United States
Environmental Protection
Agency

Research and Development

Air and Energy Engineering
Research Laboratory
Research Triangle Park, NC 27711

EPA/600/SR-92/090 December 1992

EPA

Project Summary

Simplified Modeling of Air Flow Dynamics in SSD Radon Mitigation Systems for Residences with Gravel Beds

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The technique presently considered most effective for mitigating residences for radon is subslab depressurization. Given that many such mitigation systems designed and installed by the professional community do not perform entirely satisfactorily, there is a need to better understand the dynamics of subslab air flow. This report suggests that subslab air flow induced by a central suction point be treated as radial air flow through a porous bed contained between two impermeable disks. It also shows that subslab air flow is most likely to be turbulent under actual field situations in houses with subslab gravel beds, but remains laminar when soil is present under the slab. The physical significance of a model is discussed, and simplified closed-form equations are derived to predict pressure and flows at various distances from a single central depressurization point. A laboratory apparatus was built to verify the model and experimentally determine the model coefficients of the pressure drop versus flow for commonly encountered subslab gravel materials. These pressure drop coefficients can be used in conjunction with the simplified model as a rational way to assess subslab communication in houses. Preliminary field verification results in a house with gravel under the basement slab are presented and discussed.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Subslab depressurization (SSD) has been widely adapted as a radon mitigation technique. This method relies upon reducing the pressure under the slab to values below that of the basement (or living space in the case of slab-on-grade), at least where soil gas flow into the basement could occur. In the pre-mitigation diagnostic phase, the degree of "connectivity" under the slab as well as the permeability characteristics of the subslab medium must be determined before a suitable SSD system can be designed. Proper attention to these aspects will ensure that reasonable flows, and hence the desired degree of depressurization, will prevail at all points under the slab.

Parallel with the above aspect is the concern that mitigators tend to over-design SSD systems to be on the safe side. In so doing, there is a definite possiblity that more radon from the soil is removed and vented to the ambient air than would have ocurred naturally. There is thus the need to downsize current overly robust SSD mitigation systems and decrease emission exhaust quantities of radon while simultaneously ensuring that indoor radon does not rise to undesirable levels.

One aspect of the current research is the formulation and verification of a rapid diagnostic protocol for subslab and wall depressurization systems designed to control indoor radon concentrations. The formulation of the diagnostics protocol consists of: (1) specification of practical guidelines that would enhance the effectiveness of the engineering design of the radon mitigation system, and (2) reliance on fundamental scientific studies that provide additional data and insight needed to develop, test, and revise protocols. The report addresses the latter, relying on current data and understanding and anticipating that additional data will become available to refine the approach taken here.

Specification of the Problem

In terms of modeling the induced subslab pressure fields, the prestock construction can be divided into three groups: (1) those with a gravel bed under the concrete slab, (2) those without, in which case soil is the medium under the slab, and (3) those houses which have both. In Group 2, the soil permeabilities are much lower than in Group 1, and more careful design of the mitigation system is warranted. In New Jersey, houses less than about 30 years old typically have gravel beds about 0.05-0.1 m thick under the slab. However other states seem to have very different construction practices; for example, houses in Florida are often slab-on-grade directly on compacted fine-grained soil which offers high resistance to air flow.

Figures 1 (a) and (b) depict the construction and air flow paths expected in a house with either gravel or soil under the slab, when single-suction pressure is applied through the slab. (For a radon mitigation system using subslab pressurization, a good approximation, would assume similar aerodynamic effects with the direction of air flows reversed.) Since the permeability of the gravel bed is usually very much higher than that of the soil below, one could assume, except for the irregular pattern around the footing which would occur over a relatively small length, that the subslab air flow is akin to radial flow between two impermeable circular disks with a spacing equal to the thickness of the gravel bed. Note that this model equally accounts for the leakage of air from the basement which essentially occurs from the perimeter cracks or through the basement wall.

For a house without a gravel bed (Figure 1b), suction applied at a simple penetration through the slab (as in Figure 1a) is no longer practical since the area of depressurization is usually small. To enhance mitigation effectiveness, the current practice is to increase this area either by digging a pit below the concrete slab or, more simply, by hollowing out a hemisphere of about 0.3-0.45 m radius underneath the suction hole. Even under such conditions, if the soil underneath the slab is free of major obstructions like concrete footings, duct work, piping, and large rocks, air flow can be approximated as occurring between two impermeable circular disks with a spacing equal to either the depth of the pit or the radius of the hollow hemisphere.

Preliminary Theoretical Considerations

The above duscussion suggests that flow underneath the slab be visualized as occurring in the radial streamlines terminating at the central suction point. Note that such a reprensentation would perhaps be too simplistic or even incorrect for a house with a partial basement (Group 3, above). This study is limited to understanding the flow and pressure drop characteristics through a *homogeneous bed* (of either gravel or soil) *with uniform boundary conditions*, the obvious one to start with being a circular configuration.

The first questions relate to the nature of the flow; i.e., is the flow is laminar or turbulent, and where, if at all, is there a transition from one regime to another. The Reynolds number gives an indication of the flow regime. Though there is an inherent ambiguity in the definition of the quantity characterizing the length dimension, we shall adhere to the following definition:

$$Re = \frac{q}{A} \cdot \frac{1}{v_a} \cdot \frac{d_v}{\phi} \qquad (1)$$

where q = total volume flow rate,
A = cross sectional area of the flow (for radial flow through a circular bed of radius r and thickness h, $A = 2\pi rh$),
v_a = kinematic viscosity of air,
d_v = equivalent diameter of gravel or soil particles, and
ϕ = void fraction or porosity of the gravel bed.

For flow through a gravel bed, some typical values of the above parameters could be assumed:

$h = 0.1$ m, $d_v = 0.0125$ m, v_a (at 15°C) = 14.6×10^{-6} m²/s, and $\phi = 0.4$.

The values of q encountered in practice range from 10 to 50 l/s. The Reynolds numbers for radial flow at different radii have been computed under these conditons. A safe lower limit for turbulent flow is when Re >10, and a safe upper limit for laminar flow is when Re < 1. Since basements do not generally exceed 6 m in radius, subslab *flow tends to be largely turbulent* when a gravel bed is present. This by itself is an important finding since earlier studies do not seem to have recognized this fact.

Subslab flow characteristics in a house with soil as the subslab medium have also been investigated. Soil grain diameters range from 0.06 to 2 mm, and volume flow rates in corresponding mitigation systems are typically lower, about 0.8-6.0 l/s. Assuming typical values of h = 0.1 m, $\Phi = 0.4$, and q = 2.4 l/s, the corresponding Reynolds numbers for air flow through sands of different grain diameters have been calculated from Eq. (1). The flow is likely to be laminar in most cases.

Mathematical Model for Radial Flow

The core of any model is the formulation of the correlation structure between pressure drop and Re (or flow rate). For laminar flow, Darcy's law holds, providing:

$$\frac{1}{\rho_f \cdot g} \cdot \frac{dp}{dx} = a \cdot \left(\frac{q}{A}\right) \qquad (2)$$

where P_f = density of the flowing fluid, and

g = gravitational constant.

For turbulent flows, a widely used model is:

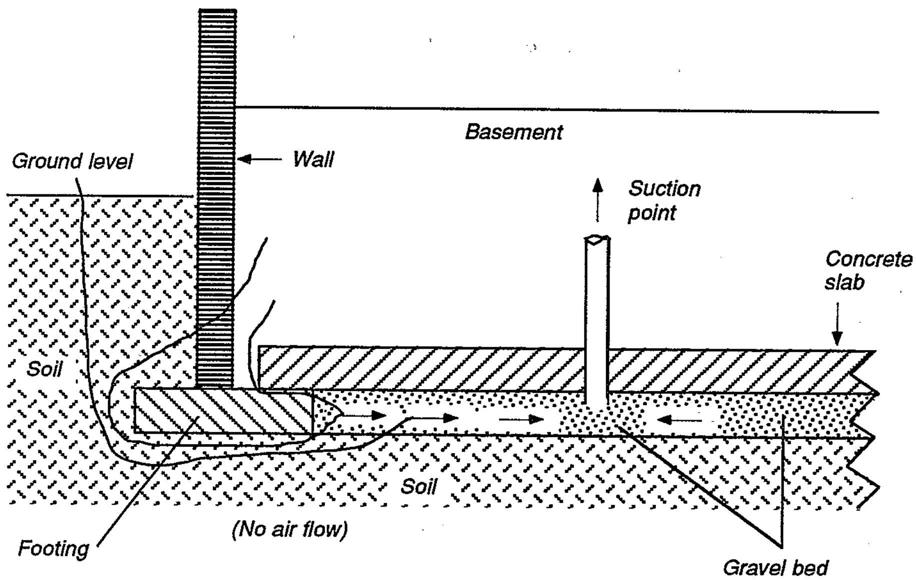
$$\frac{1}{\rho_f \cdot g} \cdot \frac{dp}{dx} = a \cdot \left(\frac{q}{A}\right)^b \qquad (3)$$

The left side is the pressure drop per unit bed length, and a can be loosely interpreted as the resistivity of the porous bed to the flow of the particular fluid. The permeability k of the porous bed is given by:

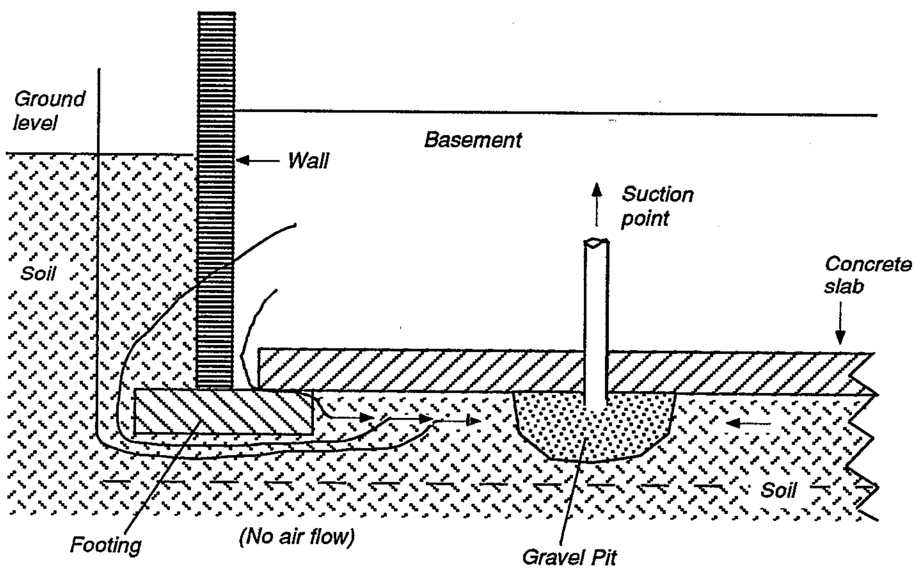
$$k = \frac{V_a}{g} \cdot \frac{1}{a} \qquad (4)$$

A mathematical expression can be derived for the pressure field when suction is applied at the center of the circle. Air flows are assumed radially through a circular homogeneous gravel bed. For the suction pressures encountered in this problem, air can be assumed to be incompressible. Thus assuming a simple model such as Eq.(3) for the pressure drop yields:

$$\frac{d}{dr}\left(\frac{p(r)}{\rho_a \cdot g}\right) = a \cdot \left(\frac{q}{2\pi h}\right)^b \cdot \frac{1}{r^b} \qquad (5)$$



(a) House with a subslab gravel bed



(b) House with a subslab soil bed.

Figure 1. *A subslab mitigation system and air flows in the basement of a house. Note that part of the air flowing through the subslab bed originates from the basement and the rest from the ambient air.*

where p(r) is the pressure of air at a radial distance r from the center, and ρ_a is the density of air.

Integrating Eq. (5), and using the boundary conditions $r = r_o$ and $p = p_a$ at the edge of the disk, yields:

$$\frac{p(r)-p_a}{\rho_a \cdot g} = a \cdot \left(\frac{q}{2\pi h}\right)^b \cdot \frac{1}{1-b} \cdot (r^{1-b} - r_o^{1-b}) \tag{6}$$

Since the pressure drop is often measured in units of head of water, it is more convenient to modify Eqs. (5) and (6) to:

$$\frac{p(r)-p_a}{\rho_w \cdot g} = a \cdot \frac{\rho_a}{\rho_w} \cdot \left(\frac{q}{2\pi h}\right)^b \cdot \frac{1}{1-b} \cdot (r^{1-b} - r_o^{1-b}) \tag{7}$$

On the other hand, during laminar flow, Darcy's Law holds and exponent b=1. Under these circumstances, integrating Eq. (5) with b = 1 and inserting the appropriate boundary conditions, yields:

$$\frac{p(r) - p_a}{\rho_w \cdot g} = a \cdot \frac{\rho_a}{\rho_w} \cdot \frac{q}{2\pi h} \cdot 1n\left(\frac{r}{r_o}\right) \tag{8}$$

It is easy to modify these equations to apply to outward radial flow as encountered in houses where subslab pressurization is used. The boundary conditions are still the same, but now the pressure at the entrance of the suction pipe is higher than ambient pressure and the quantity $[p(r) - p_a]$ is positive and represents the pressure *above* the ambient pressure.

If parameters a and b are constant for a given bed material and can be determined by actual experiments in the field, they will serve as indices for mitigation system design.

Laboratory Apparatus

The soundness of the mathematical derivation presented above needs to be evaluated, and the numerical values of the empirical coefficients of Eq. (3) needs to be determined. To this end, a laboratory model consisting of a 2.4 m diameter circular section that is 0.15 m deep was constructed. The top and bottom impermeable disks were 0.02 m thick plywood, and a wire mesh at the outer periphery of the disks was used to contain the gravel between the disks. The apparatus allowed experiments to be conducted with a maximum disk spacing (or depth of gravel bed) of 0.095 m. An open-cell foam sheet 0.025 m thick was glued to the underside of the top plywood disk. During the experiments, heavy weights were placed on top of the plywood disk which compressed the open-cell foam enough to effectively eliminate gaps between the disk and the gravel top that could short-circuit the air flow. This guarantees that air flow occurs through the bed and not over it.

The volume of the packed bed is approximately 0.43 m^3 which, for river-run gravel, translates into a net weight of about 700 kg (1530 lb).

A 0.038 m diameter hole at the center of the top disk served as the suction hole. Nine holes, were drilled on three separate rays of the top disk, and a polyvinyl chloride (PVC) pipe of 0.012 m inner diameter with chamfered ends was press-fit into these holes. Pressure measurements at these nine holes would then yield an accurate picture of the pressure field over the entire bed.

We choose a predetermined total air flow rate and gradually control the speed of the suction fan to achieve this flow. The pressure measurements (representative of the corresponding static pressure inside the porous bed) at each of the nine taps are taken with all other taps closed. This completes a series of readings pertaining to one run. In subsequent runs, the total air flow rate is set to another predetermined value and the series of readings are repeated.

Experimental Results and Analysis of Radial Flow

Table 1 summarizes the different experiments performed using the laboratory apparatus. For example, Experiments A involved river run gravel of nominal diameters of 0.012 and 0.019 m, referred to as small and large gravel, respectively. Experiments A1 and A2 differ only in the spacing between the plywood disks; i.e., the thickness of the bed was altered. Experiment A1 involved three runs each with a different total volume flow rate, the values of which are also given in Table 1. The flow regime (as specified by the corresponding calculated Reynolds number) was found to be turbulent throughout the radial disk.

The values of the mean gravel diameter and the porosity of the bed are required for computing the Reynolds number [given by Eq. (1)]. Least-square regression for both the constant 'a' and exponent 'b' was performed on the observed experimental pressure drop data using Eq. (7). R^2 values were very high (Table 2), and better fits cannot realistically be expected (given the measurement errors in the readings, we may in fact be overfitting in the sense that we are trying to assign physical meaning to random errors).

An earlier study found exponent b to be 1.56 for the cylindrical disk model. This is generally borne out in the present study where b = 1.6 for the small river-run gravel and b = 1.4 for the large gravel.

The values of permeability of the porous bed calculated following Eq. (4), included in Table 2, show a threefold difference between small and large gravel sizes. The numerical values seem to correspond to those cited in the radon literature.

Table 1. *Summary of the different experiments using river-run gravel performed with the laboratory apparatus*

Experiment	*Gravel size (nominal diameter) (m)*	*Disk spacing (m)*	*No. of runs*	*Total flow rate (l/s)*
A1	*0.012*	*0.075*	*3*	*20.5* *30.1* *37.3*
A2	*0.012*	*0.10*	*2*	*22.1* *31.4*
A3	*0.019*	*0.10*	*4*	*11.2* *15.2* *17.6* *20.8*

Table 2. *Summary of various laboratory experiments performed and the physical parameters deduced in the framework of the study using river-run gravel*

Experiment	*Diameter of particles nominal (m)*	*measured (m)*	*Measured porosity*	R^2	*Pressure drop exponent*	*Permeability of bed (m^2)*
A1 + A2	*0.012*	*0.011*	*0.374*	*0.99*	*1.60*	9.4×10^{-9}
A3	*0.019*	*0.022*	*0.424*	*0.99*	*1.40*	34×10^{-9}

Field Verification

The irregular boundary conditions and the non-homogeneity in subslab beds that arise in practice are, however, not easily tractable with a simple expression such as Eqs. (7) and (8). Resorting to a numerical computer code may be the only rigorous way to predict pressure fields under actual situations. This section shows that the simplified approach nevertheless has practical relevance in that it could be used to determine areas under the slab with poorer connectivity.

The house under investigation (H21) has a partial basement with a gravel bed under the basement slab. As shown in Figure 2, the basement (though rectangular) is nearly square (6.45 x 7.60 m). It has two sides exposed to the ambient air above grade, while the other two sides are adjacent to slab-on-grade construction. One suction hole of 0.1 m diameter was drilled at roughly the center of the basement slab to which a temporary mitigation system was installed. Though 19 holes were drilled through the slab (Figure 2), two of them (holes 11 and 12) were found to be blocked beneath the slab. Consequently, data from only 17 holes have been used in this study. This blockage was later found to be due to the presence of an oversized footing for a support column.

Three sets of runs were carried out which, depending on the air flow rate through the single suction pipe, are termed: 1) 28 l/s - high flow, 2) 23.4 l/s - medium flow, and 3) 18.1 l/s - low flow.

Note that the analytical expression for the pressure field under turbulent flow given by Eq. (7) is strictly valid for a circular disk with boundary conditions at $r = r_o$ and $p = p_a$. The rectangular basement is approximated by a circle of 3.5 m mean radius. Also included the extra path length of ambient air flowing down the outer basement wall, going under the footing, and flowing through the subslab gravel into the suction hole. This is about 2 m. Consequently, r_o = 5.5 m. The effective thickness of the subslab gravel bed, h, is about 0.05 m.

The gravel under the slab, though river-run, was highly heterogeneous in size and shape. In general, its average size was slightly less than 0.012 m. However, the properties of the 0.012 m gravel determined experimentally in the laboratory (see Table 2) were used.

Figure 3(a) shows the observed and calculated pressure drops for the low flow rate. Readings from holes 13 and 14 are lower, and poorer connectivity to these holes is suspected; i.e., some sort of blockage in this general area. Agreement between model and observation is striking, given the simplification in the model and also the various assumptions outlined above. This was also true for the other two flow rates chosen.

Figure 3(a) indicates the non-uniform areas under the slab. A better way of illustrating how well the model fares against actual observations is shown in Figure

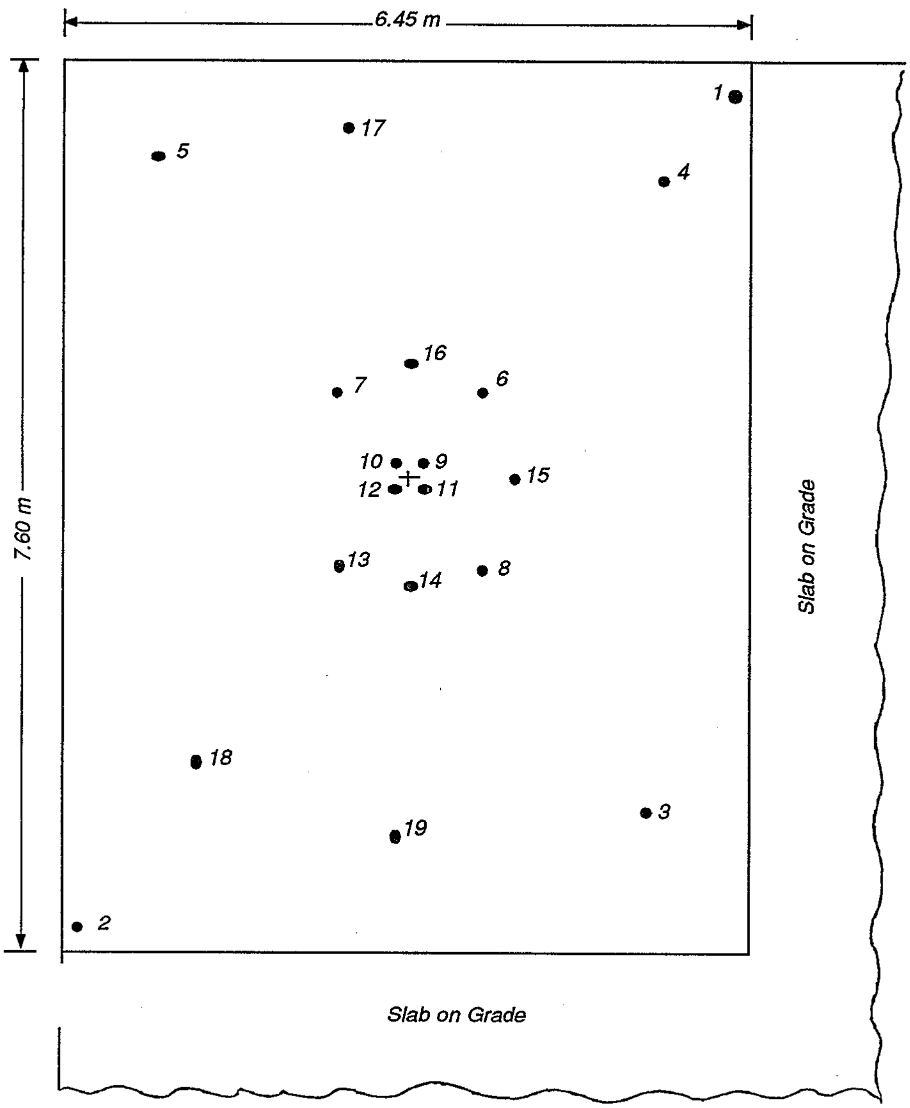


Figure 2. *The basement slab of House H21 showing the relative positions of the subslab penetrations. The mitigation system suction hole is marked +.*

3(b). The solid line represents the model predictions while observations are shown by discrete points. Again, the predictive ability of this modeling approach is satisfactory, and certain holes have pressure drop values higher than those predicted by the model.

An alternate approach, to the one adopted here and described above, would be not to assume specific gravel bed coefficients but to determine them from regression. This entails using Eq. (7) and the data set of actual observations and determining the parameters a (and permeability k) and b by regression. Such an approach yielded a value of k which is practically identical to that of the 0.012 m gravel determined experimentally in the laboratory apparatus. This suggests that even a visual inspection of the porous material under the slab can be an indicator good enough for a mitigator to select a standard bed material from a table before using the physical properties of the material to get a sound *estimate* of what the suction pressure ought to be in order to generate a certain pressure field under the slab. The need to categorize commonly found subslab materials, deduce their aerodynamic pressure drop coefficients in laboratory experiments, and tabulate them seems to be worth investigating.

Summary

Important features of the study are:

(1) The general problem of radon mitigation system design is outlined, and the scope and limitations of prior studies are discussed both in this aspect and at a more fundamental aerodynamical level. The first need should be to determine the nature of air flow below the concrete slab and how it is likely to affect the pressure drop versus flow correlation for given subslab conditions.

(2) The suggestion of a prior study, that flow under the slab of a house during mitigation using subslab depressurization (and pressurization) be likened to radial flow between two impermeable disks, is supported.

(3) It is shown that subslab air flow under actual operation of mitigation systems is likely to be turbulent if a gravel bed is present and laminar in the presence of soil.

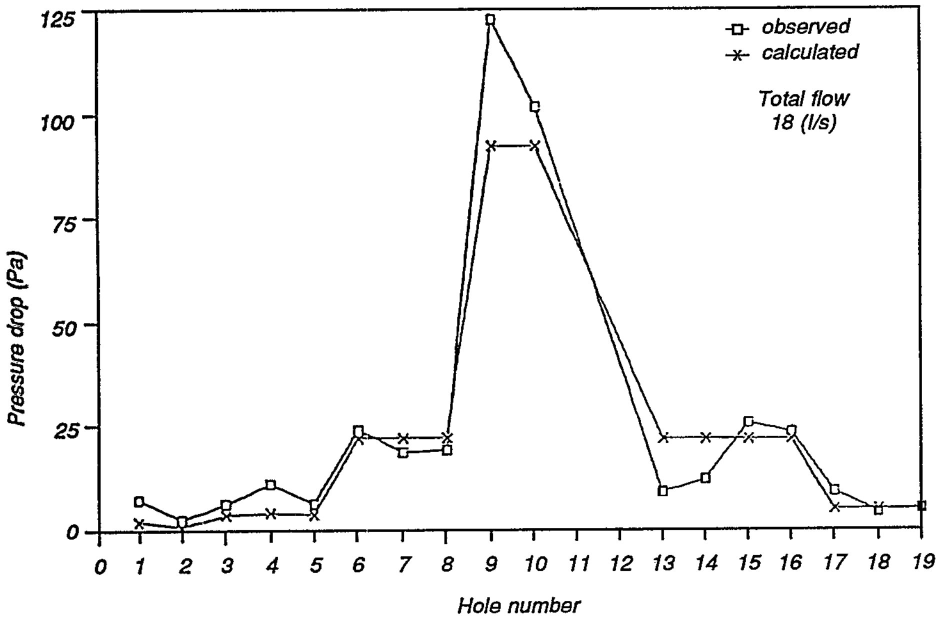
(4) A mathematical treatment, to analytically predict the pressure field in homogeneous circular porous beds when subjected to a single central suction hole, is presented.

(5) A laboratory apparatus that can duplicate conditions which occur in practice under slabs of real houses being mitigated for radon using depressurization (or pressurization) is described.The experimental procedure followed to measure the pressure field of turbulent air flow (from which the regression coefficients of the pressure drop versus flow correlation can be determined) is outlined.

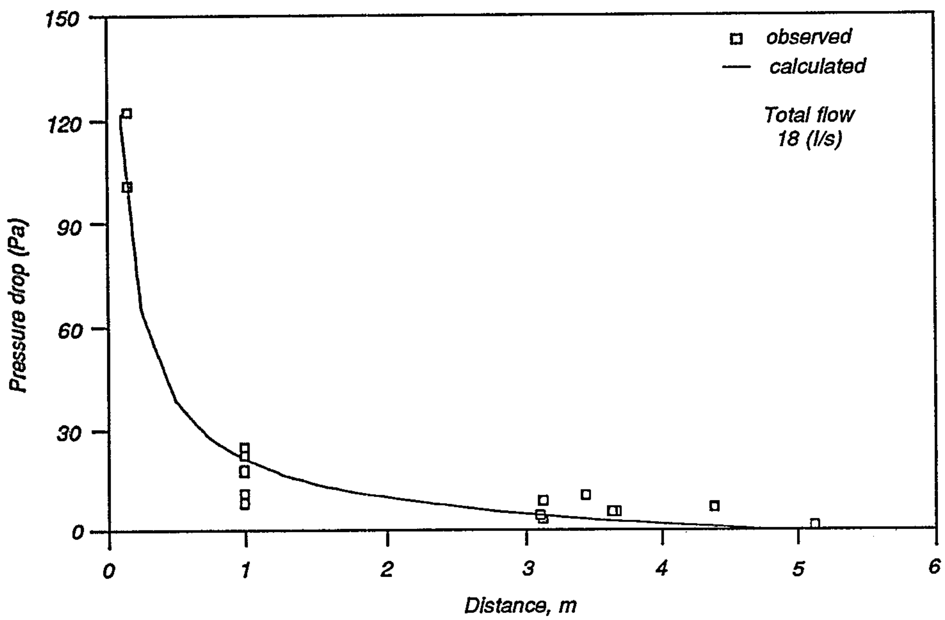
(6) Preliminary field verification results of the modeling approach in a house with gravel under the basement slab are presented and discussed. A striking conclusion of the study is that even a visual inspection of the porous material under the slab may be an indicator good enough for a sound engineering design, if used in parallel with the modeling approach and given a table containing the aerodynamic pressure drop coefficients of commonly found subslab material.

Future Work

Logical extensions of this study would involve applications of this methodology to houses with (1) homogeneous beds but with irregular boundaries, and (2) nonhomogeneous porous beds. One approach



(a) Pressure drop vs. hole number.



(b) Pressure drop vs. distance.

***Figure 3.** Comparison of observed and estimated pressure drops in House H21 using coefficients of 0.012 m gravel. Data of holes 11 and 12 are not included.*

is to develop a computer program using numerical methods (either finite element or finite difference could be used) to solve the basic set of aerodynamic and mass conservation equations.

Although the above approach offers great flexibility, it is not used easily by non-experts. Developing engineering guidelines for practitioners based on such a code demands a certain amount of effort and practical acumen. It would be wiser to define a few "standard" basement shapes, subslab conditions, and mitigation pipe locations; develop simplified closed-form solutions of these cases; and then compare these solutions with actual measurements taken in the field. If such an approach does give satisfactory engineering accuracy, its subsequent use as an engineering design tool, well within the expertise of the professional community, seems promising.

*U.S. Government Printing Office: 1993 — 750-071/60176

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The complete report, entitled "Simplified Modeling of Air Flow Dynamics in SSD Radon Mitigation Systems for Residences with Gravel Beds," Order No. PB92-195635/AS; Cost: $19.50 subject to change) will be available only from:
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