building layout. A field checklist was used to facilitate data collection.

Upon the completion of the site assessment, a feasibility study was conducted. The feasibility study varied in complexity, depending on the conditions encountered during the site visit (e.g. size and layout of building). For the single-family residential homes, areas of the concrete slab had to be selected for pilot testing. The condominium buildings necessitated an evaluation of two significantly different approaches to mitigate vapor intrusion. One approach involved horizontal directional drilling in conjunction with traditional soil vapor extraction, while the second approach consisted of a complex SSD system. The second approach was selected as the preferred alternative based on technical feasibility, constructability given the site conditions, and cost.

Following the initial site assessment and feasibility study, field pilot testing was performed at each building in order to evaluate subslab soil flow characteristics under the application of suction. Flow characteristics included soil permeability, the presence of potential obstructions, and possible short-circuiting issues. The steps to the pilot test were as follows:

1. Core one or more temporary suction test holes through the slab being tested.
2. Drill several temporary test holes through the slab at varying distances from the suction test hole.
3. Apply varying levels of suction to the suction test hole using a portable blower / suction gauge unit vented to the outside.
4. Measure the corresponding levels of suction [inches water column (W.C.)] created at each test hole, using a digital micromanometer. The information recorded during the pilot test was recorded using a standard form.
5. The test holes were then temporarily plugged pending final installation.

Site-specific assessment information and pilot test data were used to design the SSD system. The system was designed to ensure that adequate suction is created beneath all floor slabs and crawlspaces (as appropriate). The objective was to achieve complete capture of the sub-slab region. For the design, the pilot test data was evaluated to determine the amount of suction required at each planned suction hole(s) to create adequate suction levels beneath the home. Pilot test data was then used to select the fan size necessary to generate the required suction level at the suction hole(s). Figure 2 presents a typical set of pilot test flow-suction data compared to performance data for several commercially available fans. From this analysis, the overall system layout was determined and the necessary system components were selected and sized. Design details and specifications for the system include:

- Number/location/layout of suction points;
- Number/location/layout of fans;
- Size and layout of fans and piping;
- Location of monitoring systems and alarms;
- Location of electrical service and on/off switch.

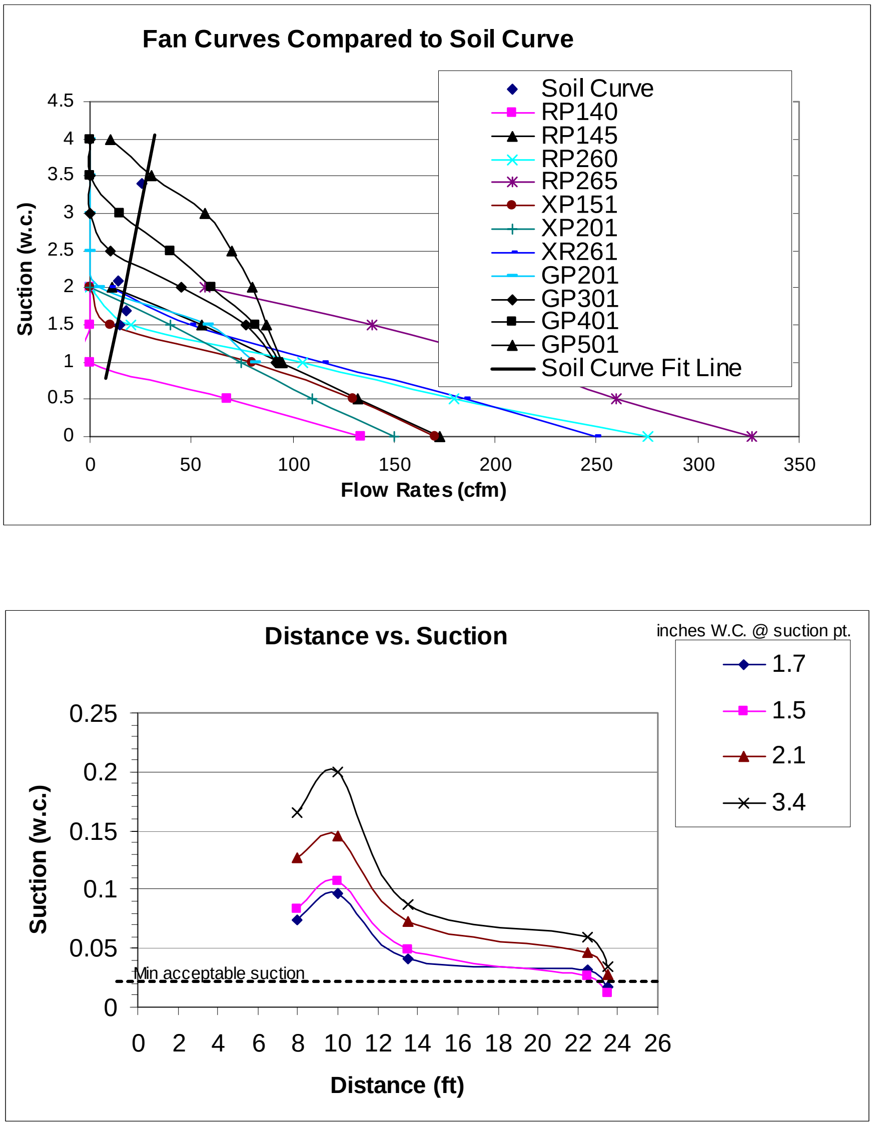

Figure 2. Example of Pilot Testing & Design Data.

Prior to installation, a plan of the proposed system was prepared and approved by the home/building owner. A critical component to the success of the installation programs was to ensure that the systems were acceptable to the home/building owner. In addition, required electrical and building permits were obtained from local governmental agencies.

Systems were installed in a design-build fashion using a variety of construction techniques. SSD system installation consisted of coring suction hole(s), installing fan(s), installing suction and exhaust piping, and installing other system components. Suction holes were cored through concrete slabs and/or foundation walls, depending on the building layout, results of the pilot testing, and input from the building owner. Piping was pitched back towards the suction holes. Fans were positioned on the exterior of buildings, while alarms were positioned in easily accessible locations in the vicinity of the suction hole(s). Traditional gutter material was used as exhaust piping in order to blend the system with the exterior of the home, and in one case, faux chimneys were constructed from enclosures built onto the building, which housed numerous fans, and terminated above the roofline. In addition, to eliminate soil gas intrusion pathways, concrete floors were repaired/replaced as necessary and all accessible cracks and openings in the foundation walls and floors were sealed with concrete, grout, caulk, and/or sealant. Electrical work was performed by a licensed electrician in accordance with the local, state, and national codes under a local permit.

Following system installation, a system performance test was conducted to confirm that the system is operating as intended. The performance test used several temporary test holes to measure and confirm that adequate suction is being created beneath the entire floor slab. The information collected during the performance test was recorded using a standard form. Following the performance test, all temporary test holes were filled and resealed with caulk or grout. Operations and maintenance issues are discussed as part of the case studies.

3. SSD INSTALLATION CASE STUDIES

3.1 Residential Neighborhood

In 2001-2002, seven homeowners and two building owners agreed to have SSD systems installed by EPA/CTDEP. During the 2003-2004 period, a total of 97 of 114 home/building owners granted access to CTDEP. This SSD installation program is summarized as follows:

- October – December 2001: 3 single-family homes & 2 commercial buildings
- October – November 2002: 4 single-family homes
- September 2003 – May 2004: 95 single-family homes & 2 apartment buildings

The residential neighborhood consisted of a variety of structures. The 102 single-family homes ranged from single- and multi-story buildings, with footprints ranging in area of ~600 to ~2,000 FT^2. These buildings were generally constructed between the early to mid 1800s to the mid to late 1900s, and varied in construction style (e.g. Colonial, Modern, Victorian). All of the homes had basements with either concrete slabs (of varying condition and configurations) or dirt floors. Foundation walls were constructed of concrete block, poured concrete, or stone masonry. A significant number of the homes had additions and/or crawlspaces. One commercial building was formerly a two-story Colonial/Cape-style residential structure.

Several homes had existing radon removal systems; these systems were evaluated and were found to provide incomplete coverage of the subslab area. This issue is discussed in the conclusions section of this paper.

The second commercial building and the two apartment buildings were constructed differently than the other buildings. The second commercial building was a ~3,500 FT^2 gymnasium of concrete block and floating slab-on-grade construction. The layout of the building consisted of a large open room and several smaller rooms. The two ~8,000 FT^2 multi-story apartment buildings were constructed of poured concrete walls and brick. Both buildings had basements with multiple floating concrete slabs.

While a number of smaller homes with simple layouts only required one suction hole and one fan to achieve complete capture of the subslab region, a significant fraction of the structures necessitated more complex approaches. The residential neighborhood presented a plethora of issues that were overcome during the installation program including: weather-related issues, deteriorated or non-existent concrete slabs, variability of subslab conditions, and a multitude of footprints and building layouts. Photographs of SSD installation features are presented as Figure 3.

Older residential structures featured masonry stone walls (some with deteriorated lime mortar), unsealed penetrations, concrete slabs in poor condition, and dirt floors. Masonry stone walls of poor condition were parge-coated with Portland cement to achieve a thorough seal. Although slabs of poor condition and dirt floors required the installation of a new concrete slab, in some cases this facilitated system installations. The absence of a concrete slab in good condition allowed for the placement of highly efficient subslab horizontal piping runs placed in stone-filled trenches. Figure 4 presents an example of one of the SSD installations that required sealing of stone walls, a new concrete slab, and horizontal piping runs. A minimal fan size was required to attain the required subslab suction field.

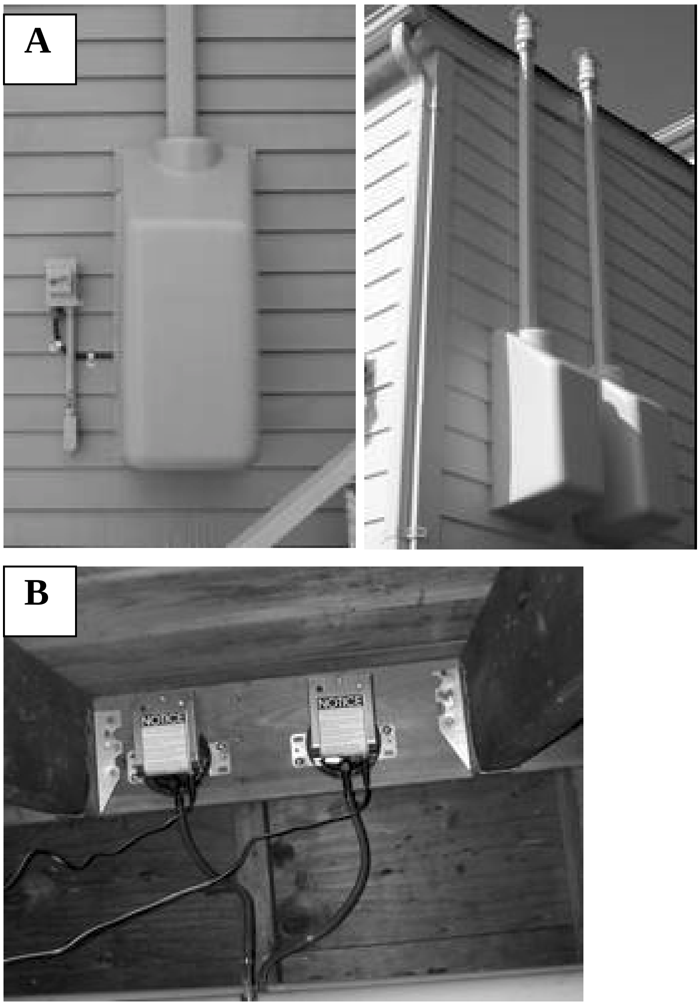

Figure 3. Photographs of Typical SSD System Installation Features. (A) Exterior SSD system components: covered fans, on/off switches, downspouts, and exhaust vent caps. (B) View of two SSD monitoring systems.

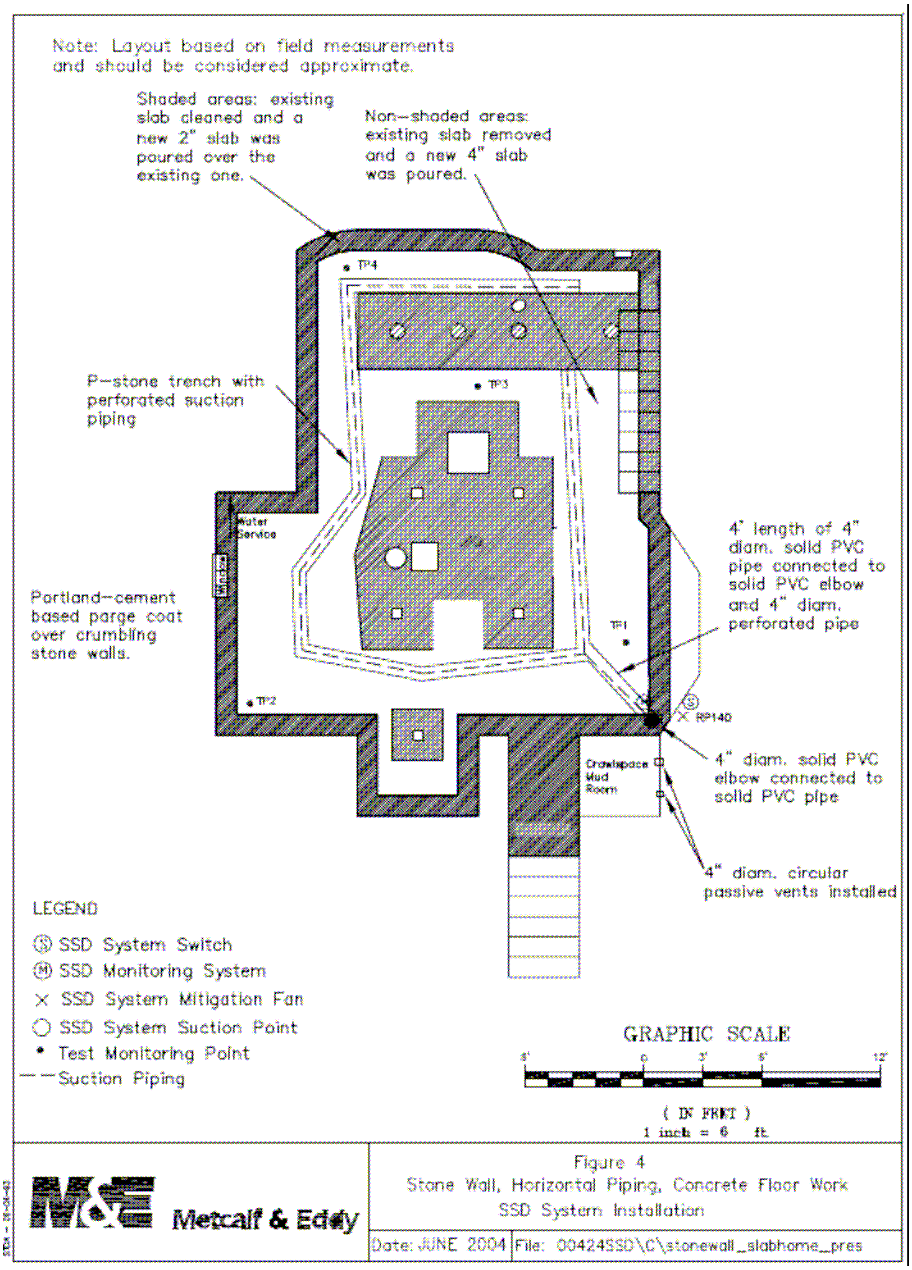

Figure 4. Single-Family Residential Structure Example 1: Sealing of Stone Walls, & Installation of Horizontal Piping Runs and a New Concrete Slab.

A significant characteristic of the neighborhood was the variability of subslab conditions and layout between the homes. A number of buildings had multiple slabs, separated by subsurface footings, with varying permeability. These cases were addressed using several suction holes, multiple pipes feeding single fans, differently sized fans, and flow control valves. An example of a multiple slab installation is provided as Figure 5. This installation required seven suction holes and two fans.

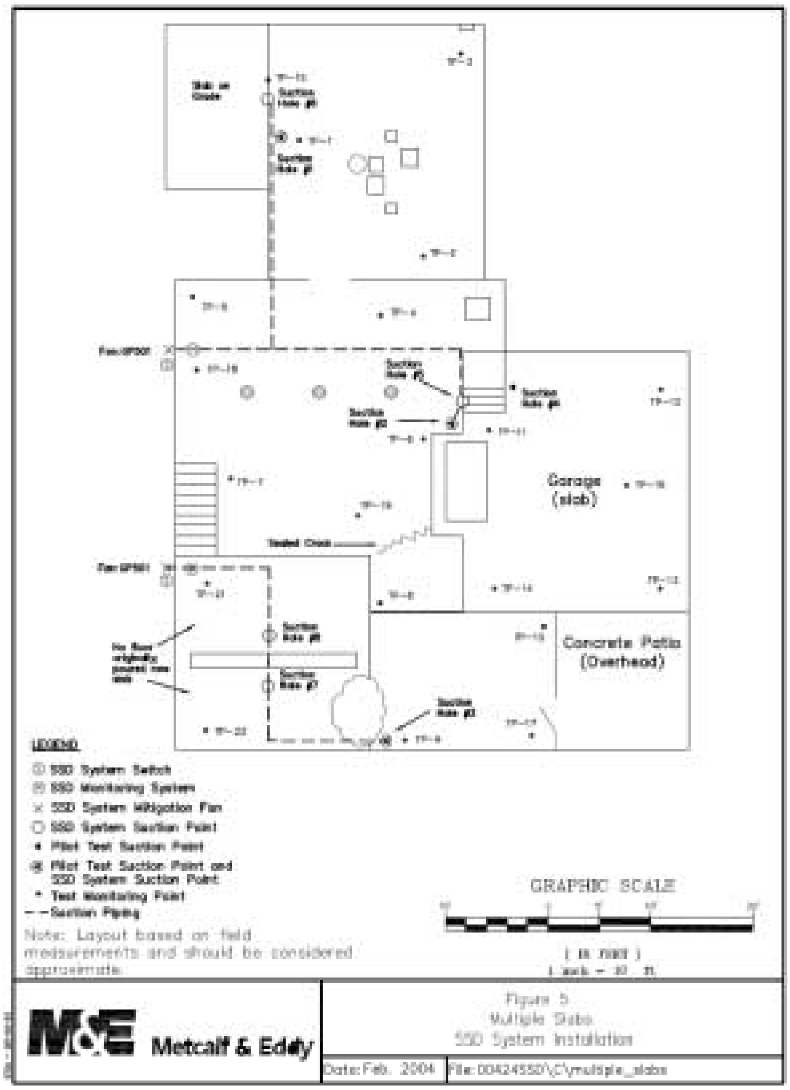

Figure 5. Single-Family Residential Structure Example 2: Multiple Slab Installation.

Additional challenges that were encountered during the installations were finished basements in some homes and crawlspaces. Finished basements required varying degrees of restoration, depending on the level of intrusion necessitated by the installation. In some cases, floors and walls were repaired and/or replaced. Crawlspaces presented another point of entry for vapor intrusion. Concrete slabs or vapor membrane barriers were installed in each crawlspace. The crawlspace was then vented separately or tied into the main SSD system with a smaller diameter suction line.

Many of the installations were conducted during winter months. Health & safety issues such as cold stress, slip/fall hazards, and working in unheated crawlspaces had to be addressed. Working styles were modified by dressing properly for the conditions, frequently cycling contractor technicians between indoor and outdoor work areas, and providing on-site heaters, if necessitated. Through these modifications, SSD system installations continued through the winter and the project schedule did not lag.

3.2 Condominium Complex

The condominium association granted access to the CTDEP to install SSD systems in five multi-unit residential buildings that CTDEP identified as having potential soil vapor volatilization issues. Installations were performed in four buildings in February to April 2004, while the fifth building received a SSD installation during the period of Fall 2004 to Spring 2005.

The first four condominium buildings were multi-storied with four identically sized units on each floor. Each of these four buildings had a footprint of ~5,000 FT^2 and the foundation walls were of concrete block wall construction. The first four buildings were each built with four identically-sized crawlspaces under each floor. The crawlspaces had separate floating concrete slabs of poor quality (extensive cracking) and were ~1.5-3 FT high, making them confined spaces. The fifth building was multi-storied with eight units on each floor, and had a footprint of approximately ~15,000 FT^2. Unlike the first four buildings, the fifth building was concrete slab-on-grade construction with eight equally-sized separate slabs.

The condominium association requested that SSD suction holes, piping, and associated appurtenances be hidden from view to the extent possible. On the first four condominium buildings, this request was satisfied by pilot testing and installing suction holes and suction piping within the crawlspaces beneath the buildings. Prior to conducting the pilot studies, each crawlspace had to be cleaned of debris and wastewater that obstructed the work areas. Due to the nature of the crawlspaces, all pilot testing and system installation activities had to be performed by engineers and contractors trained in confined-space operations.

Due to the highly variable subslab nature observed for all five buildings; suction results varied greatly from slab to slab. Fan types were selected based on pilot testing data review; smaller fans were selected for slabs with fairly permeable subslab behavior, in order to save on long-term electrical costs.

A variety of construction techniques were utilized to install the systems. Suction holes (~4 inch diameter with a 12 inch sub-slab void space) were installed by using a hammer-drill and manual excavation. Piping consisted of 3 and 4 inch diameter schedule 40 PVC and was installed while maintaining pitch and allowing for future access throughout the crawlspace. Penetrations through foundation wall and sill plates were sealed according to fire code. In addition, deteriorated and cracked portions of the concrete slabs and floor/wall joints were caulked and/or covered with concrete to achieve a seal, thereby preventing short circuiting of the vacuum. Fans and alarms were mounted on the ends of the buildings.

Figure 6 presents a typical layout of the SSD system as it was constructed in one of the first four buildings. Note the network of pilot test/suction holes and piping that were required to achieve complete capture of the subslab region. A total of 16 suction holes, ~ 300 ft of piping, and 4 fans were utilized. Note that the number of suction holes varied per crawlspace, based on pilot and performance testing. The differential pressures (inches W.C.) measured during the performance testing performed following the installation are shown. Adequate suctions are achieved throughout the subslab area.

Due to the differences in building construction, the SSD system installation in the fifth condominium structure proceeded in a different manner compared to the first four. Although pilot testing was conducted using both vertical holes inside of homeowners' units and horizontal holes through the foundation walls, the final design required that suction holes only be installed horizontally through foundation walls. To help propagate suction, perforated suction piping was inserted into all the horizontal suction holes beneath the floor slab. To insert the perforated piping beneath the floor slab, an Air Spade™ and shop vacuum were used.

A network of trenches required excavation to allow for the placement of the subsurface piping runs. Excavation was performed using a mini-excavator or by hand when subsurface utilities were encountered. As much of this phase of work was conducted during the winter months, heat coiling and insulation blankets were used to prevent soil from freezing. Due to the topography and building layout, sloping of the piping back to the suction holes could not always be achieved. Therefore, a number of condensate drip legs were installed at strategic locations within the system to allow for the removal of water from the system. The drip legs were installed with access covers to allow for future operations and maintenance activities.

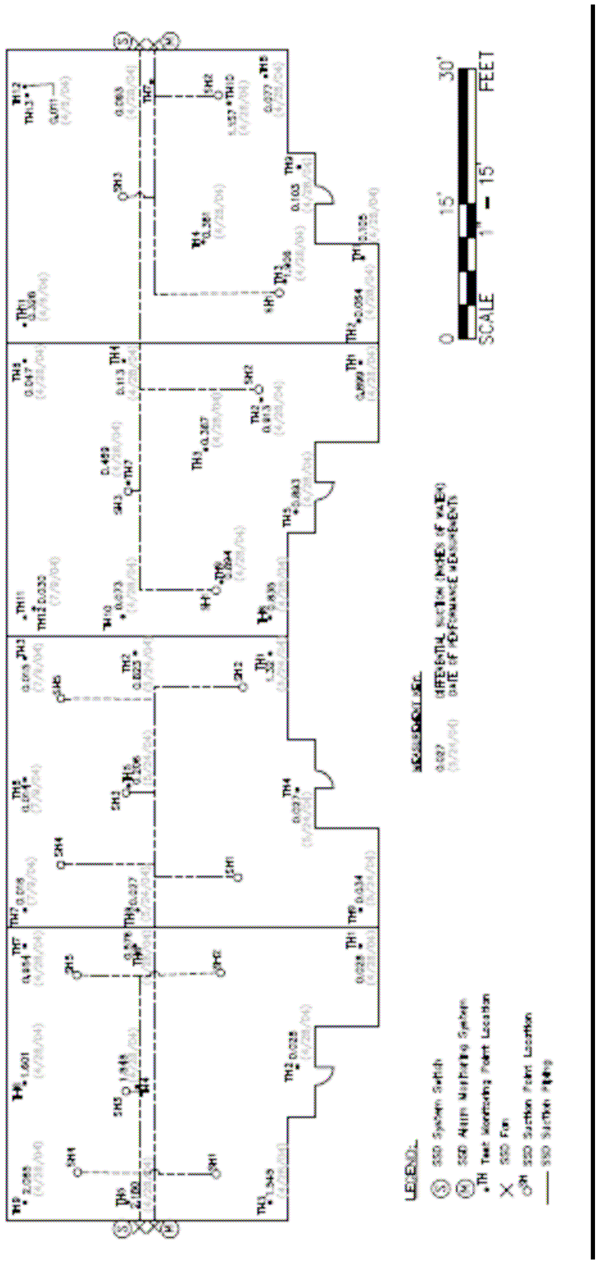

Figure 6. Condominium Building Example 1: Crawl Space Installation.

The fifth building's SSD system is presented as Figure 7. The extensive network of pilot test/suction holes and piping required to achieve complete capture of the subslab region is shown. A total of 39 suction holes, ~2,500 ft of 4 inch diameter schedule 40 PVC piping, 16 condensate drip legs, and 16 fans were utilized to construct the whole system. The fans and alarms were housed in two enclosures located on the ends of the building. The enclosures were constructed to match the exterior façade of the condominium building, and were also constructed with sound dampening materials. For each enclosure, a chimney structure was constructed to house the exhaust piping. The differential pressures (inches W.C.) measured during the performance testing performed following the installation is shown. Similar to the first four buildings, adequate suctions are achieved throughout the subslab area.

During all five installations, field changes were made to the original design. Based on the results of performance testing conducted while the installations were underway, several subslab areas requiring additional suction were identified. Additional suction holes and associated piping runs were installed to achieve required capture. Further, several instances of surface water runoff issues were encountered during the installation process. As part of the installations, these water runoff issues were corrected to alleviate future wet-crawlspace issues and to minimize the effect of water runoff on the SSD systems.

To complete the installations, site restoration activities were conducted. Site restoration consisted of the following tasks:

- Top soil placement, preparation, and establishment of grass seed
- Replacement and repair of landscape features
- Concrete sidewalk replacement and repair
- Surface drainage structure repair and replacement

3.3 System Maintenance

CTDEP has assumed responsibility for maintenance of the SSD system (including fan replacement) while there is an unacceptable risk caused by potential soil gas migration into the home. Maintenance agreements stipulating CTDEP's responsibility were signed by all parties receiving SSD system installations. The agreements were provided to each homeowner; they are signed by DEP.

Normal system operation does not require involvement from the homeowner / building owner except for routine inspection. If the audible/visual alarm signals a loss in suction within the system, the homeowner / building owner has been instructed to contact a specific person at the CTDEP. Contact information is also available on a label affixed to the system near the alarm should building ownership change, etc. Maintenance calls are then forwarded to an on-call environmental contractor. The fans that were employed for these installations have a 5 year manufacturer's warranty and are relatively simple to replace.

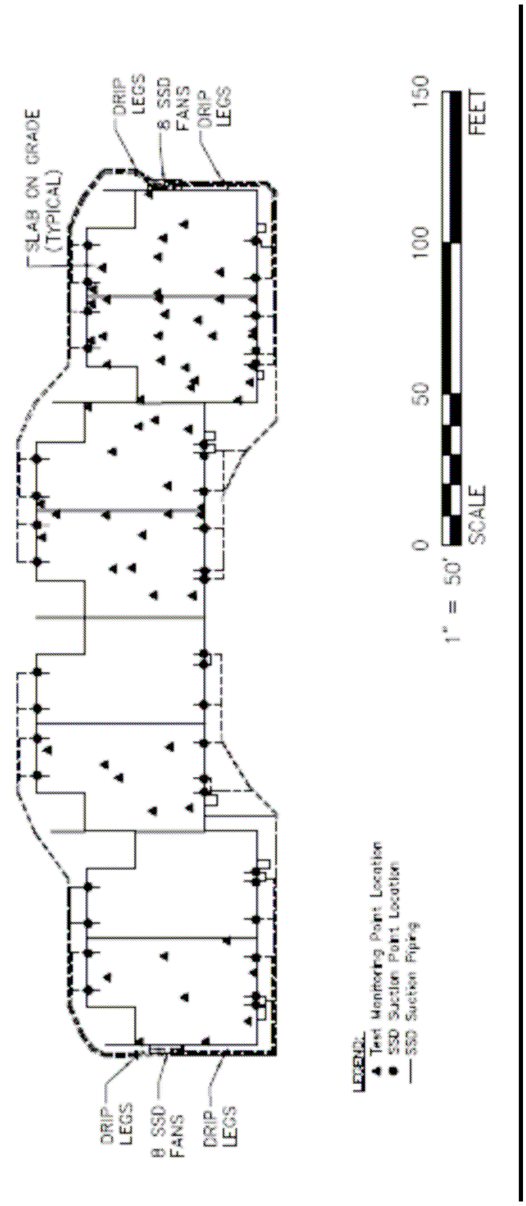

Figure 7. Condominium Building Example 2: Slab-On-Grade Installation.

Several other activities comprise the longer-term maintenance of the systems. These tasks include repairing system components damaged from extreme weather events. Particular to the installation performed at the fifth condominium building, any water that has accumulated within the drip legs requires removal. In addition, annual neighborhood inspections of the system components located on the exterior of the residential structures are performed.

4. CONCLUSIONS

4.1 System Performance

All of the systems are currently depressurizing subslab regions; several of the systems have been in operation for almost four years. A few of these systems have required minimal maintenance, including fan replacement, minor piping repairs, and removal of ice buildup during the winter. However, the majority of the SSD systems have not required attention except for the annual survey.

The post-installation performance test provides physical evidence that the system is achieving the goal of complete capture of the subslab area. However, some additional testing had been conducted. USEPA conducted some follow up testing for VOCs in indoor air of several of the homes within the residential community; the results of this testing indicated significant reductions in VOC levels. CTDEP conducted radon (as a surrogate for VOCs) testing of indoor air before and after installation in a select set of homes; these results also indicated that vapor intrusion had been mitigated. In the case of the condominium complex, CTDEP performed testing of soil gas in the close proximity of the first four buildings before and after the installation of the SSD systems. Levels of VOCs in soil gas were below the proposed revised volatilization criteria following the initiation of the SSD systems.

4.2 Critical Issues and Lessons Learned

The success of these large-scale SSD system installation programs was primarily due to the synergistic efforts of the regulatory agencies involved and the overall project approach. A critical component of the program was maintaining communication between the regulatory agencies and the stakeholders. Potential misunderstandings or mistakes were minimized, and any issues that arose were solved in a timely fashion.

The design-build approach included: pilot testing (sometimes iterative); designs that considered building owner concerns; installations with the flexibility of field changes; and performance testing. These facets allowed for expedited installations and a minimization of disturbance to residents.

The scale of the installation projects allowed for some economies of scale. Construction techniques between homes were similar and relatively simple to employ, allowing several installation crews to perfect these techniques and operate simultaneously on multiple structures. The system components were generally standardized, allowing for judicious replacement of compromised or incorrect pieces.

As indicated earlier, radon systems had been installed in several residences prior to the commencement of the residential neighborhood SSD installation program. These systems were assessed by measuring the differential pressures that existed in the well-established suction fields. The extents of adequate subslab suction field for the five systems ranged from 25 to 50 % of the slab area. This result suggests that engineered sub-slab depressurization systems provide more consistent results compared with traditional radon systems.

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