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Comparing solutions to soil gas flow problems with experiment and another solution

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Abstract

The principal soil gases of current concern to building are radon and landfill gas. The flow of these is generally thought to be dominated by viscous flow driven by pressure differences. This paper compares analytical results presented in two previous papers, an experiment to measure the flow of gas in soil and an analytical result found by another technique. The results support the findings of the previous work.

1. Introduction

The analytical solutions discussed previously [1, 2] all relate to the solution of the pressure and flow equations for a building with a bare soil floor. The justification for this work and the background theory are not reproduced here.

The purpose of the experiment described in this paper was to validate the results of the modelling studies. This involved attempting to measure the flow of gas from the soil into a building. However, this is not straightforward, as there is no direct way of measuring the flow through soil. The experiment was carried out by the author with a colleague, Paul Welsh, and a student, Stephen Sweeney.

The concept of the experiment was to measure for soil what a fan pressurisation test measures for a building, that is the overall leakage through all possible flow paths. In a fan pressurisation test, [3], a fan is installed in the outer wall of a building, usually in a doorway. The rates of flow required to produce a series of pressure differences between inside and out are measured. From these results the characteristic leakiness of the building is estimated. It is usual to express it as the number of air changes per hour (ach) at 50 Pa pressure differential, often called n_{50}. The air change rate is the volume flow rate of gas divided by the volume of the building, so it has units s^{-1} or more usually h^{-1} or ach.

There have been other studies of soil gas flow, but the work nearest to the results presented in this paper was reported by Landman and Delsante [4–6] on the heat loss through concrete floors. However, since the equations are the same (with different symbols only), the results of the different techniques can be usefully compared. This is the subject of the latter part of this paper.

2. The experiment in the BRE radon pit

The radon pit consisted of sand about 6 × 10 m and 4 m deep. The sand contained high concentrations of radium, which resulted in high radon concentrations in the soil gas in the sand. On top of the sand two structures were built. These were essentially identical, so that changes to one structure could be monitored against the other as a control. BRE was using the facility to investigate the methods to remediate houses with timber floors, but this paper does not report on these experiments.

The purpose of the test was to make measurements to predict the flow through the soil due to an applied pressure below the floor. This then gives data with which to compare the results of the modelling studies of the same problem, and helps us to understand the entry rates of radon into homes constructed with a suspended timber floor.

The main problem in doing this is that, if a fan sucks air from the space below the floor, much of the flow will occur through the floor. This is because a timber floor to a building is usually much leakier than the sub-floor walls and the soil itself. Hence a method was needed to prevent flow through the floor, or to account for it.

The method we chose to use was to balance the pressure

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in the 'house', P_m, with that in the under-floor area, P_u. The idea is shown in Fig. 1.

The pressure across the floor is changed using two fans. One fan sucks air from the main space, at a rate Q_m. A second fan sucks air from the under floor space, at a rate Q_u. All visible holes in the wall are sealed. The flow Q_u, when the pressures are equal across the floor is the 'leakage' of the soil, Q_s, and the subfloor walls, Q_w, combined. The walls here were painted on the inside with a bituminous paint, and the air bricks were carefully sealed. As a result most of the flow was probably going through the soil and not through the walls.

The fans used were not very easy to adjust, so it was not practical to obtain zero values for the pressure across the floor. Instead we took a number of readings of pressure difference across the floor for different flow rates for the main space. These then gave a curve from which we could estimate the value of the flow at zero pressure difference.

2.1. Basic results

The first set of data is plotted in Fig. 2. It shows on the y axis the pressures produced across the floor of the hut, plotted against the hut fan flow which produced it. On the second y axis is the hut to outside pressure difference, plotted at the same under-floor fan flow rate. The hut fan was left at the same setting, but the flow rate through it varies with the flow through the under floor fan.

Straight line fits to the two sets of points are also shown in Fig. 2, and for the pressure across the floor the lines showing the 95% confidence limits (assuming normally distributed errors) are also included. These linear regression equations are given by

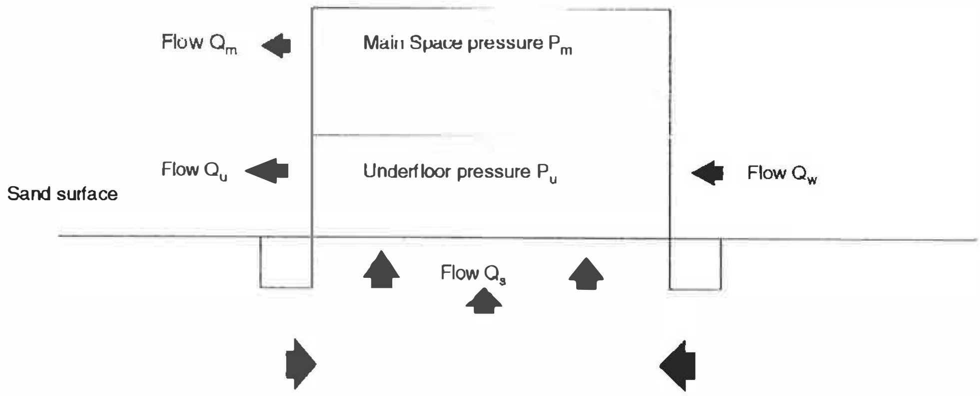

Fig. 1. The experimental arrangement.

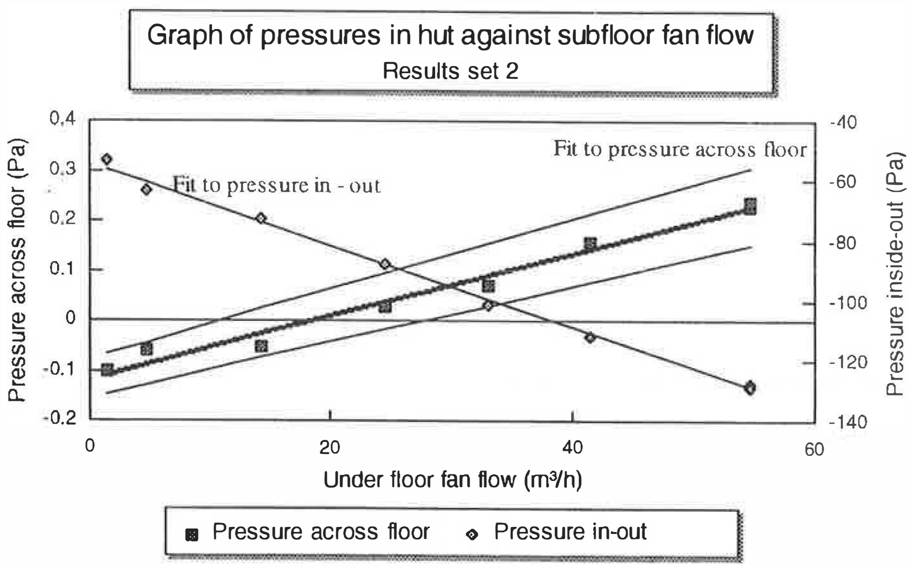

Fig. 2. Graph of pressures generated against underfloor fan flow.

$$P_{\text{floor}} = -0.12 + 0.0063\,Q_u \quad (1)$$

or with the 95% confidence limits as

$$P_{\text{floor}} = -(0.12 \pm 0.04) + (0.0063 \pm 0.0008)\,Q_u \quad (2)$$

This gives the flow through the under-floor fan at which zero pressure occurs across the floor as

$$Q_0 = 18.3\,\text{m}^3/\text{h}^{-1} \quad (3)$$

Within 95% confidence limits this is

$$11\,\text{m}^3\,\text{h}^{-1} < Q_0 < 28\,\text{m}^3\,\text{h}^{-1}.$$

This error is fairly large, despite the efforts made to improve the experiment.

2.2. Repeat tests

We carried out three more tests with the underfloor fan at different settings and all these data are plotted in Fig. 3.

The line is a linear regression calculated from the four points from data sets 2–5, with an R^2 (root mean square) of 0.8. Each of these data sets also gave 95% confidence limits, not shown here.

The straight line is given by

$$Q_u = 0.9 - 0.26.P_{\text{hut}}\,m^3\,h^{-1}$$

From this we predict the value of the flow at 50 Pa to be

$$Q_{n50} = 14\,\text{m}^3\,\text{h}^{-1} \quad (4)$$

with a 90% confidence interval of from 8 to 26 $\text{m}^3\,\text{h}^{-1}$.

2.3. Measuring the permeability of the radon pit sand

In order to compare the theoretical model to the measured flow rate from the radon pit, we needed to know the permeability of the sand. A sample of sand contained within a simple plastic pipe was measured. The air flow was provided by a compressed air cylinder, and the flow rate measured by both a rotameter, a hot wire and a hot bulb anemometer. All three were used partly to check on each other at the low flow rates needed, but also because they were being compared with each other anyway as part of another experiment. These flows were measured in a 100 mm diameter pipe; the sample was in a wider pipe to allow larger flows to be used.

This gives the result for the permeability as:

$$k = 1.3 \times 10^{-10}\,\text{m}^2 \quad (5)$$

This result is supported by a better measurement made at the National Radiological Protection Board, which from four measurements gave the average answer:

$$k = 0.9 \times 10^{-10}\,\text{m}^2 \quad (6)$$

Note that these experiments always contain some error due to the problem of the transfer of the sand from the pit to the laboratory. We do not know if the same porosity and moisture content were achieved in the laboratory, so there is inevitably some error. It is likely that the NRPB test involved better compaction of the sand, giving the lower permeability result.

3. Comparison of analytical and experimental results

3.1. The analytical result for the radon pit hut

The huts on the site were built on to a concrete ring beam which has dimensions as follows:

Full width of ring beam:	3.3 m
Horizontal thickness of beam:	0.58 m

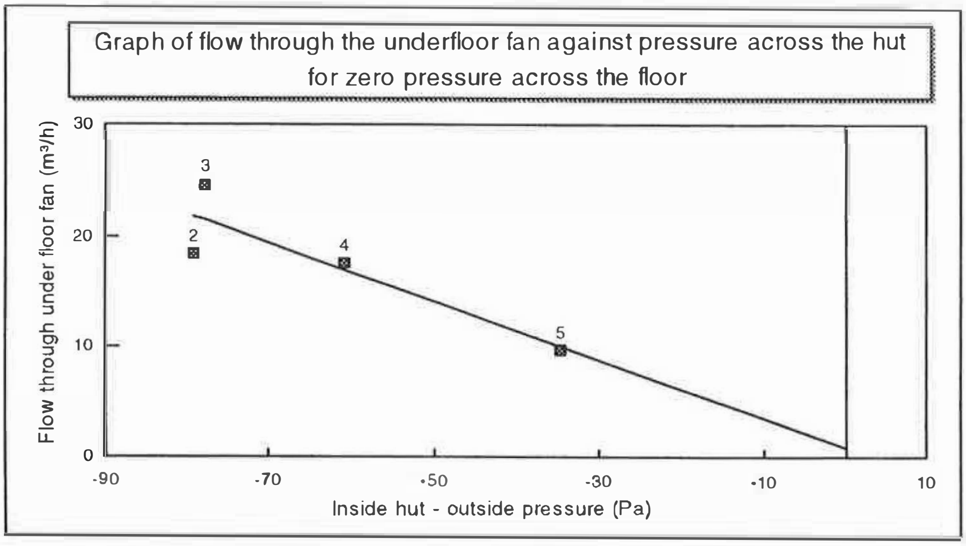

Fig. 3. Flow through the underfloor fan against the pressure across the hut.

Depth of beam: 0.4 m.

These can be used in the solution given in the previous paper [2], and the notation used below comes from that paper. From these the parameters from the Z plane are as follows:

$p = 1.07\,\mathrm{m}$

$q = 1.65\,\mathrm{m}$

$r = -0.4\,\mathrm{m}.$

Hence, $q/p = 1.54$ and $r/p = -0.374$.

From an iteration process with the numerical integration programme of [2] these same ratios of q/p and r/p are found to be given by

$a = 1, \quad b = 1.425, \quad c = 3.04 \quad \text{and} \quad d = 3.48$

Then, to find the flow rate, we use the value of d as the parameter m in Eq. (9) of [1] which gives the flow factor B as 0.6014 (from a numerical integration). Hence, using Eq. (14) of [1], the flow, Q, is given for a 50 (Pa) pressure difference, and with μ for air of 1.83×10^{-5} (Pa.s) by

$$Q = 3.3 \times 10^{6} \cdot \mathrm{k}(\mathrm{m}^3\mathrm{s}^{-1}\text{per meter run of wall}). \tag{7}$$

Since the internal length of the hut built on the ring beam is 2.14 m in each direction, this is multiplied by 4.28 to give the total estimated flow rate as

$$Q = 14 \times 10^{6} \cdot k\,(\mathrm{m}^3\mathrm{s}^{-1}) = 5 \times 10^{10} \cdot k\,(\mathrm{m}^3\mathrm{h}^{-1}). \tag{8}$$

Since the flow rate was predicted, Eq. (4), as 14 $\mathrm{m}^3\mathrm{h}^{-1}$ (range 8–26) using this in Eq. (8) suggests the permeability of the sand to be

$$K_{\text{sand-pit}} = 2.8 \times 10^{-10}\,\mathrm{m}^2. \tag{9}$$

But with the 90% confidence interval based on the uncertainty in the flow measurement being $1.6 \times 10^{-10}\mathrm{m}^2 < k_{\text{sand-pit}} < 5.2 \times 10^{-10}\mathrm{m}^2$.

This is typical for sands [7] and is close to that measured for the sand in the laboratory, Eqs. (5) and (6), which is of the order of $1 \times 10^{-10}\mathrm{m}^2$.

The cause of the difference is likely to be some or all of the following:

(1) Neglecting the corner effects in calculating the theoretical flow rate into the hut. The fact that the model assumes infinitely long walls means that the flow per metre is under-predicted near a corner. This is because the model only considered flow in two dimensions, and this is not true near the corner. The effect of this is difficult to calculate, but could be significant.

(2) The leakiness of the subfloor walls of the hut has been neglected in the theory. This means that all of the flow measured going through the fan has not necessarily come through the sand as has been assumed here. Hence the real flow through the sand at a given pressure will be less than measured, although the amount of the difference is hard to estimate.

(3) Leaks from the pipes used to measure the sand permeability in the laboratory. When the permeability of the sand was measured in the laboratory it is possible that some leakage occurred. This would suggest a greater rate of flow through the sand than actually occurs, resulting in a predicted permeability higher than the correct value.

(4) Uncertainty in the compaction and water content of the sand in the laboratory. The degree of compaction of a material, and its moisture content, affect the resulting permeability. In general a more compacted material has less air space within it, and so allows less flow through it for a given pressure. Hence, in measuring the permeability of a sample of sand, it is necessary to consider the degree of packing, and how this compares to conditions in the ground. It is likely that any sample of sand will be less compacted in the laboratory than in the ground, so that the laboratory will give a value of permeability higher than the 'real' one.

However, sand is relatively less prone to packing effects because of the small size of the particles, so that the effect due to compaction will be less than in some other materials. The moisture content also has an effect, with a high moisture content expected to decrease permeability by occupying the air space through which gas moves. If the tested sample is too dry it would be expected to give a high result, but if it is too wet it would probably be too low.

Points (1) and (2) would cause the calculated permeability to be less than the $3 \times 10^{-10}\mathrm{m}^2$ predicted, whereas point (3) would decrease the laboratory measured permeability. Point (4) could affect the permeability in either direction, and deserves further investigation. It is likely, however, that the first two effects will be larger than the others, which would decrease the prediction of permeability to closer to the laboratory result.

Overall the result is clearly very encouraging, and shows good agreement between the two methods of finding the permeability, well within the considerable errors involved in the experiments.

4. Comparing the analytical result with that of Landman and Delsante

The work closest to the result given in the earlier papers has been done by Landman and Delsante [4–6]. They were investigating the heat loss through a ground floor slab, but the solutions they produced, and the flow rate predictions they made can be transferred directly to gas flow. There are some differences in the boundary conditions between the two problems, but the physics is the same.

The technique used by them was to find a Fourier series solution to Laplace's Equation in each of a number of defined regions, and then match these at the boundaries between the regions. In general this results in an infinitely large number of simultaneous equations, to which an approximate solution can be found by assuming the terms beyond a certain number can be ignored. This gives a set of equations which can be solved by matrix inversion techniques.

They used this technique on a number of different problems of heat flow from a concrete floor, and how it is affected by positioning insulation at different places. In their first problem [4], they considered a thin vertical layer of insulation at the edge of the floor slab. They then considered a thin horizontal layer of insulation [5], and finally investigated a problem close to that of our conformal mapping result [2] with a region of insulation at the edge of the floor slab with both width and depth [6].

In order to compare the result found in this work, the solutions from the first and third papers by Landman and Delsante need to be combined. In all cases they assumed a linear fall in temperature from the inside of the house to outside. In the absence of insulation this assumption has a significant effect on the predicted flow rate. However, when there is insulation present, the difference caused by the simplifying assumption is not important.

Their geometry is given in Fig. 4. Note that δ is the width of the insulation material and d its depth, L the half width of the 'house', and 2ε the width of the wall. For all of these problems the units of length are arbitrary, provided they are self consistent. Region 4 is the insulation material, and regions 1, 2 and 3 are the soil, which is considered to be the same in each region.

The temperature distribution is given in the upper part of the diagram.

The most significant difference between the thermal and pressure problem is in the relationship between the conductivities of the different materials (for temperature)

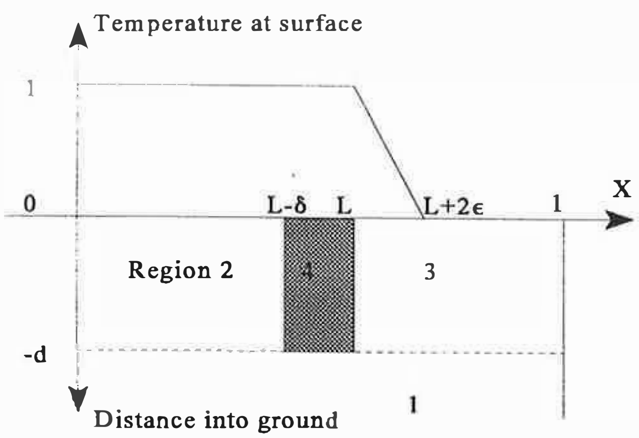

Fig. 4. Reproduction of Fig. 1 of Ref. [6].

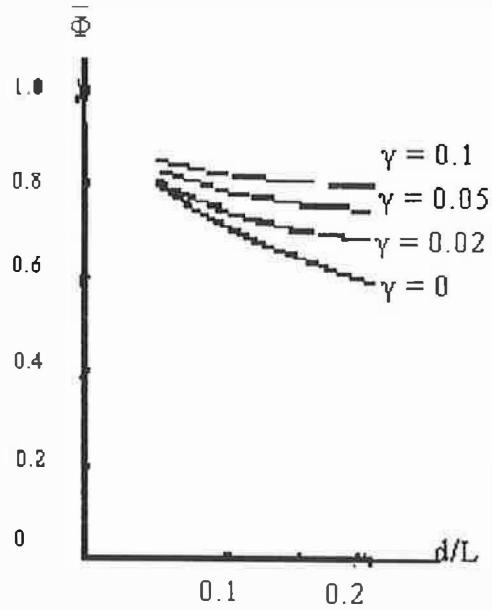

Fig. 5. Reproduction of Fig. 2 of Ref. [6]. Graph of normalised flux against the ratio of depth of insulation against building half width.

and the permeabilities (for pressure). The thermal conductivity of soil and concrete are assumed to be similar by Landman and Delsante, which is a reasonable approximation. However, the permeability of concrete is generally many orders of magnitude less than that of soil. Hence the comparison between the two modelling results is only reasonable because of the investigation of thermal insulation by Landman and Delsante. This has a very low thermal conductivity (not always treated as zero) which is equivalent to the zero flow assumed for the concrete in this work.

In [6] the rate of flow of heat through the floor is calculated for different parameters, and this is shown in their Fig. 2, reproduced here as Fig. 5.

The parameter γ used here is the ratio of the conductivity of the insulation to that of the soil. We wish to compare their solution with $\gamma = 0$, meaning a perfect insulant, which is what the concrete footing wall in the air flow case approximates to for air flow. Taking the case where their d/L is 0.2, their normalised flux is close to 0.6. The normalised flux is defined as the ratio of the flux with the insulation to that without it, i.e.,

$$\bar{\phi} = \frac{\phi}{\phi_0} \tag{10}$$

where ϕ is the flux with the insulation which is the answer we seek. The flux without the insulation ϕ_0 is given in [4 Eq. (18)] as

$$\phi_0 = \frac{2}{\pi}\left(\ln\left[\frac{L+\varepsilon}{\varepsilon}\right] + \frac{L}{\varepsilon}\ln\left[\frac{L+\varepsilon}{\varepsilon}\right]\right) \tag{11}$$

and the parameters have been defined for the figure above. Using the data given for the calculation by Landman and Delsante, the parameters are given as follows

$$L = 0.1, \quad d_L = 0.02, \quad \varepsilon = 0.002, \quad \delta = 0.0006.$$

Using these in Eq. (11) gives $\phi_0 = 3.133$, so that using (10)

$$\phi = 0.6 \times 3.133 = 1.88 \tag{12}$$

and this is used to define the total flow as

$$Q_T = \phi \Delta T k_s \tag{13}$$

where

Q_T = total heat flux ($\mathrm{Wm^{-2}}$ of wall),
ΔT = Temperature difference between inside and outside the building (K),
k_s = thermal conductivity of soil ($\mathrm{Wm^{-2}K^{-1}}$).

Hence the variable ϕ is equivalent to twice the variable B defined by Eq. (9) of Ref. [1], if the pressure difference is factored out of the expression for B.

Given the parameters defined above, it is possible to use the method of the previous paper [2] to find the value of B appropriate for the same geometry. The values of L, d and δ given above produce values of the parameters defined by Fig. 4 of the previous paper [2] as

$$p = 0.1, \quad q = 0.1006, \quad r = -0.02, \quad s = 0.$$

By iteration, using the integration code developed for the previous paper, these are given by the following set of parameters in the transformed plane:

$$a = 1, \quad b = 1.22, \quad c = 1.29, \quad d = 1.51.$$

This gives the key result that the ratio of d is 1.51 times a, which is equivalent to the parameter 'm' of Ref. [1] being 1.51. This gives a result for B as

$$\frac{B}{P_0} = 0.95 \therefore \frac{2B}{P_0} = 1.9 \tag{14}$$

The two results (12) and (14) agree well, indicating that the methods are producing the same result in this case. This gives considerable confidence in the method used here.

5. Conclusions

In this paper a method for measuring the flow rate through the soil below a building with no concrete oversite was described, and results presented. The technique will not be generally applicable because of the leakiness of most buildings, but could be of some use in measuring soil leakages.

The results of this experiment have been compared with the theoretical work discussed in previous papers, through the permeability they predict for the sand at the BRE radon pit. Considering the variability of permeabilities and the difficulty of measuring them accurately, the predictions compare well with a direct experimental measurement of permeability.

In addition, the overall flow rate has been compared with that predicted by a different theoretical method produced by other workers investigating heat flow. This produces a result in close agreement to that given by this work, suggesting that both methods give good answers.

It would be possible to use the modelling techniques discussed here and in the previous papers to generate an 'atlas' of standard shapes and their corresponding flow rates. This would apply to heat flow problems as well. It is left to future workers to continue studies in these areas.

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