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MODELLING THE INFLUENCE OF ACTIVE SUBSLAB DEPRESSURISATION (ASD) SYSTEMS ON AIRFLOWS IN SUBSLAB AGGREGATE BEDS

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Abstract — A simple model is presented that allows the pressure difference in a subslab aggregate layer to be estimated as a function of radial distance from the central suction point of an active subslab depressurisation (ASD) system by knowing the average size, thickness, porosity, and permeability of the aggregate along with the total flow rate. The flow regimes may span the range from fully developed turbulence, through the transition, to Darcian flow.

BACKGROUND

Active subslab depressurisation (ASD) systems used to reduce the levels of indoor radon are known to perform most reliably when a layer of aggregate such as coarse gravel is present under the slab. However, the performance of ASD systems has been observed to vary widely from one installation to another. Reliable models are needed to characterise the performance of ASD systems and to develop diagnostic procedures for designing and testing these installations. Because of accelerations and decelerations associated with the contorted flow paths in gravel beds, the inertial properties of the gas are exaggerated relative to flow in an open tube. Consequently, flows in porous media may exhibit non-Darcian behaviour at flow rates that would be laminar in open tubes where these accelerations would not occur.

MODEL DESCRIPTION

Flow in gravel beds is most easily modelled in cylindrical symmetry where the only component of flow is radial, e.g. Matthews *et al*[1]. The formulation used here is more along the lines of Gadsby *et al*[2] who simulated the flow in a large disc of gravel in the laboratory. It was surmised that the flow would be Darcian for Reynolds numbers less than about 1 and turbulent for Reynolds numbers greater than about 100.

For radial flow, the velocity and hence the Reynolds numbers vary with radial distance. Consequently, for large diameter discs, the nature of the flow changes from turbulent near the centre to laminar near the perimeter. In many cases, the bulk of the region of interest constitutes the transition region between turbulent and laminar flows. A number of empirical approaches[3–5] have been used to model the transition region between these two regimes. Following Gadsby *et al*[2], a power-law relationship between the pressure gradient and flow rate is assumed.

The Burke–Plummer equation[4] for turbulent flow in a packed column is applied near the central suction point, and Darcy's law is used at large radii. The empirical power law is used in the transitional region. Since the empirical expression contains an arbitrary constant, it will be chosen to match the gradients of the solutions at the Darcian transition. This transition will occur at a radius determined by specifying the critical Reynolds number. The equation describing the radial pressure profile becomes

$$
\begin{aligned}
P(r) = P(r_0) &+ \frac{3.5\rho}{2D_p}\left(\frac{q}{2\pi T}\right)^2 \frac{1-\varepsilon}{\varepsilon^2}\frac{1}{r_0}\left(1-\frac{r_0}{r}\right), \quad r_0 \le r \ge R_T \\
&= P(R_T) + \frac{\mu}{k_g}\frac{q}{2\pi T}\frac{1}{f-1}\left(\frac{R_d}{R_T}\right)^{f-1} \left[1-\left(\frac{R_T}{r}\right)^{f-1}\right], \quad R_T < r < R_d \\
&= P(R_d) - \frac{\mu}{k_g}\frac{q}{2\pi T}\ln\left(\frac{R_d}{r}\right), \quad R_d \le r \le R_L \qquad (1)
\end{aligned}
$$

where P(r) is the pressure at radius r, r is the radial distance from the centre of the suction point, r_0 is the radius of the suction hole in the gravel bed, ρ is the density of air, D_p is the average diameter of gravels, q is the flow rate, T is the thickness of the gravel bed, ε is the porosity of the gravel bed, R_T is the radial location of the Burke–Plummer transition, k_g is the permeability of the gravel bed, μ is the viscosity of air, f is the exponent in the power law ($1 < f < 2$), R_d is the radial location of the transition to Darcian flow, and R_L is the effective radius of the gravel bed. The first line in Equation 1 represents the Burke–Plummer equation, while the third line represents Darcy's law.

Consider an imaginary disc of nearly infinite radius filled with gravel. Then the transition region occurs between radii R_T and R_d. The exponent in the empirical power-law relation would vary from 2 at R_T to 1 at R_d. As a simple approach, suppose that the exponent varies linearly with Reynolds number or, equivalently, as the reciprocal of the radial distance. The parameter, f, in Equation 1 would then be the average value of this exponent between R_T and R_d or R_L, whichever is smaller. That is

$$f = 1 + \left(\frac{R_T}{R_d - R_T}\right)\left[\left(\frac{R_d}{R_L - R_T}\right)\ln\left(\frac{R_L}{R_T}\right) - 1\right], \quad R_d > R_L$$

$$= 1 + \left(\frac{R_T}{R_d - R_T}\right)\left[\left(\frac{R_d}{R_d - R_T}\right)\ln\left(\frac{R_d}{R_T}\right) - 1\right], \quad R_d < R_L \qquad (2)$$

The two transition radii are given by

$$R_T = \frac{\rho D_p}{\mu \varepsilon}\,\frac{q}{2\pi T}\,\frac{1}{Re_T} \qquad (3)$$

and

$$R_d = \frac{\rho D_p}{\mu \varepsilon}\,\frac{q}{2\pi T}\,\frac{1}{Re_d} \qquad (4)$$

where Re_T and Re_d are the critical values of Reynolds number at the turbulent and Darcian transitions, respectively. Most of the area under a slab would lie in the transition region between turbulent and laminar flows.

RESULTS

Comparisons of the predictions of Equation 1 with measured pressure profiles in aggregate beds under slabs are illustrated in Figures 1 and 2. These pressure profiles are induced by mitigation fans mounted on suction pipes penetrating the central portion of the slab. Values of the critical parameters used to make projections with Equation 1 are shown in Table 1. These quantities are all either measured or calculated by the four equations, except for k_g which is chosen to match predictions with measurements at a single arbitrarily selected point. Values of additional parameters that were estimated to be about the same for all these cases are: ρ = 1.22 kg.m^{-3}, D_p = 0.0254 m, T = 0.10 m, ε = 0.5, and $\mu = 1.7 \times 10^{-5}$ kg.m^{-1}.s^{-1}. In Figures 1 and 2 the curves represent predictions of Equation 1 while the symbols represent measured values. Figure 1 shows pressure profiles in subslab gravel layers in

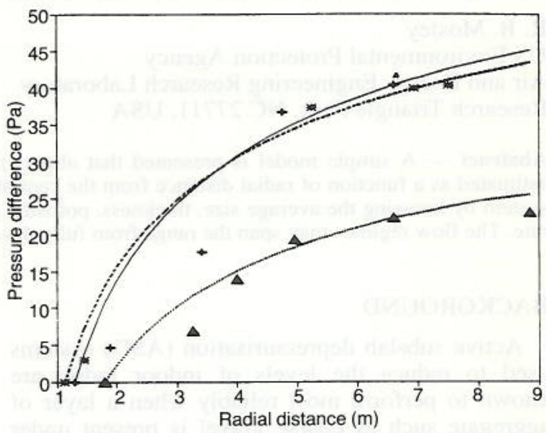

Figure 1. Subslab pressure profiles for three basement houses with gravel layers. Curves represent model predictions and symbols represent measurements: (▲, ...) a, (*, ---) b, (+, —) c.

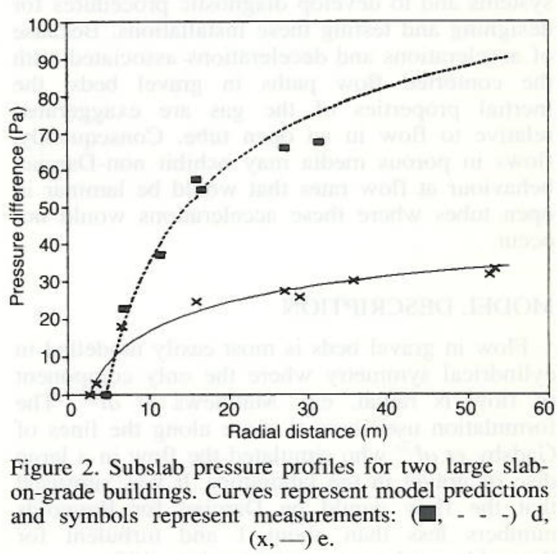

Figure 2. Subslab pressure profiles for two large slab-on-grade buildings. Curves represent model predictions and symbols represent measurements: (■, - - -) d, (x, —) e.

Table 1. Parameters used to compute theoretical curves.

Parameter	a	b	c	d	e
k_g (10^{-7} m^2)	2.69	1.00	1.19	0.25	3.93
f	1.427	1.381	1.415	1.333	1.160
q (m^3.s^{-1})	0.031	0.0195	0.0222	0.111	0.100
R_T (m)	1.8	1.13	1.29	4.83	2.74
R_d (m)	180	113	129	483	274

three typical basement houses. The experimental values have been adjusted so that both the predicted and measured pressures are referenced to the pressure at the predicted turbulent transition location given by Equation 3. Consequently, only the transitional region is illustrated. The only parameter that has been chosen to improve the agreement of the predictions with measurements is k_g. The exponent, f, which determines the shape of the curve is computed from Equation 2. A better illustration of the pressure profiles is provided by the much larger slabs shown in Figure 2. The effective diameters of these slab-on-grade buildings are up to seven times that of typical residential buildings.

According to Table 1, the effective permeability of the gravel bed under building d is about an order of magnitude smaller than that of building e. This difference in permeability is the most important factor influencing the large differences in pressures. A sample of the same gravel as used under building e was tested in the laboratory by Princeton University. The laboratory value of permeability was 6×10^{-7} m^2 compared with 3.9×10^{-7} m^2 from Table 1. However, when this value is adjusted for the laboratory measurements of porosity (0.45), the permeability becomes 5.3×10^{-7} m^2 which differs by only 12% from the laboratory measurement. This is the only instance in this study for which there are independent confirmatory measurements.

DISCUSSION AND SUMMARY

By knowing the average size, thickness and porosity of the aggregate bed, along with the total flow rate, the present model allows one to determine the shape of the pressure–flow relationship. If the permeability of the gravel bed is also known, the pressure–flow relationship is determined. This simple model appears to provide an adequate description of the flow in subslab aggregate beds. In order to describe ASD's influence on radon entry, this model should be coupled to a model for flow through the soil and the slab.

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