1994_28

MODELING OF THE SUB-SLAB DEPRESSURIZATION (SSD) RADON MITIGATION SYSTEMS FOR LARGE STRUCTURES

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ABSTRACT

There are several Active Soil Depressurization (ASD) computer based models that have been specifically designed and calibrated for residential structure ASD system applications and mitigation practices. Large structures encountered in large buildings are significantly different than residential structures and consequently different treatments are required. Considerations for substantially larger slab sizes, slab shape, foundation type, construction soil, slab openings and other differences need to be accounted for in the design and operation of a Sub-Slab Depressurization (SSD) system for large building installations. A mathematical model that is based on the solution of both soil gas mass conservation and pressure driven flow equations in porous media is utilized. A computer code is developed using the model to simulate the operation of the SSD system for large slab on grade structures that are constructed on low permeability soil and fill materials. Finite difference techniques are employed to numerically solve the three dimensions partial differential equations of the model. Large structure features are compensated in the set of the model boundary conditions. The computer code is capable of predicting the pressure filed extension in the soil volume underneath the slab utilizing multi-suction points and different SSD operating considerations. It is also allows for examination of different SSD design parameters including the size and shape of the suction pit(s) and/or matting.

INTRODUCTION

Active Soil Ventilation and Depressurization (ASV&D) systems are based on creating a low pressure area underneath the structure so that radon-rich soil gas may be transported into the low pressure area and exhausted outdoors instead of penetrating into the building interior. ASV&D systems applications have been pointed into four designs that are based on the structure features to provide the maximum soil gas removal, these are Drain Tile Ventilation, Block-wall Ventilation, Isolation and Venting of Area Sources, and Sub-Slab Depressurization (EPA 1988). Drain Tile Ventilation systems are used for houses having slabs with drain tile loops built for water drainage. The system efficiency is strongly dependent on the degree of loop integrity. The system creates low pressure field in the soil under and around the structure by maintaining depressurization in the footing drain tiles. Block-Wall Ventilation System provides depressurization in a hollow-block foundation type to draw soil gas from the soil into the outdoors. The house must be constructed with such foundation and the void network is reasonably connected. The system efficiency is highly affected when major wall opening, that reduce wall integrity, and slab cracks are exist. Isolation and venting of source area applications are utilized for crawl space structures when crawl space ventilation is not preferred, slab on grade and basement structures with major cracks that are difficult to seal. The system application required identification of the source, isolation of the source from the building interior, and the application of depressurization in the isolated area.

Generally, Sub-Slab Depressurization (SSD) systems are by far the most effective and widely used active soil depressurization system. In this system, depressurization is established under the slab by drawing suction on pipes installed into the soil/fill/aggregate area. Highly permeable materials are used as pits and matting connected to the end of the suction tube to provide better pressure filed distribution and prevent blocking of the suction tube. The success of the SSD system is dependent on the extent to which negative pressure can be maintained under the slab area. This parameter is usually referred to as the pressure field extension (PFE).

The success of SSD system installations in residential structure has been well documented and approved. Currently, however, only limited information is available for large building applications. Compared to residential structures, documentation of the SSD performance in large buildings is much more complicated due to limited availability of structures, the uniqueness of the structure, limited research works, limited experiences in radon mitigation practices, magnification effects of the structure features such as slab size, slab shape, foundations, soil and fills, slab penetrations and openings, and the effects of the operation of the building support systems such as the heating, ventilating and air-conditioning (HVAC) systems. Credit for using the SSD systems in large building radon mitigation is being increased, however, in many cases the reduction of indoor radon levels needs to be achieved by combined effects of other systems operation such as the HVAC systems. In this context, EPA recommended three radon prevention techniques for construction of schools and other large buildings: (1) installation of an ASD system, (2) pressurize the building using the HVAC system, and (3) sealing of major radon entry routes (EPA 1993).

In this work, a mathematical modeling for the SSD systems for large building radon mitigation application is introduced. The model is based on the soil gas mass balance and pressure driven flow in porous medium. A finite element solution is provided to transfer the model into a programmable computer format. A computer algorithm is developed to utilize the model in predicting the PFE under large slabs and different suction matting orientation. The sets of boundary conditions that may be used to study the effects of large building features are discussed.

THEORETICAL CONSIDERATIONS

Radon (Rn-222) may enter the building interior from the sub-structure soil area by convective and molecular diffusion. Pressure-driven transport is the most dominate radon contribution. Radium content building materials may emanate radon that contribute to the indoor radon concentration. Contribution from water may also occur when radon dissolved in water became airborne during water activities inside the building. The contribution of the last two sources has rarely been found to be the cause of elevated indoor radon concentration. Therefore, in this treatment only the convective radon component is considered.

The time rate of change in position of a fluid particle in porous medium can be expressed by the change in its velocity. If a differential volume of dV is considered in the soil, the mass conservation equation of the soil gas in this volume can be established. Considering cartesian coordinate the net mass flow rate leaving the differential volume in a specific direction can be expressed by the change of the fluid velocity in the same direction. Neglecting the effect of gravity,

$$q_i = \rho(\delta v_i/\delta_i) dV \qquad (1)$$

were i is x, y, or z direction, ρ is the density of soil gas (Kg/m^3) and it is assumed to be independent on the gas position, q_i is the soil gas net mass flow rate (Kg/s) in i direction, and dV is the differential volume (dx.dy.dz) in m^3.

A simple differential volume in cartesian coordinate is a cube of six equal faces. Eqn. 1 expresses the net flow rate of the gas in the differential volume, that is, it compensates for the inward gas mass flow rate into the volume and the outward mass flow rate out of the volume. The net flow out of the six faces of dV can then be expressed as,

$$q_v = -\rho(\delta v_x/\delta x + \delta v_y/\delta y + \delta v_z/\delta z)\ dx\ dy\ dz \qquad (2)$$

The negative sign indicates that this mass flow rate algebraically contradicts the accumulation of the gas mass in the differential volume. Applying the mass conservation principle, the time rate of change of the soil gas mass in dV, the accumulation rate, must equal to the net mass flow rate out of the volume. The mass of the soil gas in the differential volume can be expressed as,

$$m=\rho\epsilon dV \quad (3)$$

were m is the soil gas mass (Kg) and ϵ is the ratio of volume of void space to the bulk volume of porous medium, or porosity. The time rate of change of m is then,

$$q_A=\delta m/\delta t=\delta\rho/\delta t \ \epsilon \ dx \ dy \ dz \quad (4)$$

were q_A is the accumulated mass flow rate (Kg/s) in the differential volume. To satisfy the mass conservation principle, the quantity q_A and q_v must be the same,

$$-\rho(\delta v_x/\delta x+\delta v_y/\delta y+\delta v_z/\delta z) \ dx \ dy \ dz = \delta\rho/\delta t \ \epsilon \ dx \ dy \ dz \quad (5)$$

Considering the steady state situation, Eqn. 5 reduces to,

$$\delta v_x/\delta x+\delta v_y/\delta y+\delta v_z/\delta z = 0 \quad (6)$$

This equation governs the relation among the spacial change in the soil gas velocity components. To represent the pressure under the slab for the purpose of estimating the PFE, Darcy's law can be employed to relate soil gas velocity into pressure. Darcy's law may be written as,

$$v=-(1/\mu)[k].\nabla P \quad (7)$$

were [k] is the 3D intrinsic soil permeability (m^2) matrix, μ is the soil gas viscosity (Kg/s.m), and ∇P (Pa) is the pressure gradient. For isotropic soil permeability, [k] is simply k. If the expression of the velocity in Eqn. 7 is substituted into Eqn. 6, then,

$$(\delta^2/\delta x^2+\delta^2/\delta y^2+\delta^2/\delta z^2).P = \nabla^2 P =0 \quad (8)$$

Eqn. 8 governs the steady state pressure condition in porous medium.

ALGORITHMIC CONSIDERATIONS

The 3D linear partial differential equation above need to be converted into algebraic equations suitable for algorithmic application. The latter equation along with boundary conditions can then be simultaneously solved to predict the PFE for different structure configurations. Utilizing a control volume approach the soil system volume is divided into a number of non-overlapping equally spaced control volumes for simplicity. The value of the dependent variable (P) is calculated in the center of the control volume and assumed to stay constant over that volume. Each center of a control volume is represented as a node in the soil system and can be located by its coordinates (x,y,z) values. The pressure values are called by the indices i,j,k that correspond to the coordinates x,y,z, respectively. Figure 1 illustrates the control volume approach and related coordinates.

Applying the finite element technique into the control volume in Figure 1, the value of the first derivative of the variable P in x-direction can be approximated as,

$$\delta P/\delta x = [P(x+h,y,z)-P(x,y,z)]/h \quad (9)$$

were h is the distance in the x-direction between the center of the control volume and the next volume. Similar expressions could be written for y and z directions. The finite element approximation to the second derivative of P in x-direction is,

$$\delta^2P/\delta x^2 = [P(x+h,y,z)-2P(x,y,z)+P(x-h,y,z)]/h^2 \qquad (10)$$

If the distance h adapted between the current control volume and the adjacent volumes in y and z direction. And by substituting similar approximation for both second derivatives in y and z direction in Eqn. 8, the pressure at node i located at (x,y,z) is,

$$P(x,y,z) = (1/6)\ [P(x+h,y,z)+P(x,y+h,z)+P(x,y,z+h)+P(x-h,y,z)+P(x,y-h,z)+P(x,y,z-h)] \qquad (11)$$

Eqn. 11 can be programmed for calculating the PFE developed by the SSD system. The value of the pressure at any node point is the average of the six-node pressures in the control volumes adjacent to the node in three dimensions. This treatment assumes incompressible soil gas as implied with the use of constant density in the previous section. It is also assumes a constant (no-deformation) control volume in the soil system.

The algorithm is constructed using a set of indices to control the pressure calculations, locate the boundary conditions, and control the iterations. A mesh generator is used to develop the node network in the solution volume V_s limited with the slab length L, slab width W and selected soil depth D. The number of node generated dependent on the selected space (h) between nodes and the solution volume. The indices i,j,k are used to represent nodes in x,y, and z direction respectively. The range of the indices are,

$$\begin{aligned} &i=0 \text{ to } (L/h)\\ &j=0 \text{ to } (W/h) \qquad (12)\\ &k=1 \text{ to } (D/h)+1 \end{aligned}$$

Pressure calculations are performed in the horizontal planes controlled by indices i,j from 1 to (L/h)-1 and 1 to (W/h)-1 respectively. The pressure values at the slab edges, represented by the i, j limits in Eqn. 12 are assumed zero. This treatment represent the first set of boundary conditions that can be used in the solution. Special pressure values can be assigned, as constants, and used as boundary conditions attached to specific index value representing special foundation features, barometric pressure variations, or possibly wind effects. Index k=1 represent the horizontal layer immediately underneath the slab, and calculations are performed to the depth k=(D/h). Index k value of (D/h)+1 is the horizontal layer at the depth h after the last calculations and all pressure nodes in i,j are assumed equal to zero. Nodes for full i,j range with index k=0 are reserved for boundary conditions representing slab penetrations and features.

The algorithm starts with initial pressure value of zero at all nodes. The pressure is then updated in one node located at i,j,k=1,1,1 with a positive pressure increment. The value of the increment can be arbitrary selected, however, it must not produce any negative pressure values. After the first iteration, this increment is controlled by the program. In each iteration the pressures in all nodes are calculated and then flow rate calculations are performed into and out of the control volume specified by the boundary conditions. All air flows into the soil system (solution volume V_s) are calculated from the updated pressure values in each iteration and compared with the air flow out of the SSD suction tube(s). When the difference between the both flows reach less than 1% , the iteration stops and the last pressure calculations are transferred into the program output files. Figure 2 illustrates the flow chart of the program.

RESULTS AND DISCUSSION

Although the theoretical treatment of modeling the SSD system for large buildings is similar to residential structures, there are many differences in the model development, programming structure and applications. In large buildings, the slab size and shape encounter more complicated mesh generation requirement to produce reasonable resolution in the PFE calculation. This may be cause a problem in computation memory and run times. Therefore, it is generally requires larger memory be made available to handle the large size subscript variables, better calculation subroutines and better data handling and process acceleration to improve the run time. The program needs to be structured in a way that can incorporate a wider variety of structure features encountered in large buildings compared with residential structures. Such requirements may dramatically change the programming process of the SSD model.

It is important to handle boundary conditions. Most of the large building features are in fact encountered by the use of boundary conditions. Basic boundary conditions have been applied in the solutions illustrated here. These are: (1) pressures of all nodes start with zero and stay constant (steady state) after the last iteration in the program. (2) Pressure values for all nodes purposely connected into the suction tube(s) using high permeability materials, such as Rn matting, are constant and equal to the suction pressure. (3) Nodes located immediately below the slab have only five-face flow instead of six except for those labeled for suction tube, suction matting, and/or cracks. This condition is represented for the case of no air flow from the concrete slab. (4) Pressure nodes located on or after the outer surface of the solution volume have pressure values of zero.

Slab and poured concrete wall cracks may also need to be included in the model application for large buildings. Although such consideration is not utilized in this work, cracks can be implemented with the same index structure of the program as a boundary conditions. If such selected, the flow across the cracks can be calculated by,

$$Q=K.A.(\Delta P)^n \tag{13}$$

were Q is the flow rate through the crack (m^3/s), A is the effective leakage area (m^2), K is a constant of 1.29 and n is the slope of the line generated by log-log plotting of the measured flow rate vs. differential pressure. The quantity of additional air added into the solution volume will then be contributed by the cracks air leakage. This contribution is calculated for each node pressure updated provided that the crack effective leakage area was inputed into the program. The location of the crack, including its length specification, is entered by specifying the corresponded nodes at level index k=0 for slab on grade structures. Differential pressure across the cracks can be calculated as the difference between the updated node pressure and the barometric pressure above the slab.

In some cases improvement in the algorithm running time can be made by accelerating the updated nodes pressures by starting non-zero initial pressure values so the number of iterations required to solve the same configuration is reduced. Utilization of such acceleration was made in this work by calculating the pressure values at each grid node using an analytical model developed by Hintenlang and Barber (1991),

$$P(r)=P_o\{1-[(1-r_o/r)/(1-r_o/r_s)]\} \tag{14}$$

were P is the initial pressure value in the soil system at a distance r from the suction pressure location, P_o is the applied suction pressure, r_o is the radius of the suction pit, and r_s is the radius of a circular slab. The model in Eqn. 14 was developed for a circular slab with a centrally located suction hole and required pressure to drop to zero at the edge of the slab. In this treatment initial pressure values were calculated for nodes located in a semi-hemispherical shape volume with a radius less than the nearest distance between the suction tube location or the matting index and the slab edge. Nodes located out of this volume are kept with initial pressure condition of zero.

Figure 3 illustrate the program output of PFE map for a slab on grade structure of approximately 30.5x30.5 meters (100x100 feet) with one suction tube located at the center of the slab, and a matting located at the center of the slab and extended 10 feet to both sides parallel with the x-axis. The SSD system provides suction at the tube-mat contact of 400 Pa. The soil is assumed homogenous with constant permeability. Figure 4 illustrates the PFE map generated by the same SSD system for the same slab in Figure 3 but with different suction location and matting orientation. In this figure the suction tube located in the upper right quarter of the slab at feet from each edge, the matt is layed out from the suction tube and down to 30 feet from the opposite slab edge, parallel to y-axis. Figure 5 illustrates the change of the absolute ratio of the difference between the air flow into the soil system and the air exhausted by the SSD system to the first difference plotted vs. the iteration number for the both cases above. This graph illustrates how the solution approaches the steady state equilibrium values of the pressures in the soil system.

Figure 6 illustrates the contour map of the PFE for the same SSD configuration of Figure 3 with a loop foundation wall of 5 feet depth.

CONCLUSIONS

Modeling of the Sub-Slab Depressurization systems for indoor radon mitigation applications in large buildings require much more complicated approach than the modeling for residential structures installations. Theoretical basis to model a pressure field extension developed by an SSD installation can be performed by substituting the soil gas velocity expression in porous medium, based on Darcy's law, into the steady state mass conservation equation of the soil gas in a specific volume in the soil system under the structure. Solutions to the pressure variable in the partial differential equation govern pressure field in the soil system can be carried out by using a finite element technique. A computer algorithm then can be developed to predict the PFE for particular configurations. Hardware and software requirements are needed to execute large numbers of grid points in order to improve the solution resolution, minimizing the number of iterations, and reducing the computational time. Special attention must be given to the set of boundary conditions used in applying the model into large buildings. Most of large building features can be analyzed by employing suitable boundary condition into the algorithm. Due to the limited availability and access into large buildings, with regard to indoor radon mitigation applications, utilization of the computer model can be of great benefit. Such utilization can provide aids in the SSD design for large buildings by specifying the required amount and best location(s) of the applied suction, optimizing the SSD operation, and analyzing large building features and their effects on the SSD system performance and operation.

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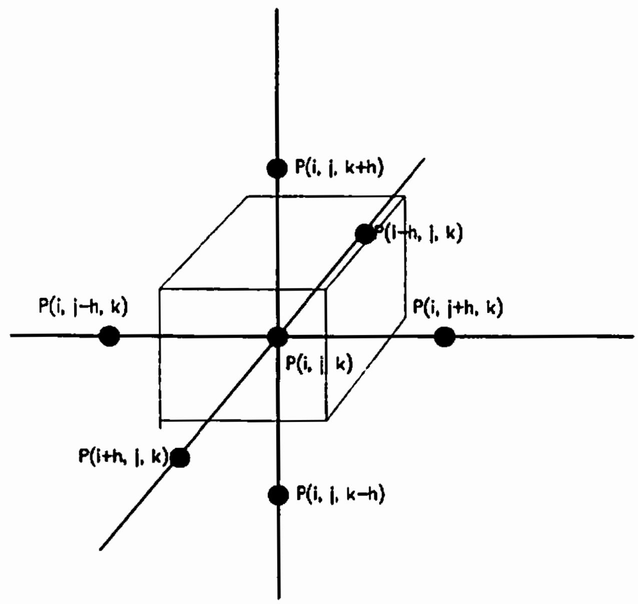

Fig. 1: The Differential Volume Element Used in The Control Volume Approach For The SSD Modeling.

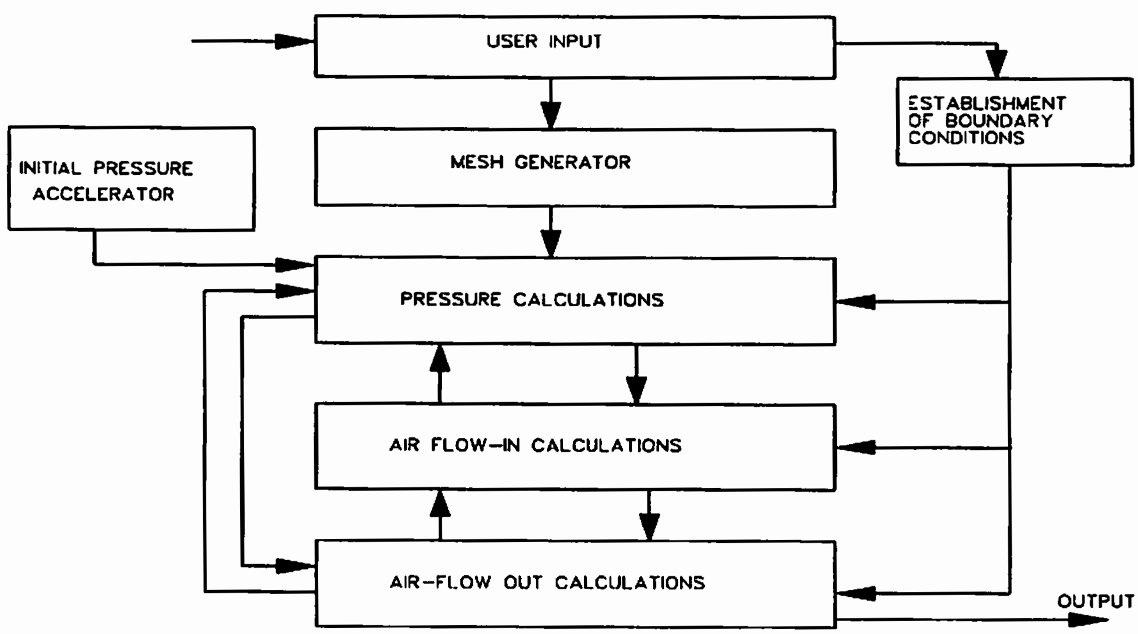

Fig. 2: The General Flow Chart of The SSD Computer Model For Large Buildings.

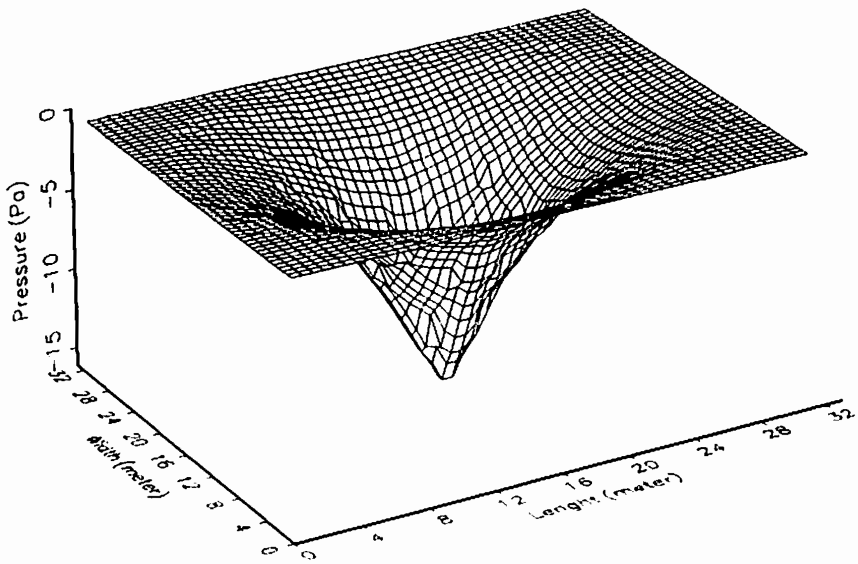

Fig. 3: The PFE Map For Approximately 30.5x30.5 meters Slab on Grade with Central SSD of 400 Pa.

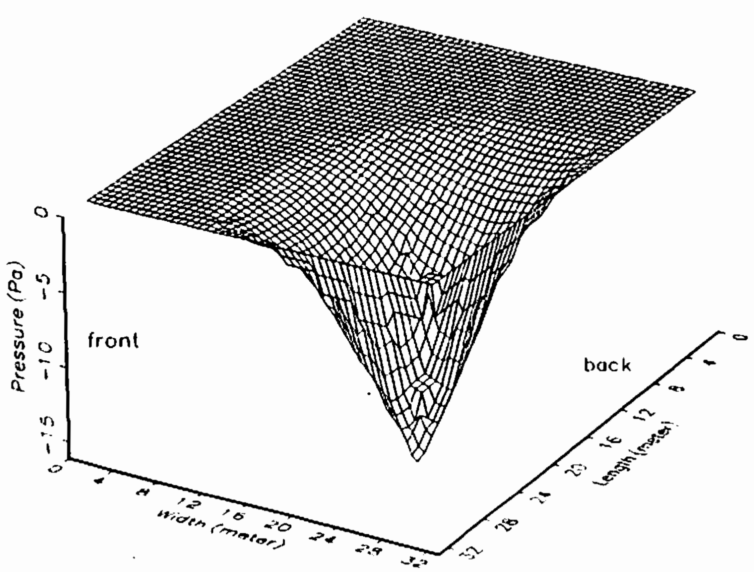

Fig. 4: The PFE Map For Approximately 30.5x30.5 meters Slab on Grade with SSD at 6 meters From The Upper-Right Slab Corner, Suction Pressure of 400 Pa.

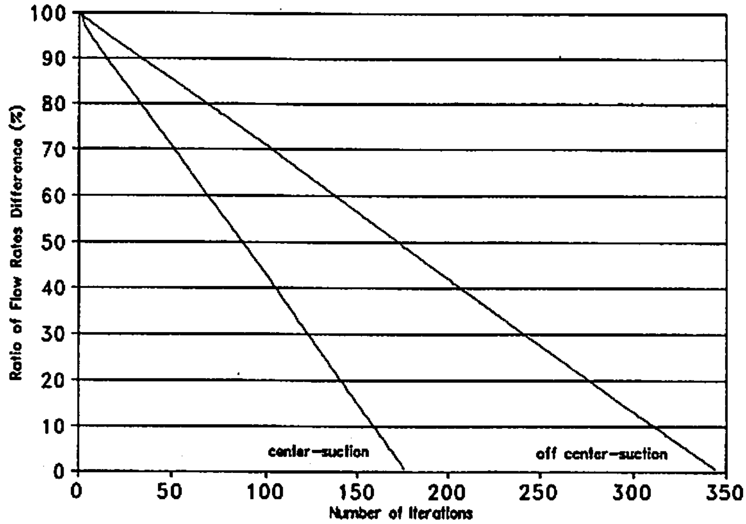

Fig. 5: The Change of The Absolute Ratio of The Air Flows Difference During The Program Operation.

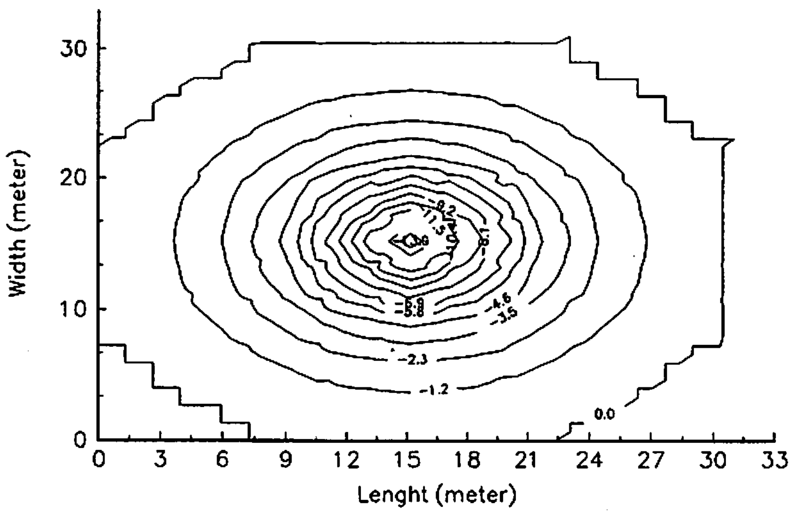

Fig. 6: The Contour Map of The PFE For an Approximately 30.5x30.5 meters Slab on Grade, 1.5 meter Foundation Wall with Central SSD of 400 Pa.