VENTILATION SYSTEM PERFORMANCE

11th AIVC Conference, Belgirate, Italy
18-21 September, 1990

Paper 26

PREDICTION OF THE PERFORMANCE OF VARIOUS STRATEGIES OF SUBFLOOR VENTILATION AS REMEDIAL ACTION FOR RADON PROBLEMS

P. Cohilis, P. Wouters, D. L'Heureux

Belgian Building Research Institute
Rue d'Arlon 53/10
1040 Brussels - Belgium

ABSTRACT

In order to reduce the convective flow which is the principal responsible for the high indoor ^{222}Rn concentrations, several mitigation technics have been developed and used in many countries. Since they don't always respond as expected, there is a need of instruments helping in their design and their evaluation. This paper suggests the use of a numerical code, based on the finite difference method, for the evaluation of ^{222}Rn mitigation strategies in dwellings. It is supposed that ^{222}Rn transport from soil into a dwelling occurs mainly by pressure-driven air-flow. The programme used calculates the pressure fields under the buildings, supposing a laminar air-flow in the soil and adopting the steady-state condition. Clear graphic outputs are delivered. The results of sample calculations are presented in order to illustrate the possibilities of the code. These calculations concern a house without basement, with an entry route for soil-gas : the floor-wall joint. A particular subslab depressurization system is included in the calculations. The code appears to be a powerful tool for the prediction and the evaluation of the performances of subfloor ventilation strategies.

1. INTRODUCTION

Radon (^{222}Rn) is a radioactive noble gas which decays by alpha-emission with a half-life of 3.8 days. It is the unique gaseous element (at normal temperature) of the ^{238}U natural radioactive decay family, whose elements are present all over the earth's crust with concentrations which vary as a function of the nature of the soil. The fact that ^{222}Rn is chemically unreactive under normal conditions implies that as soon as it is produced by the disintegration of radium (^{226}Ra, another element of the ^{238}U family), the ^{222}Rn atom is free to move away from its place of birth. In the soil, the fraction of radon atoms that succeeds in escaping to the exterior of the solid medium - the emanating fraction - will be mixed with the soil gas present in the pore space. Then, the ^{222}Rn atoms can move throughout the void space and, because of their relatively large half-life, a part of them will reach the soil-air interface. This transport of radon is related to two distinct mechanisms : molecular diffusion and forced flow (pressure-induced flow).

It is known that radon can be trapped in the interior of buildings, where it can reach elevated concentrations (much above the concentration outdoors) : ^{222}Rn produced in the soil, near the building foundations, migrates inside the building by a combination of the two mechanisms mentionned above. However, it is believed that forced air flow through the soil and across the building substructures is, in most cases, the principal responsible of the high indoor ^{222}Rn concentrations[1]. This forced flow is induced either by climatic conditions (such as wind and stack effects) and operational conditions (use of exhaust ventilation, HVAC system, ...) which create pressure fields favoring soil-gas infiltration through any opening (cracks, construction joints, ...) that connects the house, particularly the basement, with the underlying soil or rock. Other factors affecting these indoor radon concentrations are the radon production in soil and the physical characteristics of the soil, especially the permeability which affects the soil-gas entry rates[1, 2].

In order to reduce the flow of air through the building substructure, several techniques have been used during the last decade : sealing of entries, basement pressurization, soil depressurization, ...[3]. For example, it is well known that a fan-and-pipe system that depressurizes the layer of soil or gravel immediately below the substructure can reduce the entry of radon. However, it seems that a large number of such mitigation systems do not perform up to expectations, and there are many cases of houses which remain above the recommended radon level after subslab-depressurization[4].

So it is clear that there is a need of instruments helping in the design of radon-mitigation systems and in the evaluation of the performances of various strategies of subfloor ventilation as remedial action for radon problems.

We are presently involved in a CEC program dedicated to the modelling of the entry of radon from soil into dwellings, through the basement, to better perform remedial actions[5]. Within this framework, we need instruments allowing us to model the pressure field around the basements. In the present paper, we examine the possibility of using a three-dimensional finite difference code (which solves any kind of linear flow models)[6] to calculate pressure-driven flow rates in the ground, taking into account some environmental conditions (like soil permeabilities and outdoor-indoor pressure differences) and some structural conditions (cracks and joints in the basement, presence of a mitigation system, ..). The program we use runs on a PC and delivers very simple and useful graphical outputs (2 and 3 dimensions) so it could be particularly well suited for practical evaluations of mitigation systems performances.

2. MODELS OF RADON ENTRY FROM SOIL INTO RESIDENTIAL BASEMENTS BY PRESSURE-DRIVEN FLOW

As far as we know, much work has been done concerning the molecular diffusion transport mechanism (see e.g.[10], [11]), but only a few papers are devoted to the modelling of radon transport by pressure-driven air flow through the soil. Nevertheless, the approximation of a negligible diffusion is generally good, and the forced flow mechanism is believed to be the major factor responsible for high ^{222}Rn indoor concentrations. In fact, diffusion can be neglected if[1] :

$$\frac{k\,\Delta P}{\mu} >> \frac{D_e}{\varepsilon} \qquad (1)$$

where :
k [m^2] is the soil permeability,
ΔP [Pa] is the driving pressure difference,
μ [Pa.s] is the dynamic viscosity of air,

ε is the soil porosity and
D_e [m^2/s] is the effective diffusion coefficient of radon in the soil pores.

In reference [1], W.W. Nazaroff applied a combination of analytical and numerical methods to the problem of computing ^{222}Rn transport by pressure-driven air flow from soil into a dwelling having a basement. The building was represented by a very idealised physical system. The steady-state ^{222}Rn transport in the soil was described by a set of equations expressing the conservation of air mass in the soil pores, Darcy's law, and the radon activity balance in the soil pores. It was shown that for small flow rates of air through the soil, the radon entry rate into the basement increases in proportion to the outdoor-indoor pressure difference ΔP at the soil level. For large flow rates, the entry rate increases with $\Delta P^{2/3}$. It was also shown that soil with ordinary radium (^{226}Ra) content can cause high indoor radon concentrations if it is even moderately permeable (say $k \sim 10^{-10}\ m^2$), because of this pressure-driven air flow. Results of this work are essential for our understanding of the radon entry process. However, the method employed in order to calculate the pressure field in the soil pores is of a limited interest for practical extensions : it is an analytical calculation, so one needs to consider very simple and probably unrealistic geometries (basement, cracks, joints, ...).

T.A. Reddy *et al.*[4] addressed themselves to the general problem of modelling the pressure-induced air flow below the slab, in order to calculate pressure fields and to optimize the design of subslab depressurization systems. More specifically, they proposed a mathematical formulation for modelling the pressure field induced by a single suction point, with the particular hypothesis that air flows radially through a porous bed contained between two impermeable disks (one of them being the concrete slab, the other a very impermeable soil bed) centered at the suction point. The authors pointed out that the nature of the subslab air flow, under operation of mitigation systems, is related to the nature of the subslab medium : turbulent flow conditions will generally prevail through subslab gravel beds, whereas laminar flows are likely to occur in houses having soil (no gravel) below the concrete slab. They specially concentrate on a model predicting analytically the pressure field of turbulent flows in homogeneous circular porous beds (gravel) when suction is applied at the centre of the circle.The model coefficients of the pressure drop versus flow were determinated empirically for different types of gravels. For the laminar case, Darcy's law was used in the calculations. Here again, as in reference [1], the calculation of analytical solutions restricts the configurations for which pressure fields can be predicted. However, some of the authors are presently working to see how their simplified model and their empirical coefficients could be used by professional mitigators, for practical purposes, in a large number of situations[8].

In the work of C.O. Loureiro[7], numerical methods were used to solve the basic equations of a model which simulates the steady-state transport of radon from soil into houses with basements under constant negative pressures. The model simulates the generation and decay of radon within the soil, its transport throughout the soil due to diffusion and convection induced by the pressure disturbance applied at a crack in the basement, its entrance through the crack and the resultant indoor radon concentration. It supposes a steady-state condition, a fixed geometry (a house with a basement and a crack at the wall-floor joint in the basement), a constant indoor-outdoor negative pressure applied at the crack and a laminar flow through the soil (Darcy's law holds). Two three-dimensional finite difference computer programs were used to solve the mathematical equations of the model. It was concluded that the most important parameters involved in the transport of radon into the house are the soil permeability (k), the inside-outside pressure difference and the ^{226}Ra concentration in the soil particules. For a pressure difference of 5.0 Pa, it was shown that the entry rate of radon into the house was dominated by diffusion for $k \leq 1.0\ 10^{-12}\ m^2$ and by convective transport for $k \geq 1.0\ 10^{-12}\ m^2$, in which case the indoor radon concentration was found to be strongly dependent (almost linerarly) on the soil permeability. Among other results, we note that the indoor radon concentration was found to be directly (though not linearly) related to the pressure difference. The fact that the two programs of reference [7] used numerical methods for solving the basic equations of the model allows one to treat problems related to more realistic configurations (irregular boundary conditions, ...). However, these programs are related to the geometry considered by their author. To adapt them to other configurations (different crack geometries, presence of one or several subslab depressurization pipes with different possible geometries, ...) would be a hard task for professional mitigators who wants practical and rapid advices for the design and the evaluation of mitigation systems applied to each particular building type.

3. THREE-DIMENSIONAL FINITE DIFFERENCE CALCULATIONS

As it was said above, radon from the ground is the principal accountable for buildings high indoor radon concentrations. For moderate or high soil permeabilities (say $k \geq 10^{-12}$ m^2), the radon entry rate depends primarily on the possibilities of air entering the building from the soil, by convection, and it was shown that the indoor radon concentration depends directly on the indoor-outdoor pressure difference. So it seems reasonable, when evaluating the performance of a mitigation system, to concentrate on the effect of such a system on the air flow rates between the ground and the building and to calculate the pressure fields below the building, especially around any opening connecting it with the underlying soil. In order to perform such calculation, one needs to know the model relating the air flow per unit cross-sectional area to the pressure gradient. According to T.A. Reddy *et al.*[4], air flow should generally be laminar when soil (instead of gravel) is present under the slab. In this case, Darcy's law holds :

$$\vec{v} = -\frac{k}{\mu} \vec{\nabla} P \qquad (2)$$

where

$\vec{v}$ [m/s] is the Darcian velocity,

k [m^2] is the permeability,

μ [Pa.s] is the dynamic viscosity and

$\vec{\nabla}P$ [Pa/m] is the pressure gradient.

As this is a linear relation, we have decided to use the numerical code TRISCO[6], based on the finite difference method, which solves any kind of linear flow models (like three-dimensional heat transfer problems for example). This program runs on a PC-compatible under MS-DOS and achieves high performance, is user-friendly, provides high capacity (up to 60 000 nodes) and has a clear graphic output. An important merit of the code is the simple data structure, allowing one to describe even complex geometries in a fast and easy way. Note that the steady-state condition is adopted, for reasons of simplicity and reduction of computing costs; in fact, for most purposes, one can say that flows stabilise relatively quickly after a change in pressure[2].

As an input to the code, one has to formulate the problem, ie., describe the geometry (the object must be decomposed in homogeneous, beam shaped blocks), soil and material permeabilities and boundary conditions. One also has to select a grid of nodes, for discretisation purposes, which consists of perpendicular planes. Test calculations have been done for the following geometrical configuration : the soil block is represented as a parallelepiped in the centre and upper part of which there is a house, also considered as a small parallelepiped . This house has no basement and there is only one entry route for soil gas into the house : a gap located at the joint between the floor-slab and the wall, along all the perimeter of the slab. A subslab depressurization system is represented by a vertical pipe, through the slab, connected to an horizontal pipe situated just below the slab. The system is located at the center of the house floor. This configuration is presented in figure 1.

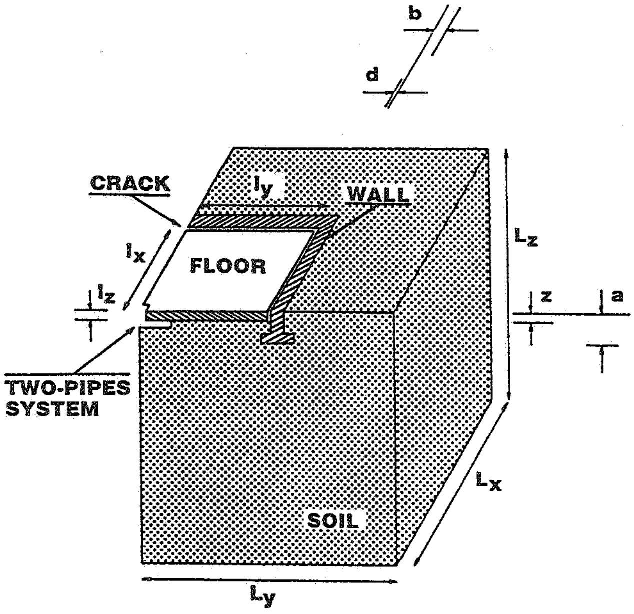

Figure 1 : Geometrical configuration adopted for the first set of calculations (see text)

In fact, only one quarter of the geometrical configuration is presented in the figure, because of the symetry in the plane parallel to the floor slab. Calculations have to be done only in this reduced configuration and are, in this case, greatly simplified. Of course, it is also possible to consider non-symetrical situations and a greater number of cracks and depressurization pipes. All those details can be defined to the program in a very friendly way. However, the number of nodes necessary to discretisate the problem and the calculation time will depend on the complexity of the configuration.

The calculations suppose implicitely that the soil is isotropic with respect to permeability. The pressure at the soil surface was assumed to be uniform and constant. The indoor pressure was also supposed uniform and constant, at a slightly lower value than the outdoor pressure. The same situation was assumed to hold for the two-pipes system, but with a greater pressure difference with regard to the outdoor pressure. Concerning the crack, it can be shown[9] that the air-flow through the crack is related to the pressure difference by the following expression :

$$\Delta P = A.Q + B.Q^2 \qquad (3)$$

where :
ΔP [Pa] is the pressure drop
Q [m^3/s] is the volume flow rate and
A and B are constants for a given crack.

With values of A and B given in the work of P.H. Baker *et al.*[9] for the crack geometry considered here it appears that, for the typical pressures of our problem, the evolution of Q with ΔP (predicted by expression (3)) can be modeled by a linear relation similar to expression (2). So it is also possible to define a permeability for the crack, which allow the program to calculate the pressure field inside the crack.

Table 1 presents the soil and building parameters used in the first set of calculations. During these calculations the entire soil block was supposed homogeneous with respect to a fixed value of the permeability (see table 1). Figures 2 and 3 present the results of these calculations for a difference of -50.0 Pa (fig. 2) and -100.0 Pa (fig. 3) between the outdoor pressure and the two-pipes system pressure. These figures illustrate some of the output possibilities of the code. The solid isobar line corresponds to -3.0 Pa (the difference between outdoor and indoor pressures). A comparison of figures 2 and 3 immediately indicates that for the considered mitigation system, a pressure difference of -50.0 Pa is not sufficient to ensure that the soil immediately below the floor-slab is at a lower

Soil permeability	10^{-10} m^2
Crack permeability	6.2 10^{-8} m^2
Floor and wall permeability	10^{-15} m^2
Pressure difference (building)	-3.0 Pa
Pressure difference (two-pipes system)	-50.0 Pa or -100.0 Pa
Soil block dimensions	$L_x = 9.62$ m $L_y = 10.70$ m $L_z = 5.0$ m
Floor-slab dimensions	$l_x = 4.22$ m $l_y = 5.30$ m $l_z = 0.15$ m
Wall characteristics	a = 0.80 m b = 0.30 m
Crack depth	$z = l_z = 150.0$ mm
Crack with	d = 1.0 mm
Vertical pipe dimensions (mm)	70 x 70 x z
Horizontal pipe dimensions (mm)	70 x 140 x 1200

Table 1 - Soil and building parameters used in the first set of calculations (see also figure 1)

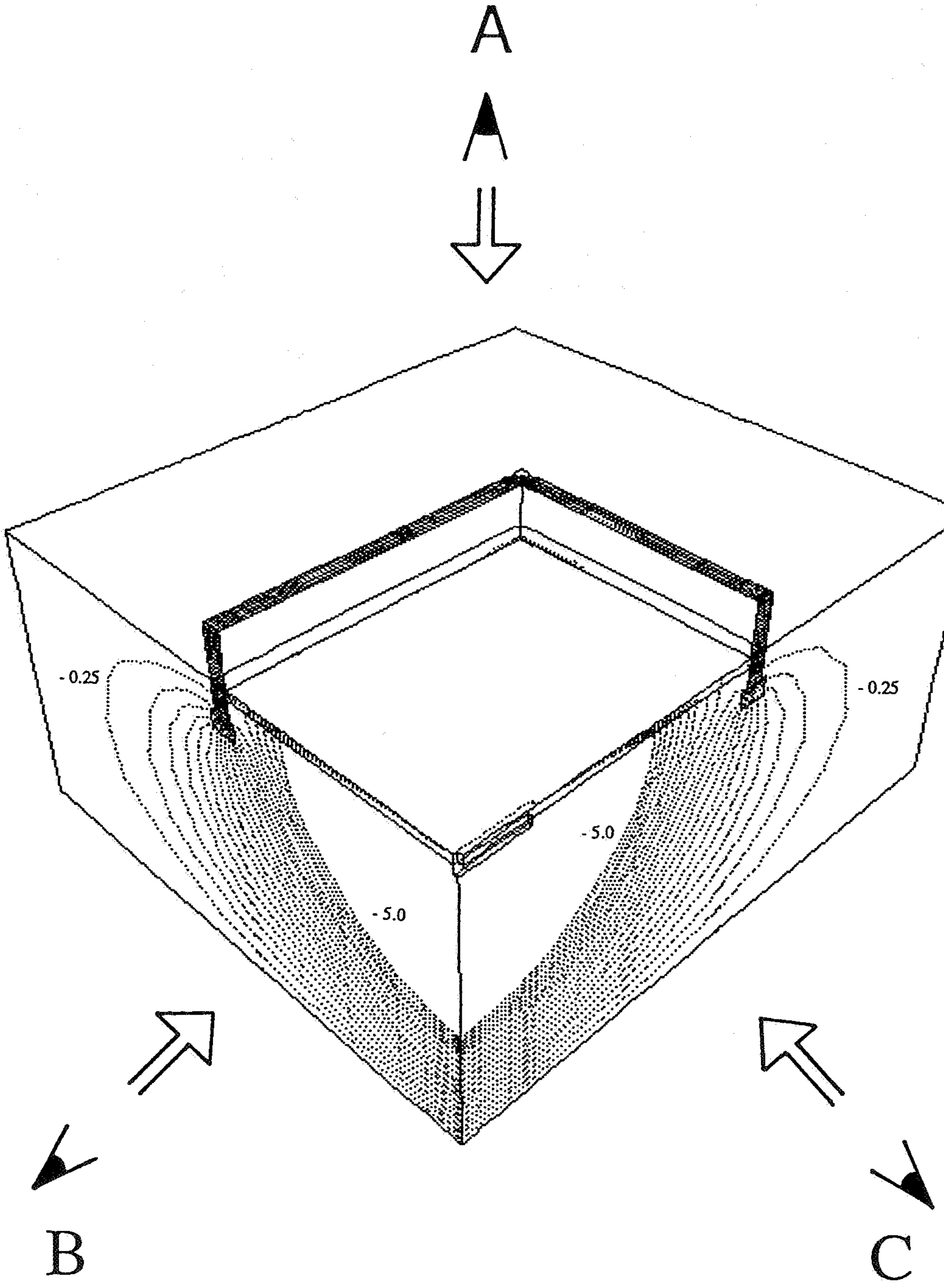

Figure 2.a. : Isobars (Pa) in the soil for a pressure difference (two-pipes system) equal to -50 Pa : three-dimensional view of the configuration (see table 1 for the soil and building parameters used in the calculation). For reasons of clarity only the isobars between -5.0 Pa and 0.0 Pa are presented, with a step of 0.25 Pa.

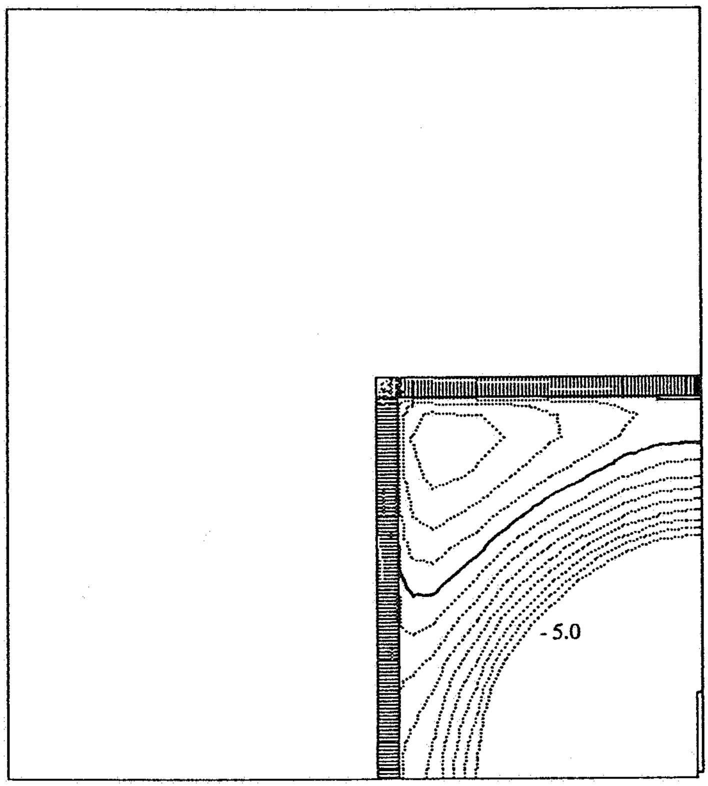

Figure 2.b. : Isobars : view A (immediately below the floor-slab, see fig. 2.a.)

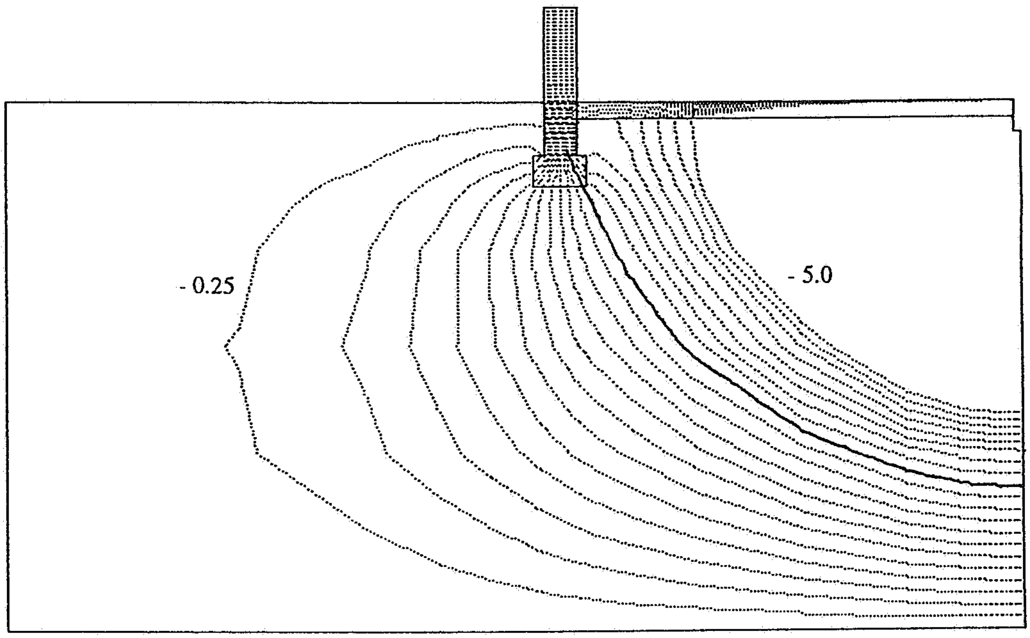

Figure 2.c. : Isobars : view B (see fig. 2.a)

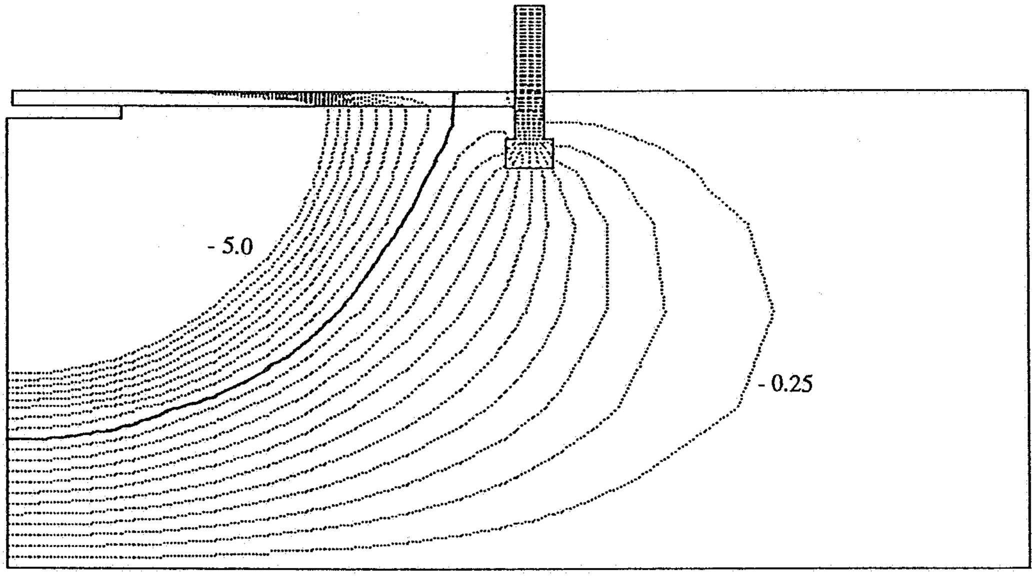

Figure 2.d. : Isobars : view C (see fig. 2.a.)

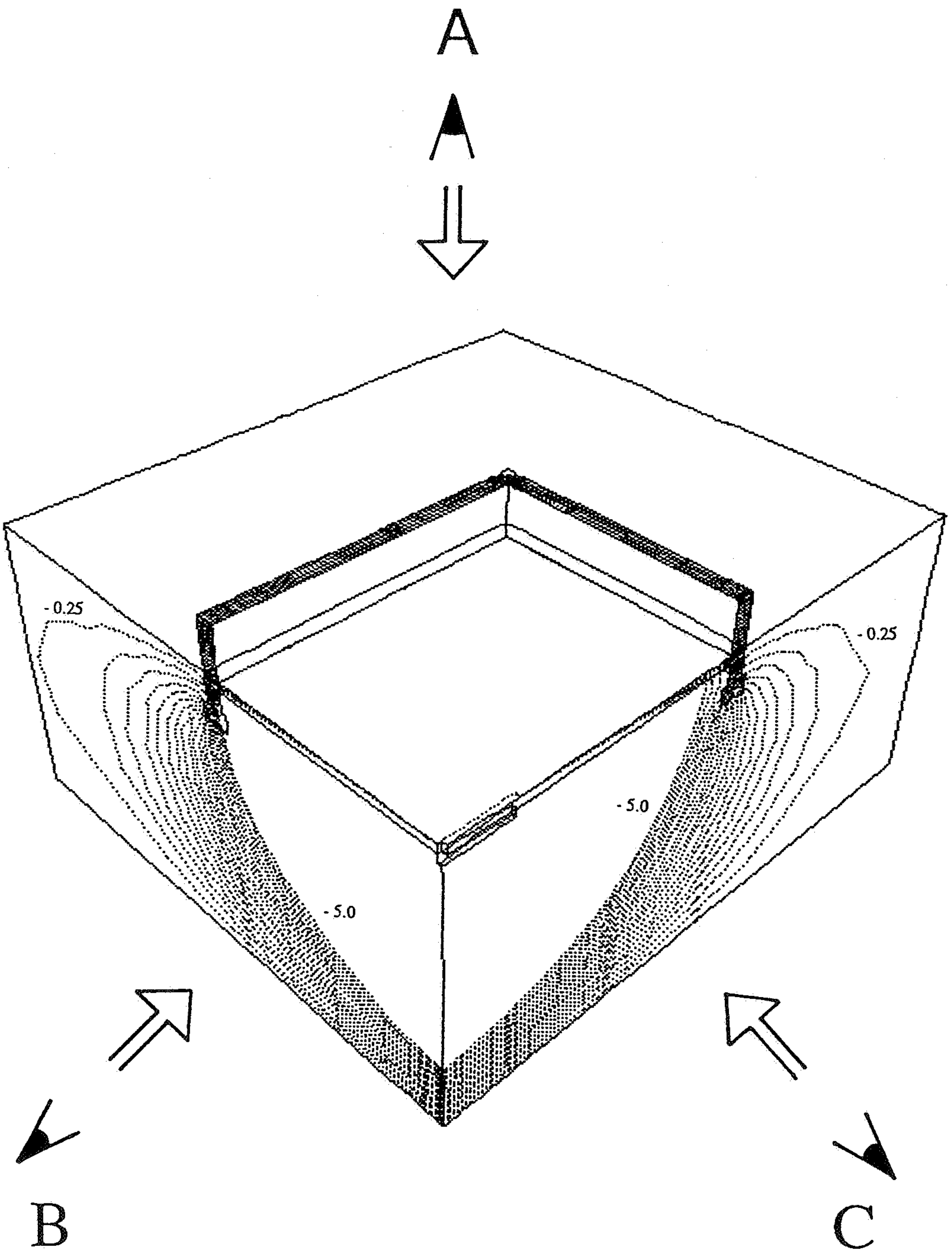

Figure 3.a. : Isobars (Pa) in the soil for a pressure difference (two-pipes system) equal to -100 Pa : three-dimensional view of the configuration (see table 1 for the soil and building parameters used in the calculation). For reasons of clarity only the isobars between -5.0 Pa and 0.0 Pa are presented, with a step of 0.25 Pa.

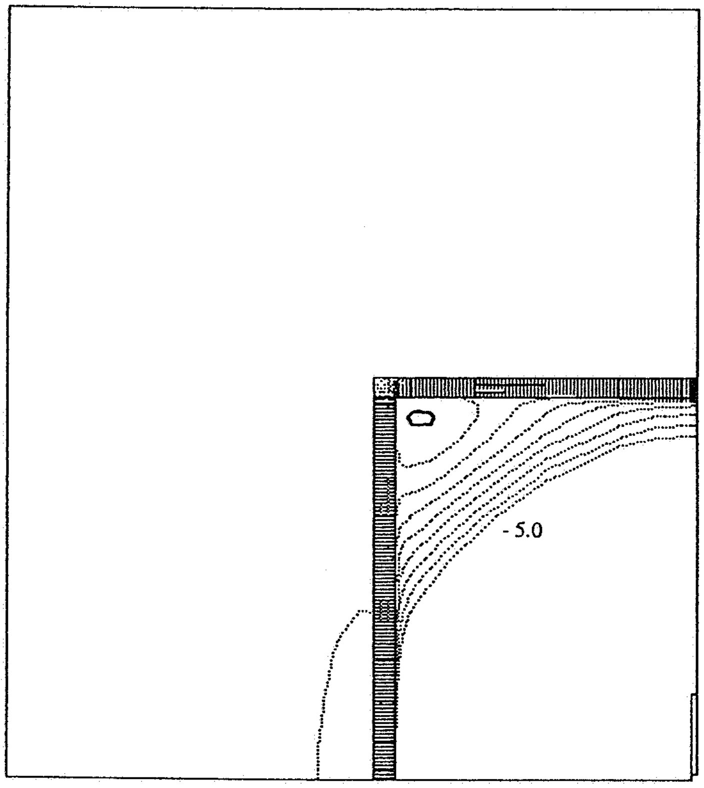

Figure 3.b. : Isobars : view A (immediately below the floor-slab, see fig. 3.a.)

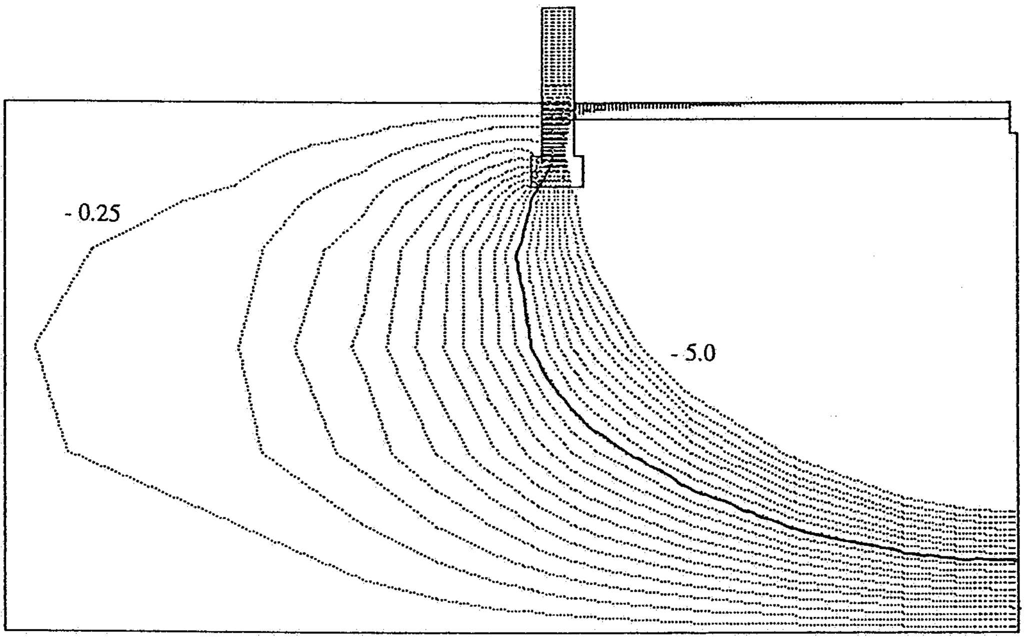

Figure 3.c. : Isobars : view B (see fig. 3.a)

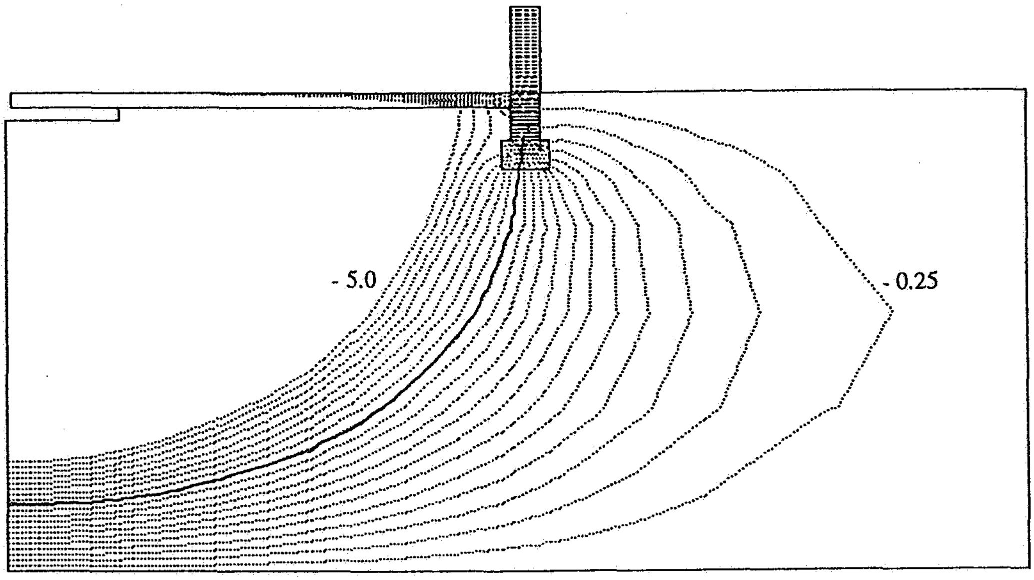

Figure 3.d. : Isobars : view C (see fig. 3.a.)

pressure than the indoor pressure, especially around the corners. Figure 3 indicates that if the pressure difference is set to -100.0 Pa, the situation looks much better from the point of view of the ability of the mitigation system to avoid the penetration of the soil-gas inside the house. Of course, an alternative solution would be to adopt another mitigation system : several suction points located closer to the corners for example. All those alternative mitigation strategies may be easily simulated and evaluated with the code TRISCO.

In figures 4 and 5 we present another calculation illustrating the possibilities of the programme. For this second calculation, we have adopted the same geometrical configuration and the same mitigation system than for the first set of calculations. However, it is supposed that a layer of gravel is present just below the floor-slab. This layer is separated from the soil by a plastic foil located just below the horizontal pipe of the mitigation system. Figure 4 illustrates this situation. All the parameters were set as in table 1, and the difference between the outdoor pressure and the two-pipes system pressure was fixed to -100.0 Pa. The permeability of the gravel was supposed to be ten times greater than the soil permeability. We must stress that it may be delicate to consider much greater values for the gravel permeability because of the implicit hypothesis of a laminar flow adopted by the programme. For pratical purposes, the plastic foil was supposed to be one centimeter thick, with a permeability equal to 10^{-12} m^2.

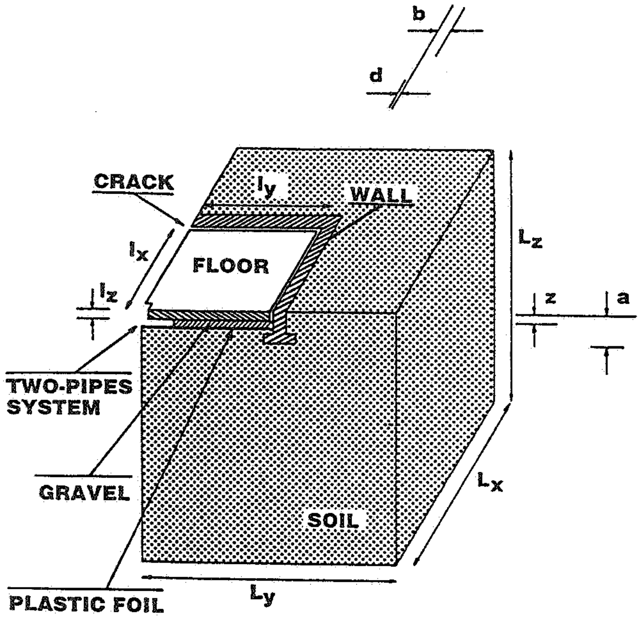

Figure 4 : Geometrical configuration adopted for the second calculation (see text)

Figure 5 presents the results of this calculation. The solid isobar line corresponds to -3.0 Pa. It appears, as expected, that the situation looks even better than for the case presented in figure 3 from the point of view of the performances of the mitigation strategy.

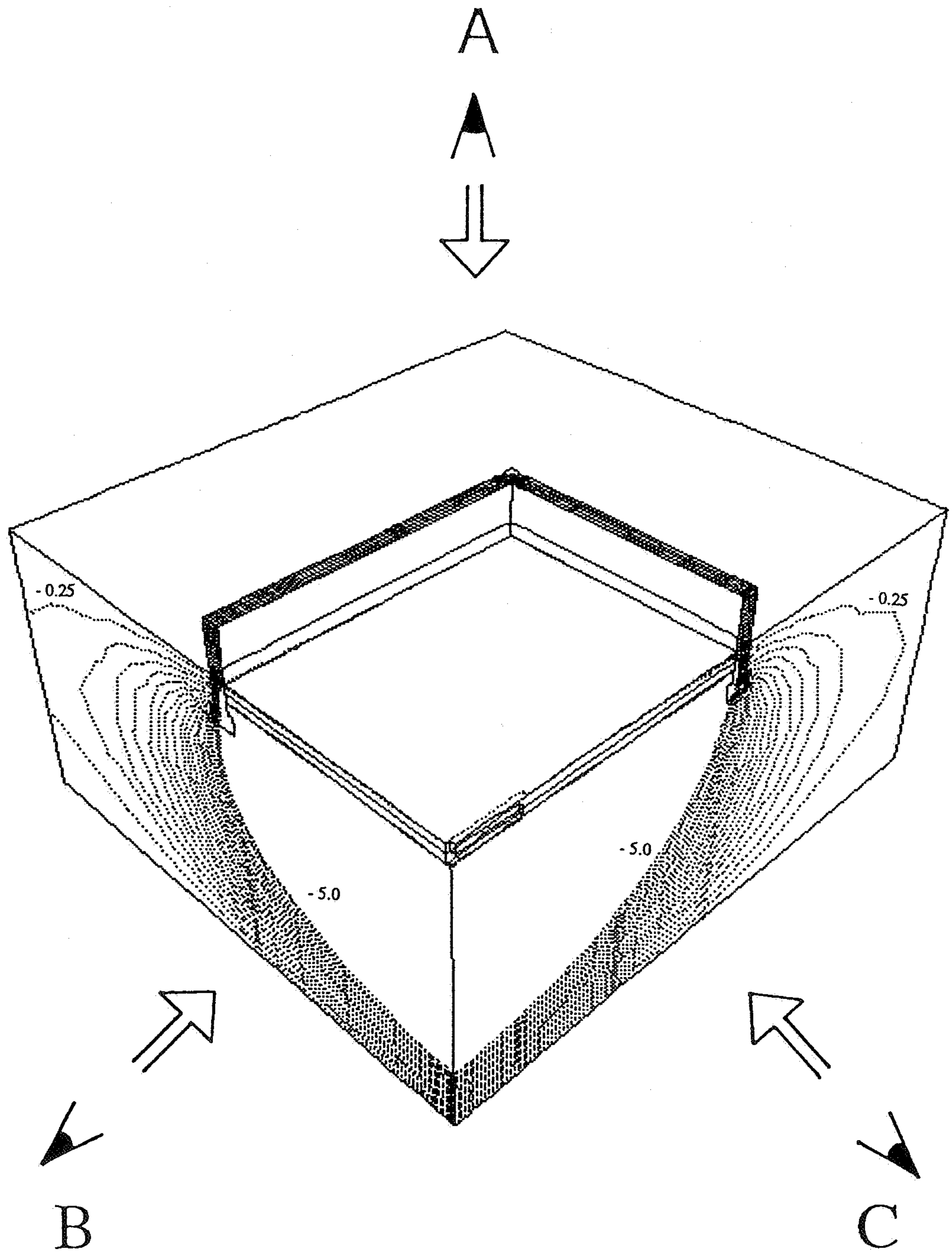

Figure 5.a. : Isobars (Pa) in the soil for a pressure difference (two pipes system) equal to -100 Pa : three-dimensional view of the configuration (see text for the soil and building parameters used in the calculation). For reasons of clarity only the isobars between -5.0 Pa and 0.0 Pa are presented, with a step of 0.25 Pa.

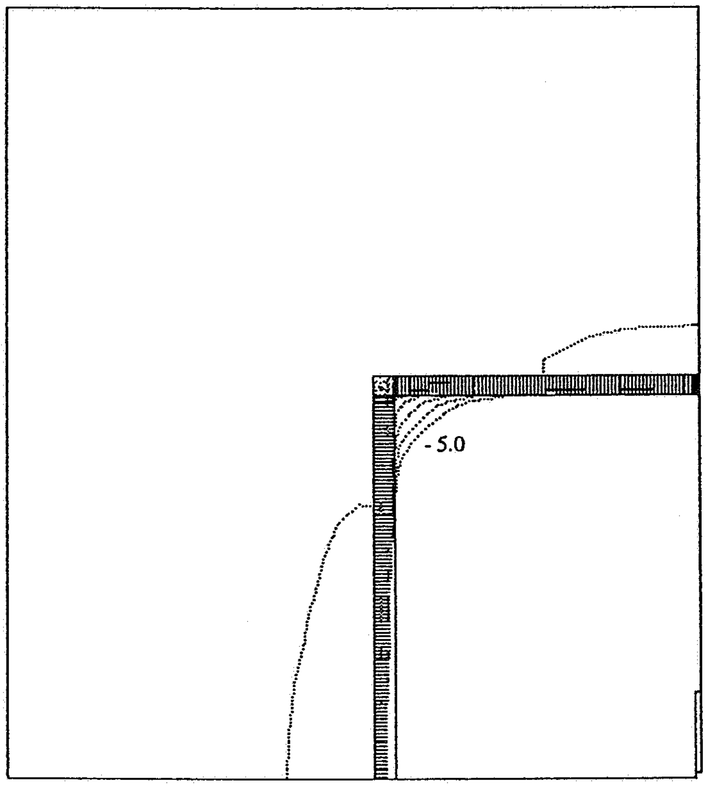

Figure 5.b. : Isobars : view A (immediately below the floor-slab, see fig. 5.a.)

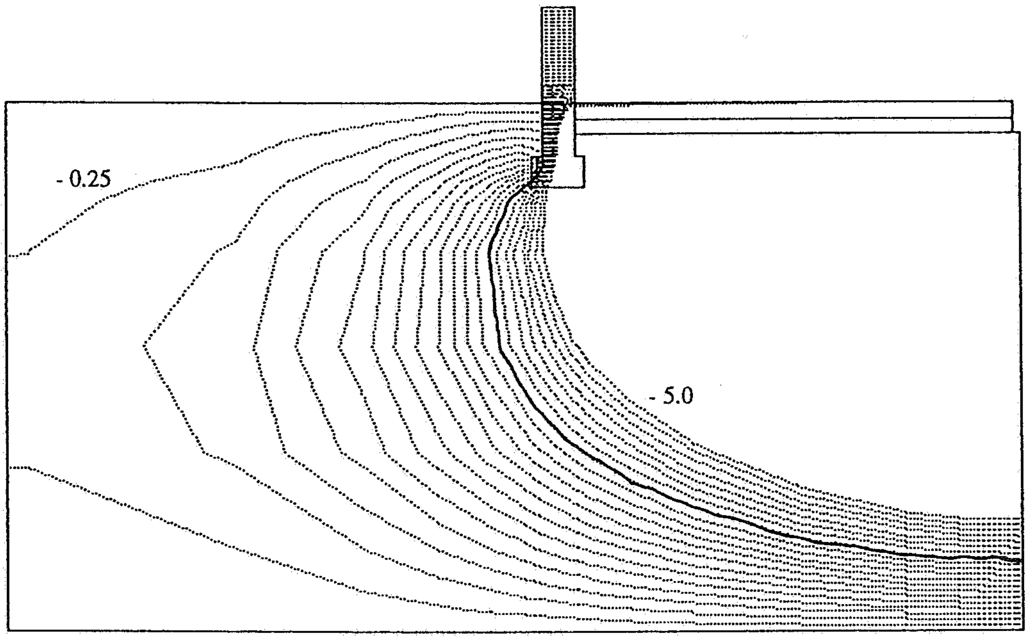

Figure 5.c. : Isobars : view B (see fig. 5.a)

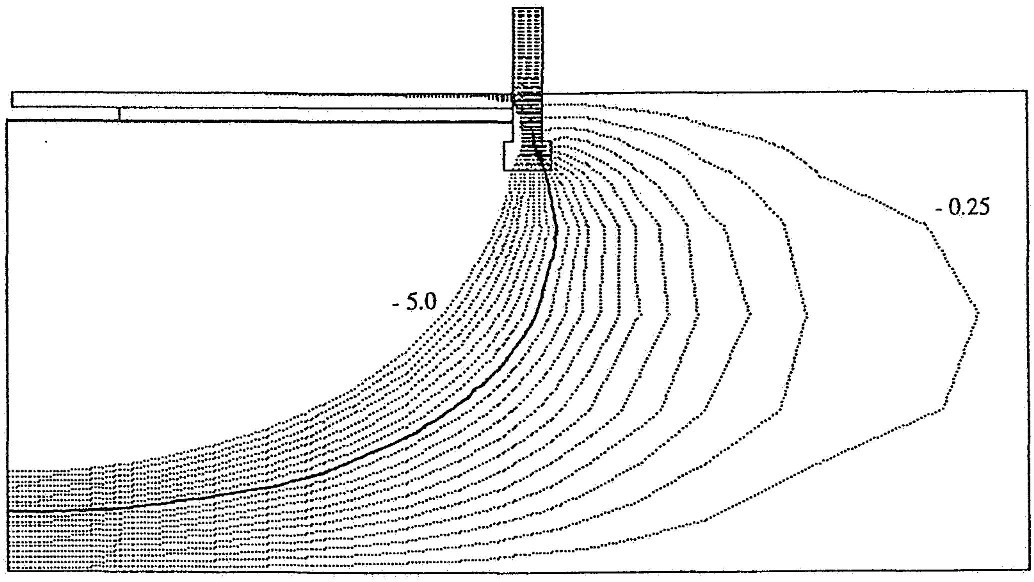

Figure 5.d. : Isobars : view C (see fig. 5.a.)

The calculation time depends on the complexity of the configuration. For cases similar to those presented here, typical calculation times are 10 hours for a 80486/33MHz system and around 100 hours for a 80286/10MHz system.

4. SUMMARY

There is a need for instruments helping in the design and the evaluation of radon mitigation systems in dwellings. This paper suggests the use of a three-dimensional computer code, based on the finite difference method, to perform such evaluations.

-With the hypothesis that the pressure-driven air flow through the soil is the major factor responsible for high ^{222}Rn indoor concentrations, the used programme calculates the pressure fields under the floor-slab. It allows the control of the ability of mitigation systems to avoid the penetration of the soil-gas into the house.

The sample calculations presented in the paper illustrate the possibilities of the programme. Because one can take into account all the details of the configuration in a very simple way, and because of the simple and useful graphical outputs (2 and 3 dimensions), the code appears to be particularly well suited for practical evaluations of mitigation systems performances.

As it is implicitly supposed that the linear Darcy's law holds, it has to be kept in mind that a particular hypothesis is made about the nature of the air flow under the slab : it is supposed to be laminar. This is the case when soil with not too large permeabilities (say $k < 10^{-9}$ m^2) is present under the slab. However, it is believed that this is not a too serious limitation to the usefulness of the proposed approach, because the cases for which the design of a mitigation system may be the most delicate are probably those for which soil (instead of gravel) is present under the slab.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. D.T. Harrje, Dr. A. Poffijn and Dr. H. Vanmarcke for fruitful discussions.

This work was partially supported by the Commission of the European Communities.

REFERENCES

[1] W.W. Nazaroff, "Predicting the rate of ^{222}Rn entry from soil into the basement of a dwelling due to pressure-driven air flow", Radiat. Prot. Dosim. 24, 199 (1988)

[2] A.V. Nero and W.W. Nazaroff, "Characterising the source of radon indoors", Radiat. Prot. Dosim. 7, 23 (1984)

[3] L. Hubbard, K. Gadsby, D. Bohac, A. Lovell, D. Harrje, R. Socolow, T. Matthews, C. Dudney and D. Sanchez, "Radon - Entry into detached dwellings : house dynamics and mitigation techniques", Radiat. Prot. Dosim. 24, 491 (1988); D. Saum, A.B. Craig and K. Leovic, "Radon mitigation in schools", ASHRAE journal, January-February 1990.

[4] T.A. Reddy, H.E. Black, III, K.J. Gadsby, D.T. Harrje, and R.G. Sextro, "Modeling air flow dynamics through a homogeneous gravel porous bed using subslab depressurization", Princeton University, PU/CEES Report n° 246, January 1990.

[5] CEC contract n° PL 890087, "Radon sources, Models and Countermeasures".

[6] TRISCO-software is a programme developed and commercialised by Physibel, Maldegem, Belgium.
P. Standaert, "Twee- en driedimensionale warmteoverdracht : numerieke methoden, experimentele studie en bouwfysische toepassingen", Katholieke Universiteit Leuven, Thesis, 1984; "Evaluation des effets des ponts thermiques", CSTC-revue, n° 1, cahier n° 4, 1989.

[7] C. de Oliveira Loureiro, "Simulation of the steady-state transport of radon from soil into houses with basements under constant negative pressure", Ph. D. Thesis, Lawrence Berkeley Laboratory, LBL Report n° 24378, May 1987.

[8] K. J. Gadsby, T.A. Reddy, R. de Silva and D.T. Harrje, "A simplified modelling approach and field verification of airflow dynamics in SSD radon mitigation systems", Princeton University, private communication.

[9] P.H. Baker, S. Sharples, I.C. Ward, "Air flow through cracks", Build. and Environ., 22, 293 (1987)

[10] K. Brown, P.J. Dinbylow and P. Wilkinson, "Modeling indoor exposure to natural radiation," Radiat. Prot. Dosim. 7,91 (1984)

[11] R.F. Holub, R.F. Droullard, T.B. Borak, W.C. Inkret, J.G. Morse and J.F. Baxter, "Radon- 222 and ^{222}Rn progeny concentrations measured in an energy-efficient house equipped with a heat exhanger", Health Phys. 49, 267 (1985)