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The Influence of a Subslab Gravel Layer and Open Area on Soil-Gas and Radon Entry into Two Experimental Basements

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Abstract

Measurements of steady-state soil-gas and ^{222}Rn entry rates into two room-sized, experimental basement structures were made for a range of structure depressurizations (0 - 40 Pa) and open floor areas (0 - 165 x 10^{-4} m^2). The structures are identical except that in one the floor slab lies directly on native soil whereas in the other the slab lies on a high-permeability gravel layer. The subslab gravel layer greatly enhances the soil-gas and radon entry rate into the structure. The radon entry rate into the structure with the subslab gravel layer is four times greater than the entry rate into the structure without the gravel layer with an open floor area of 165 x 10^{-4} m^2; however the ratio increases to 30 for an open floor area of 5.0 x 10^{-4} m^2. The relationship between open area and soil-gas entry rate is complex. It depends on both the amount and distribution of the open area as well as the permeability of the soil near the opening. The entry rate into the experimental structures is largely determined by the presence or absence of a subslab gravel layer. Therefore open area is a poor indicator of radon and soil-gas entry into the structures. The extension of the soil-gas pressure field created by structure depressurization is a good measure of the radon entry. The measured normalized radon entry rate into *both* structures has the *same* linear relationship with the average subslab pressure coupling *regardless* of open area or the presence or absence of a subslab gravel layer. The average subslab pressure coupling is an estimate of the extension of the soil-gas pressure field. A three-dimensional finite-difference model correctly predicts the effect of a subslab gravel layer and different open area configurations on radon and soil-gas entry rate; however, the model underpredicts the absolute entry rate into each structure by a factor of 1.5.

Keywords -- ^{222}Rn, ^{222}Rn entry, soil-gas entry, soil-gas pressure field, soil permeability, numerical modeling

Introduction

Advective flow of radon-laden soil gas is the dominant transport mechanism of radon into houses with elevated indoor radon concentrations (Bruno 1983; Åkerblom et al. 1984; Nero and Nazaroff 1984; Nazaroff et al. 1985; Nazaroff et al. 1988; Turk et al. 1990a). Since solid concrete is essentially impermeable to air (Rogers and Nielson 1992), soil gas flows into a basement primarily through cracks, gaps, holes, and other penetrations through the building's foundation. Large gaps are commonly found around plumbing fixtures, utility penetrations, and the perimeter of a floor slab due to the shrinkage gap between the wall and a poured concrete slab. Smaller cracks are created by differential settling of the concrete slab (Scott 1988). A typical basement with concrete wall and floor areas of 120-200 m^2 can have open areas up to a several hundred square centimeters (Scott 1988). Open area is defined as the total cross-sectional area of all penetrations through a foundation. A field study done in Elliot Lake Ontario found that open area of the joints between the walls and the floor slab was typically around 0.03 m^2 (Eaton and Scott 1984). In the extreme, cracks with a combined area of 1.5 m^2 were found in a house in New Jersey (Turk et al. 1991a). In addition to flow through cracks, there may also be significant bulk soil-gas flow through basement walls constructed out of a high permeability material such as hollow concrete blocks (Garbesi and Sextro 1989; Ruppersberger 1991).

The importance of cracks as an advective soil-gas entry pathway led to the development of sealing as a radon mitigation technique. However, results from several radon mitigation studies indicate that sealing is often ineffective at reducing indoor radon concentrations (Henschel 1988; Turk et al. 1991a; Turk et al. 1991b). The ineffectiveness of sealing as a mitigation technique was attributed to a failure to seal a significant fraction of the total crack area, and therefore failing to significantly increase the resistance of the foundation to soil-gas flow with respect to the resistance of the soil. Sealing only becomes effective when the total substructure crack resistance approaches that of the soil (Mowris and Fisk 1988).

Despite the role of cracks in soil-gas entry into houses and the apparent ineffectiveness of sealing as a radon mitigation technique, little work has been reported on the relationship between open area and soil-gas or radon entry. In a field study, Brennan et al. (1991) found that indoor radon concentrations were independent of changes in open area. They hypothesized that the failure of indoor radon concentrations to increase with increases in open area was caused by elevated soil-gas flow rates diluting the radon concentration of the soil gas. In a modeling study of the influence of different structural factors on radon entry, Revzan et al. (1992) found that radon entry rate was independent of opening width for soils with a permeability less than 10^{-10} m^2, and that the sizes and numbers of openings in the slab were relatively unimportant as long as the total open area is small in comparison to the slab area. That study concluded that the presence of a subslab gravel layer was the most important structural factor considered with the potential to increase the radon entry rate by as much as a factor of five. Based on the predictions of an analytical model, Mowris (1986) found that cracks wider than 1 x 10^{-3} m created insignificant resistance to flow in comparison to the resistance of the soil.

This paper reports on a soil-gas and radon entry study carried out at two experimental structures located in the Santa Cruz Mountains, California. These basement structures were designed and constructed to study the importance of structural and environmental factors on radon and soil-gas entry into houses. The two structures are identical except for the presence of a high-permeability gravel layer underneath the floor of one of the structures. Inclusion of a subslab gravel layer is a customary construction practice in some areas to prevent the slab from coming into contact with wet soil. In addition, the new residential building code proposal (US EPA 1994) requires the installation of a subslab gravel layer in conjunction with a passive subslab ventilation system in houses built in high radon areas. In case an active (i.e. fan-powered) mitigation system is necessary, the gravel layer will greatly enhance its performance (Henschel 1993).

The structures were designed with a simple geometry and precisely defined soil-gas entry points to facilitate comparison with existing numerical models. Such models are a valuable tool for investigating soil-gas and radon entry into houses; however, comparison between measurements of radon entry into houses and predictions of these models have indicated significant discrepancies. Initial measurements in the structure with the gravel layer confirmed this discrepancy (Garbesi 1993; Garbesi et al. 1993a). Further work has shown that a large portion of this difference is due to the scale-dependence of soil permeability (Garbesi 1993; Garbesi et al. 1993b).

The goals of this work are: 1) to examine the effect of a subslab gravel layer on radon entry rate, 2) to examine the relationship between open area and radon entry rate, and 3) to compare predictions of a three-dimensional finite-difference model with these detailed measurements of radon and soil-gas entry. The experiments use constant depressurization of the structure, in the range of 10 to 40 Pa below atmospheric pressure. Open areas are varied by opening or sealing a series of holes and precisely machined slots located in the structure's floor. The results of these experiments can be extrapolated to the few Pascal depressurizations experienced by real houses under ordinary operating conditions because soil-gas flow into the structures is governed by Darcy's law, where flow is a linear function of pressure.

Materials and Methods

Structure Design and Instrumentation

Fig. 1 is a schematic drawing of a basement structure. Each structure is a single chamber with a floor dimension of 2.0 x 3.2 m and a height of 2.0 m (inside dimensions); only about 0.1 m of the walls extend above grade. The structures are identical except for the presence of a 0.1-m-thick gravel layer underneath the slab of one of the structures (Fisk et al. 1992). This structure will be referred to as the gravel structure, and the structure which lies on native soil will be referred to as the no-gravel structure.

A set of slots and holes have been installed in the floor of each structure to provide well-characterized openings through which soil gas flows into the structure. Each structure has six smooth-walled slots to simulate the shrinkage gap that can develop at the floor-wall joint located at the perimeter of poured concrete floors in real houses. Each slot is 3.2×10^{-3} m wide, 0.86 m long and extends though the entire 0.15-m-thick slab. The open area of each slot is 27×10^{-4} m^2. As shown in Fig. 1 the slots are inset 0.34 m from, and run parallel to, each wall of the structures. There are two slots along each of the east and west walls, and only one along each of the shorter north and south walls. These slots provide negligible resistance to soil-gas flow over the range of conditions considered in this study (Fisk et al. 1992). In addition there are four 0.013-m-diameter circular holes in the floor slab, one hole in the center of each quadrant of the structure floor. The open area of each hole is 1.3×10^{-4} m^2. There is also a 0.038-m-diameter circular hole in the center of the gravel structure floor, having an open area of 11×10^{-4} m^2. The total open area was varied by sealing the various slots and holes in the floor of the structures with aluminum plates and silicone sealant. Great care has been taken to seal all other cracks and other unintended openings between the structure and the soil environment to minimize uncharacterized soil-gas entry points.

Thirty-two soil probes have been installed around each structure to measure soil-gas pressure disturbances, soil-gas radon concentrations, and soil permeability. As shown in Fig. 1, horizontal probes penetrate the walls at three different elevations, and vertical probes extend through the slab to monitor the subslab region. Table 1 summarizes the distribution and length of the soil probes around both structures. The probes are constructed out of 0.021-m-diameter steel pipe with a 0.15 m section of cylindrical well screen, for sampling, and a 0.04 m driving tip welded onto the end of the pipe (Fisk et al. 1992). A 5-m-long reference probe extends horizontally into the soil from the slab level of the each structure.

Continuous radon monitors (CRM) are used to measure the ^{222}Rn concentration of the air in the structure, slots/holes, and soil. An oscillating fan continually mixes the structure air to allow accurate sampling of structure radon concentration from a single location. Air is drawn from the bottom of all the openings through 0.15-m-long needles, mixed into one sampling line, and delivered to a CRM. Soil-gas samples are multiplexed from the probes to one CRM. The method described by Thomas et al. (1979) was used to interpret the CRM data from the structure and slot CRMs. Since soil-gas samples are multiplexed the algorithm developed by Busigin et al. (1979) was used to interpret the data from the probe CRM (Modera and Bonnefous 1993).

Soil moisture and temperature, indoor and outdoor temperature, wind speed, wind direction, barometric pressure, rainfall, and water table depth are also monitored. A computer-controlled mass flow controller maintains the structure depressurization within $\pm 5\%$ of the set-point. The structure depressurization is the measured pressure difference between the interior of the structure and the reference probe. Further details of the design and instrumentation of the structures are found in Fisk et al. (1992) and Garbesi et al. (1993a).

Soil Properties

Table 2 reports the measured permeability of the gravel, backfill, and undisturbed soil at the structure site. The permeability of the undisturbed soil is scale dependent, increasing by more than an order of magnitude when the length scale increases from 0.1 to 3.5 m (Garbesi 1993; Garbesi et al. 1993b). High permeability flow paths such as old plant roots, animal burrows, and water leach pathways are thought to cause the scale dependence of the permeability of the undisturbed soil. The permeability of the undisturbed soil listed in Table 2 is the value measured at the 3 m scale because that is the characteristic length of a soil-gas flow path from the soil surface to an opening in the structure floor. The backfill region, shown in Fig. 1, was excavated during the construction of the structures. It was carefully refilled to minimize the disturbance of the native soil environment (Fisk et al. 1992). The careful packing of the backfill region is thought to have destroyed features which create the scale dependence observed in the undisturbed soil.

Table 3 summarizes measurements of soil-grain density, porosity, emanation fraction and radium content at the structure site. Soil samples were taken from several bore holes, a soil trench, and the walls of the excavations for the structures. Further geological details of the structure site are described in Flexser et al. (1993) and Brimhall et al. (1992).

Pressure Field

The soil-gas pressure field created by depressurization of the interior of the structure drives advective soil-gas entry into the structure. The pressure field quantifies the field of influence of the structure and provides information on the advective soil-gas transport pathways. The soil-gas pressure field is reported in terms of the non-dimensional parameter pressure coupling (Garbesi et al. 1993a; Nazaroff et al. 1987).

Given Darcy flow and negligible flow resistance though the openings relative to the soil, pressure coupling is independent of structure depressurization.

The pressure coupling at probe j is defined as

$$PC_j = \frac{\Delta P_{ref} - \Delta P_j - \left[\rho(T_{soil}) - \rho(T_{in})\right] g h_j}{\Delta P_{ref}}. \quad 1$$

ΔP_{ref} is the measured pressure difference between the structure interior and the reference probe. ΔP_{ref} is corrected for any pressure coupling in the reference probe by comparing ΔP_{ref} with the time-averaged structure-to-outdoor pressure difference at the soil surface. ΔP_j is the measured pressure difference between the structure interior and probe j. The term $\left[\rho(T_{soil}) - \rho(T_{in})\right] g h_j$ is a small hydrostatic pressure correction which references PC_j to the floor slab level. The density (ρ) of the soil gas and the air inside the structure is calculated based on their temperature.

Radon and Soil-gas Entry Rate

Experiments were conducted to determine the steady-state advective radon and soil-gas entry rates into each structure as a function of open area and structure depressurization. Each experiment lasted at least seven days to ensure that the structure and soil-gas radon concentrations had achieved steady-state. All of the experiments were conducted during relatively stable environmental conditions -- no large rainfall events, or high winds (less than 4 m s^{-1}). During each experiment the interior of the structure was held at a constant depressurization relative to the reference probe.

The total advective radon entry rate was computed using a steady-state mass balance

$$S_{adv} = I_{struc} Q_{exh} + I_{struc} \lambda V - S_{diff} \quad 2$$

where S_{adv} is the total advective radon entry rate into the structure, I_{struc} is the steady-state activity concentration of radon inside of the structure, Q_{exh} is the exhaust flow rate from the structure, λ is the radioactive decay constant of radon (2.1 x 10^{-6} s^{-1}), V is the volume of air inside the structure (13.4 m^3), and S_{diff} is the diffusive radon entry rate. The measured diffusive radon entry rate through the walls, floor, and openings into both structures, with no imposed structure depressurization, is 0.10 Bq s^{-1} (Garbesi et al. 1993a). The diffusive entry rate is assumed to be independent of structure depressurization and open area configuration because the measured soil-gas radon concentration field was relatively invariant during this study.

Although advective radon entry occurs primarily through the slots and holes, it must be corrected for entry through other, undetectable, unintentional openings to make valid comparisons with the numerical model and to study the influence of open area on radon entry. The uncharacterized radon entry rate was estimated by sealing all of the slots and holes in the floor of the structure and depressurizing the structure. The measured advective radon entry rate is then defined as the uncharacterized radon entry rate. This estimate is an upper bound on the uncharacterized radon entry rate because opening slots or holes changes the soil-gas pressure field around the structure, reducing the pressure drop across the structure walls which in turn decreases the flow through any unintentional openings. The estimated uncharacterized radon entry rates are 0.03 Bq s^{-1} Pa^{-1} and 0.06 Bq s^{-1} Pa^{-1} into the gravel structure and no-gravel structure respectively. The radon entry rate through the slots and holes (S_c) is then calculated by subtracting the estimate of the uncharacterized radon entry rate (S_u) from the total advective radon entry rate:

$$S_c = S_{adv} - S_u. \qquad 3$$

In this paper the term "radon entry rate" refers to the advective radon entry rate through the slots and holes, S_c, unless otherwise noted.

After calculating the radon entry rate through the holes and slots, the soil-gas entry rate into the structure is determined using a ^{222}Rn mass balance.

$$Q = \frac{S_c}{I_{open}}, \qquad 4$$

where Q is the soil-gas flow rate into the structure through the characterized openings, and I_{open} is the measured ^{222}Rn concentration of the entering soil gas, averaged over all of the openings.

Numerical Modeling

A steady-state, three-dimensional, finite-difference model based on a code written by Loureiro et al. (1990) and modified by Revzan et al. (1992) was used to simulate the soil-gas pressure field around and the advective radon entry into the experimental structures. Garbesi et al. (1993a) made detailed comparisons between the predictions of this model and measurements made in the gravel structure to study the discrepancy between field measurements and predictions of numerical models.

The model assumes isothermal conditions and Darcy flow. Soil gas flows into the structure through openings defined in the floor of the simulated structure; the rest of the floor and the walls are treated as no-flow boundaries. The model assumes that all openings in the floor provide no resistance to flow of soil gas, i.e. that the openings provide negligible resistance to soil-gas entry in comparison with the soil. To reduce storage and computational requirements, the model simulates flow in one-quarter of the soil block by assuming two planes of symmetry along the north-south and east-west centerlines of the structure (Loureiro et al. 1990).

Two types of openings are defined in the floor of the simulated structure: long slots with the same dimensions and locations as the slots in the experimental structures, and square holes with the same area and location as the circular holes in the floor of the experimental structure. The assumption of insignificant pressure drop across openings is valid for all configurations except for the case of the gravel structure with only holes open. In this configuration the flow rate through the openings is high enough to cause some pressure drop in the openings --- on the order of 5% of the total imposed pressure on the structure. Corrections for pressure drop in the holes were made using a correlation developed by Shah (1978) which predicts the pressure drop in the inlet region of non-circular ducts.

To simulate the soil-gas flow field the soil block was divided into three regions: undisturbed soil, backfill, and subslab region (Garbesi 1993). The different soil regions are shown in Fig. 1 and are assigned the measured permeabilities reported in Table 2. The subslab region in the no-gravel structure is assigned the permeability of the undisturbed soil. The soil block was divided into layers to simulate the soil-gas radon concentration field (Garbesi 1993). The depths and properties assigned to the simulated layers correspond to those listed in Table 3.

Results and Discussion

Soil-Gas Entry as a Function of Structure Depressurization with Six Slots Open

Fig. 2 shows the measured soil-gas entry rate into the gravel and no-gravel structure as a function of structure depressurization. The measured soil-gas entry rate was determined from a radon mass balance. All of the measurements presented in Fig. 2 were made with six slots open, a total open area of 165×10^{-4} m^2. As expected from Darcy's law and the negligible resistance of the slots to flow, the soil-gas entry rate is a linear function of structure depressurization. A linear regression of the soil-gas entry rate as a function of structure depressurization, weighted by the measurement uncertainties, yields slopes of 9.8×10^{-6} m^3 s^{-1} Pa^{-1} ($r^2 = 0.99$) for the gravel structure, and 2.5×10^{-6} m^3 s^{-1} Pa^{-1} ($r^2 = 0.98$) for the no-gravel structure. With all six slots open the measured soil-gas entry rate into the gravel structure is approximately four times greater than the measured soil-gas entry rate into the no-gravel structure. To verify the accuracy of determining the soil-gas entry rate with a radon mass balance, the soil-gas entry rate through the 0.038-m-diameter hole in the gravel structure was calculated with a radon mass balance and directly measured using a hot wire anemometer. The two measurements were within 5% --- which is less than the experimental uncertainty. Fig. 2 shows that the model underpredicts the soil-gas entry rate into both the gravel and no-gravel structure by a factor of 1.5 and 1.4 respectively. Although the discrepancy for the no-gravel structure is slightly smaller than for the gravel structure, this difference in the discrepancies falls within the uncertainties of the permeability measurements input into the model and soil-gas entry rate measurements.

Garbesi et al. (1993a) reported a soil-gas entry rate into the gravel structure of 1.7×10^{-5} m^3 s^{-1} Pa^{-1} based on a radon balance. The apparent reduction in soil-gas entry rate reported in this study is due to improved accuracy in the measurement of the radon concentration of the slot air. In the present study 0.15-m-long needles were used to sample air from the bottom of the slots. In the previous study 0.016-m-long needles were used to sample air from the slots; these shorter needles may have entrained air from the structure, diluting the slot air radon concentrations.

Pressure Coupling with Six Slots Open

Pressure coupling measurements made around both structures with six slots open are presented in Figs. 3, 4, and 5. As expected the pressure coupling decreases as one moves away from the openings. The only exception is found in the mid-wall of the no-gravel structure, shown in Fig. 5. However, these small values of pressure coupling have large experimental uncertainties associated with them. The pressure gradient is much larger in the subslab region where the soil-gas flow field converges into the slots (Fig. 3) than around the low and mid-wall probes where the soil-gas flow field is more spread out (Figs. 4 and 5).

A comparison of the measured subslab pressure coupling underneath both structures, shown in Fig. 3, reveals the dramatic effect of a subslab gravel layer. The pressure coupling of 0.96 measured in the two 0.24-m-long subslab probes underneath the gravel structure indicates that the pressure in the gravel layer is essentially the same as the pressure inside the structure, and that the pressure gradient in the gravel immediately underneath the structure is relatively small. In contrast, the much smaller value of pressure coupling measured in the two 0.24-m-long probes underneath the no-gravel structure indicates that a large pressure gradient exists immediately underneath the no-gravel structure.

The gravel layer enhances the soil-gas entry rate into the structure by reducing the pressure drop in the critical near-slot region of the soil. The soil gas accelerates as it converges into the slots causing the highest soil gas velocities to occur in the soil immediately adjacent to the slots. This acceleration can be seen by comparing the spacing of the pressure coupling contours in both Figs. 6a and 6b. Because of the high soil gas velocities in the near-slot region, large pressure gradients are required to drive the converging soil gas flow into the slots. However, the addition of a *high-permeability* subslab gravel layer significantly reduces these pressure gradients, increasing the total soil-gas entry rate into the structure.

The effect of the gravel layer is clearly illustrated in the predicted pressure coupling fields around both structures. Fig. 6a shows that the soil-gas flow field converges uniformly into the gravel layer underneath the structure, indicating that the gravel layer is a plenum. Despite the large soil gas velocities caused by the convergence of the soil-gas flow field into slots, the high-permeability gravel presents negligible resistance to soil gas flow in comparison with the low-permeability undisturbed soil. Consequently, the gravel layer effectively increases the area over which the soil-gas flow field converges, reducing the velocities in the low-permeability soil, and increasing the entry rate into the structure. In contrast, Fig 6b shows the soil-gas flow field converging into each of the slots in the floor of the no-gravel structure. Since no high-permeability layer exists underneath the no-gravel structure, large pressure gradients are required to drive the converging soil gas flow field into the narrow slots.

The performance of the numerical model can be assessed by comparing the model predictions and measurements of pressure coupling around both structures. Figs. 3, 4, and 5 show that the model underpredicts the pressure coupling around both structures at every probe location except the two 2.39-m-long probes in the no-gravel structure low-wall. Around the gravel structure, the model predictions of pressure coupling are more accurate in regions closer to the openings. Fig. 3 shows that the model underpredicts the pressure coupling measured in the 0.24 and 0.5-m-long probes in the subslab of the gravel structure by less than 10%. The accuracy of the model predictions in the region near the gravel layer indicates that the model correctly simulates the effect of a subslab gravel layer. However, the model underpredicts the pressure coupling measured in all of the low-wall probes in the gravel structure by more than a factor of two, and in all of the mid-wall probes by more than a factor of three. This indicates that the model fails to predict the horizontal extension of the soil-gas pressure field around the gravel structure.

Around the no-gravel structure, Figs. 3, 4, and 5 show that the model underpredicts the pressure coupling by at least a factor of two at most probe locations, *including* the subslab. This general underprediction of the pressure coupling by the model suggests that it does not correctly simulate the soil-gas pressure field in the critical near-slot region. If the model overestimated the pressure drop in the soil near the slots, it would then underpredict the pressure coupling in the rest of the soil block. Such an error could be caused by the value of permeability assigned to the subslab region of the simulated soil block being too small, or an incorrect definition of the interface between the soil and the bottom of the slab. The model assumes that a perfect interface between the soil and the bottom of the slab exists; however, settling could create air gaps under the slab of the no-gravel structure which would reduce the pressure gradient for a given flow compared to the model.

Pressure coupling measurements provide details of the soil-gas flow field created by the depressurization of the interior of the structure. The failure of the numerical model to correctly predict the *shape* of the pressure coupling field indicates that it does not accurately simulate the soil-gas flow field around the structures. Consequently, the factor of 1.5 discrepancy between the measured and predicted soil-gas entry rates into both structures is *not* caused by the permeability measurements used as inputs for the model being a factor of 1.5 too low. Simply increasing the permeability inputs into the model will *not* change the shape of the predicted pressure coupling and soil-gas flow fields. In fact, the comparison of the measurements and model predictions of pressure coupling suggests that the cause of this discrepancy may be different in each structure.

^{222}*Rn* *Entry Rate as a Function of Open Area*

Fig. 7 shows the measured and predicted radon entry rate into the structures as a function of open area. The radon entry rates have been normalized by structure depressurization. The measured radon concentration of the air in the openings varied by less than 8% over the entire range of pressures and open areas considered during these experiments; consequently, the radon entry rate can be assumed to vary linearly with structure depressurization. Fig. 7 shows the measured radon entry rate into the gravel structure rapidly increases with open area, reaching a maximum entry rate of approximately 0.8 Bq s^{-1} Pa^{-1} for open areas greater than 5 x 10^{-4} m^2. In contrast, the measured radon entry rate into the no-gravel structure gradually increases with open area. The slightly non-linear response of the measured radon entry rate into the no-gravel structure to changes in open area indicates that there is some coupling between the openings in the floor of the no-gravel structure. However, this response also indicates that a high-permeability region does *not* exist underneath the no-gravel structure. During the construction of the no-gravel structure great care was taken to prevent the formation of any air gaps or regions of loosely packed soil underneath its slab. Consequently, the results from the no-gravel structure may not be representative of some real houses. Fig. 7 shows that the model accurately predicts the response of radon entry rate into both structures to changes in open area, despite underpredicting the absolute entry rate into both structures by approximately a factor of 1.5. As expected, the model predicts that the radon entry rate into the no-gravel structure will approach the entry rate into the gravel structure as the open area approaches the dirt floor limit, i.e. when no concrete slab is present.

The ratio of radon entry rate into the two structures depends on open area. For the base configuration of six-slots open (165 x 10^{-4} m^2), Fig. 7 shows that the measured radon entry rate into the gravel structure is four times greater than the entry rate into the no gravel structure -- the same as the ratio of the measured soil-gas entry rates with six slots open. However, with an open area of 5 x 10^{-4} m^2 the measured radon entry rate into the gravel structure is more than a factor of 30 greater than the entry rate into the no-gravel structure. To significantly reduce the radon entry rate into the gravel structure the open area must be much smaller than 2.5 x 10^{-4} m^2. This is similar to the results of a field study that concluded that the total open area of a basement must be very small in order to consider it radon resistant (Eaton and Scott 1984).

The soil-gas and advective radon entry rate into the structures also depends on the spatial distribution of the open area. The spatial distribution of open area affects: 1) the pressure drop in the critical region of the soil near the openings, and 2) the resistance of the opening itself to soil-gas flow.

Spreading the open area to reduce the soil gas velocities in the critical region of the soil near the openings increases the entry rate into the structure. For example, in the gravel structure, the measured soil-gas entry rate through the four 0.013-m-diameter is 30% *higher* than the entry rate through the 0.038-m-diameter hole in the center of the floor despite the four-hole configuration having a total open area of more than a factor of 2 *smaller* than the one-hole configuration. The single 0.038-m-diameter hole forces the soil-gas flow field to converge more sharply than the four hole configuration. Spreading the open area in the floor of the gravel structure reduces the soil-gas velocity in the gravel near the mouth of the opening, thus reducing the pressure drop in this region. This more effectively depressurizes the gravel layer and increases the total soil-gas and advective radon entry rate into the structure. This phenomenon can also be observed in the no-gravel structure. Model predictions of radon entry rate into the no-gravel structure through two opening configurations with the same open area, 110×10^{-4} m^2, were compared: two 0.0064-m-wide slots versus four 0.0032-m-wide slots. In the four narrow-slot case the predicted radon entry rate into the no-gravel structure was 30% higher than the two wide-slot case.

The resistance of the openings themselves to soil-gas flow also affects the advective radon entry rate into the structure. The relatively wide openings considered in this study cause negligible resistance to soil-gas flow in comparison with the soil. However, the geometry of the gaps and cracks in real houses may be such that the opening itself will present significant resistance to soil gas flow. Therefore, for a fixed open area, distributing the area to maximize the pressure drop in the openings, for example very thin cracks, will reduce the advective radon entry rate into the structure.

^{222}Rn and Soil-gas Entry as a Function of Pressure Coupling

Our results demonstrate that a complex relationship exists between open area and radon entry rate. Consequently open area is a poor indicator of radon entry potential. Even if the amount of open area can be measured, the radon entry into the structures depends strongly on the presence or absence of a subslab gravel layer as well as the spatial distribution of the open area.

A theoretical relationship between the soil-gas entry rate and the extension of the soil-gas pressure field can be derived using Darcy's law and the principle of conservation of mass. This analysis can be extended to the radon entry rate into the structures because the concentration of slot air was essentially constant during these experiments. By conservation of mass the flow rate across any surface, S, which extends through the soil underneath the structure connecting the walls and enclosing the floor is equal to the soil-gas entry rate into the structure; an example of such a surface is the 0.1 pressure coupling contour shown around the gravel structure shown in Fig. 6a. Assuming incompressible flow and writing the soil-gas velocity in terms of Darcy's law, the soil-gas entry rate into the structure can be expressed as an integral over the surface S;

$$Q = \int_S \overline{u} \cdot \overline{n} dA = \int_S -\frac{k}{\mu} \nabla P \cdot \overline{n} dA \qquad 5$$

where $\overline{u}$ is the soil-gas velocity, k is the permeability of the soil, μ is the dynamic viscosity of the soil-gas, ∇P is the pressure gradient across the surface S, and $\overline{n}$ is the unit normal vector to surface S. If the surface S is defined such that both $k\nabla P \cdot \overline{n}$ and the soil-gas viscosity are constants, then the soil-gas entry rate into the structure can be written as

$$Q = -\frac{k}{\mu} \nabla P \cdot \overline{n} \int_S dA = -\frac{k}{\mu} \nabla P \cdot \overline{n} A \qquad 6$$

where A is the area of surface S. Equation 6 shows that for a given structure depressurization soil-gas entry rate into the structure is proportional to the area of a surface of constant $k\nabla P \cdot \overline{n}$.

Although soil-gas entry rate is proportional to the area of a surface of constant $k\nabla P \cdot \overline{n}$, such a parameter is not a practical predictor of soil-gas entry rate because the calculation of it requires exact knowledge of the soil-gas pressure field. However, the area of a surface of constant $k\nabla P \cdot \overline{n}$ is a measure of the extension of the soil-gas pressure field. The larger the area of such a surface the greater the extension of the pressure field; the greater the extension of the pressure field the larger the region from which the structure draws radon-laden soil gas.

Individual measurements of pressure coupling indicate the extension of the soil-gas pressure field. Comparing measurements of pressure coupling made in the *same* location around each structure provides an estimate of the relative extension of the soil-gas pressure field around the structures. The effect of local soil-heterogeneity on an individual measurement of the extension of the pressure field can be reduced by averaging pressure coupling measurements made in several different probes.

In Fig. 8 the total advective radon entry rate normalized by structure depressurization is plotted as a function of average subslab pressure coupling, which is an average of the pressure coupling measurements made in all of the 0.24, 0.5, and 1.71-m-long subslab probes during each experiment. The open area of these experiments was varied between 0 and 165 x 10^{-4} m^2. All of the measurements in Fig. 8 in the *gravel structure* with an entry rate less than 0.5 Bq s^{-1} Pa^{-1} were made with imperfectly sealed openings. Initially duct tape and Dux-seal were used to seal the openings in the structures; however, this seal did not eliminate the entry rate through the openings. All of the measurements in the *no-gravel structure* with an entry rate less than 0.1 Bq s^{-1} Pa^{-1} were made with an open area 5.0 x 10^{-4} m^2 or less.

Fig. 8 shows that the radon entry rate into *both* structures varies linearly with the average subslab pressure coupling *regardless* of subslab permeability and open area configuration. A linear regression of the radon entry rate into *both* structures as a function of average subslab pressure coupling yields a slope of 1.2 Bq s^{-1} Pa^{-1} per unit of pressure coupling and an intercept of -0.03 Bq s^{-1} Pa^{-1}, $r^2 = 0.97$. Despite incomplete knowledge of the soil-gas pressure field, a crude estimate of the extension of the pressure field is a good measure of the radon entry rate into the structures. Estimating the extension of the pressure field with an average of the pressure coupling measurements made in a different set of probes, for example the mid-wall probes, does *not* change the linearity of the relationship between the radon entry rate and the extension of the pressure field. However using measurements made in a different set of probes to estimate the extension of the pressure field will change the slope of this relationship.

Conclusions

The results of this study demonstrate that a high permeability subslab gravel layer can substantially affect soil-gas and radon entry into houses. The measured radon entry rate into the gravel structure is four times greater than the entry rate into the no-gravel structure with an open area of 165 x 10^{-4} m^2. The ratio of the entry rates into the two structures increases as the open area is reduced; with an open area of 5.0 x 10^{-4} m^2 the entry rate into the gravel structure is factor of 30 greater than the entry rate into the no-gravel structure. The high permeability gravel layer couples the openings in the floor of the gravel structure together, enabling very small open areas to effectively depressurize the gravel layer the same amount as the interior of the structure. Once this occurs, the radon entry rate through openings in the floor is maximized. In contrast the openings in the floor of the no-gravel structure act relatively independently of each other. Consequently, an increase in open area in the floor of the no-gravel structures increases the radon entry rate.

The impact of a high permeability gravel layer on the soil-gas and radon entry rate underscores the importance of the permeability of the soil near an opening on determining the advective entry through that opening. Since the sharp convergence of the soil-gas flow field causes most of the pressure drop to occur in the soil near an opening, changing the permeability of the soil near an opening dramatically affects the soil-gas entry rate through that opening. Increasing the permeability will increase the entry rate through the opening. Decreasing the permeability will decrease the entry rate through the opening.

The impact of a subslab gravel layer on radon and soil-gas entry will depend on the permeability of the gravel layer and the surrounding soil. This study only considered the specific combination of soil permeabilities measured at the structure site, see Table 2. However, the results of this study help validate the predictions of numerical models on the effect of different structural and soil parameters on radon and soil-gas entry rate into houses.

Open area is a poor indicator of radon or soil-gas entry rate into the experimental structures. A complex relationship exists between open area and radon and soil-gas entry rate. Although the amount and distribution of open area can affect the radon entry rate, the entry into the experimental structures is largely determined by the subslab permeability. The results of this study demonstrate that the extension of the soil-gas pressure field created by depressurization of the structure interior is an excellent predictor of the radon and soil-gas entry into the experimental structures. The radon entry rate into *either* structure has the *same* linear relationship with average subslab pressure coupling *regardless* of open area or the presence or absence of a subslab gravel layer. The average subslab pressure coupling is a measure of the extension of the pressure field. Although a theoretical relationship exists between the extension of soil-gas pressure field and soil-gas entry rate, rigorous application of it requires detailed knowledge of the soil-gas pressure field . The success of the average subslab pressure coupling in predicting the radon entry rate into *both* structures indicates that a crude estimate of the extension of the pressure field may be a useful measure of the soil gas and radon entry potential for real houses without requiring precise knowledge of the physical characteristics of the building or the surrounding soil. Turk et al. (1990b) have incorporated measurements of the soil-gas pressure field into a technique for assessing soil gas and radon entry potentials. However a simpler approached based on making pressure coupling and soil permeability measurements at several locations around a building may provide a good relative measure of soil gas entry within a set of similarly characterized buildings.

Comparison of measurements with predictions of a numerical model indicates that a finite-difference model based on Darcy's law with regionally-defined soil parameters accurately simulates the effect of different structure depressurizations, open areas, and subslab permeabilities on radon and soil-gas entry rate. However, the model underpredicts the soil-gas and radon entry rates into both structures by approximately a factor of 1.5. Comparison of the soil-gas pressure fields around both structures suggests that the source of this discrepancy may be different in each structure. The discrepancy in the case of the gravel structure may be caused by the failure of the model to predict horizontal extension of the pressure field. However, in the case of the no-gravel structure the discrepancy appears to be caused by the model overestimating the pressure drop in the soil near the slots.

The results of this study also help explain the ineffectiveness of sealing as a radon mitigation technique. In houses with a subslab gravel layer one must seal essentially all of the openings to significantly reduce radon entry. In addition it has implications for building codes which require the inclusion of a subslab gravel layer for homes constructed in high radon areas to improve the effectiveness of a passive subslab ventilation system (US EPA 1994). If the passive mitigation system is inadequate or if an active mitigation system is not installed or functioning properly the gravel layer can greatly enhance the radon entry rate, potentially increasing indoor radon concentrations.

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Table 1. Location of soil probes around both structures. As shown in Fig. 1, high-wall, mid-wall, and low-wall probes extend horizontally from the walls at the specified depth, and subslab probes extend vertically through the slab of each structure. Probe length is measured from the outside of the wall or floor slab to the middle of the sampling screen. The labels N,S,E,W identify one horizontal probe and the wall from which it extends -- North, South, East, or West.

		Probe Length (m)				
		0.24	0.5	1.11	1.71	2.39
Level Name	Depth Below Grade (m)	Number and Location of Probes				
High-wall	0.2	0	N,S,E,W	0	E,W	N,S
Mid-wall	0.8	0	N,S,E,W	0	E,W	N,S
Low-wall	1.6	0	N,S,E,W	0	E,W	N,S
Subslab (No-Gravel)	2	2	2	2	2	0
Subslab (Gravel)	2	2	2	0	3	1

Table 2. Measured soil and gravel permeability at structure site.

Soil Type	Horizontal Permeability (m^2)	Vertical Permeability (m^2)
undisturbed[a]	3.0×10^{-11}	1.8×10^{-11}
backfill[b]	3.5×10^{-12}	3.5×10^{-12}
gravel[c]	2.0×10^{-8}	2.0×10^{-8}

[a](Garbesi 1993; Garbesi et al. 1993b)
[b](Garbesi et al. 1993)
[c](Fisk et al. 1992)

Table 3. Measured soil properties at structure site.

Depth of Layer (m)	Soil-grain Density[a] ($kg\ m^{-3}$)	Radium Content[b] ($Bq\ kg^{-3}$)	Air-filled Porosity[a]	Emanation Fraction[b]
0 - 1.4	2.80×10^3	30	0.45	0.31
1.4 - 2.25	2.80×10^3	30	0.45	0.45
2.25 - 6	2.80×10^3	30	0.25	0.31

[a](Brimhall and Lewis 1992)
[b](Flexser et al. 1993)

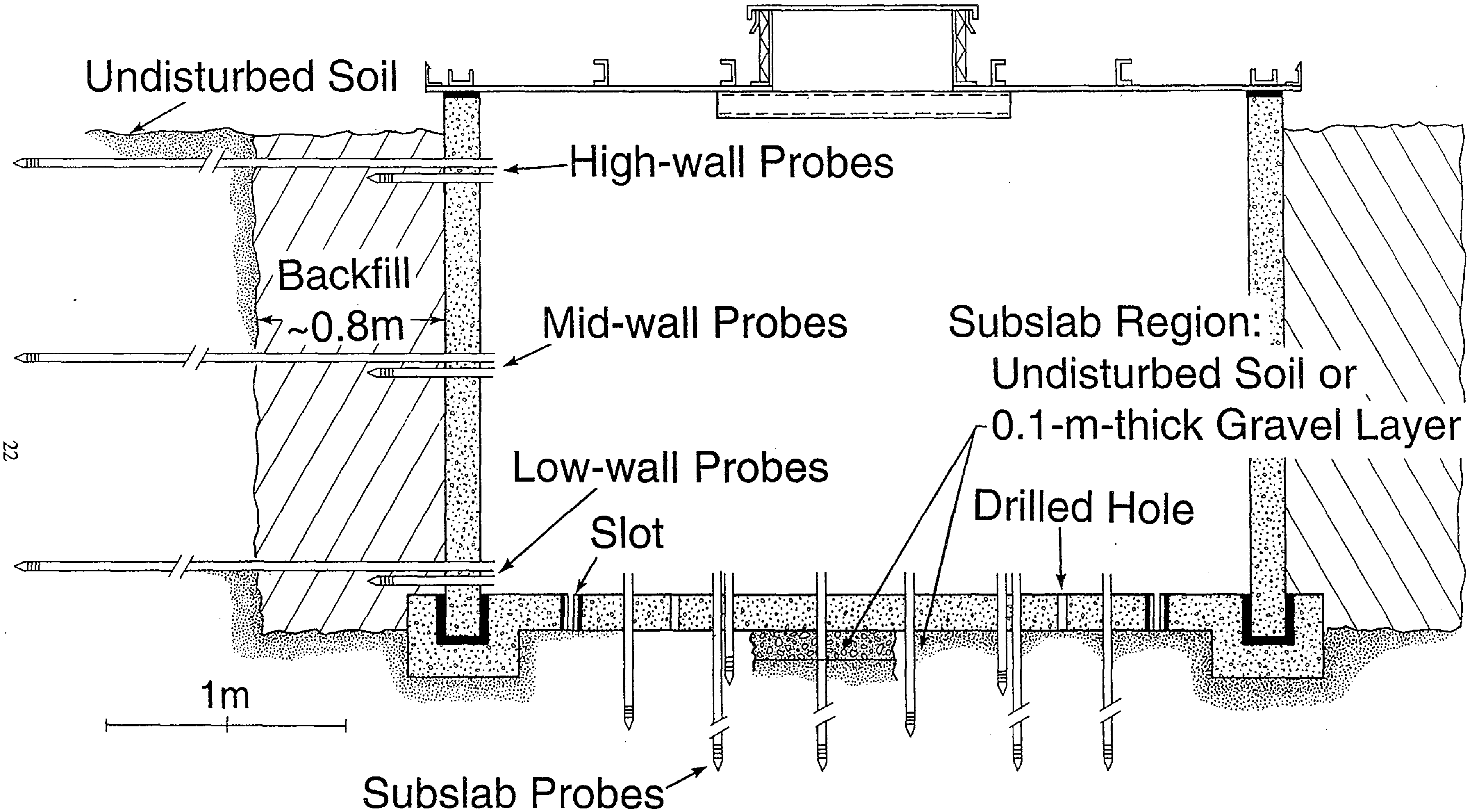

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Fig. 1. Schematic diagram of north-south cross section of the experimental structures. Soil probes extend from all four walls of the structure, but are omitted for visual clarity

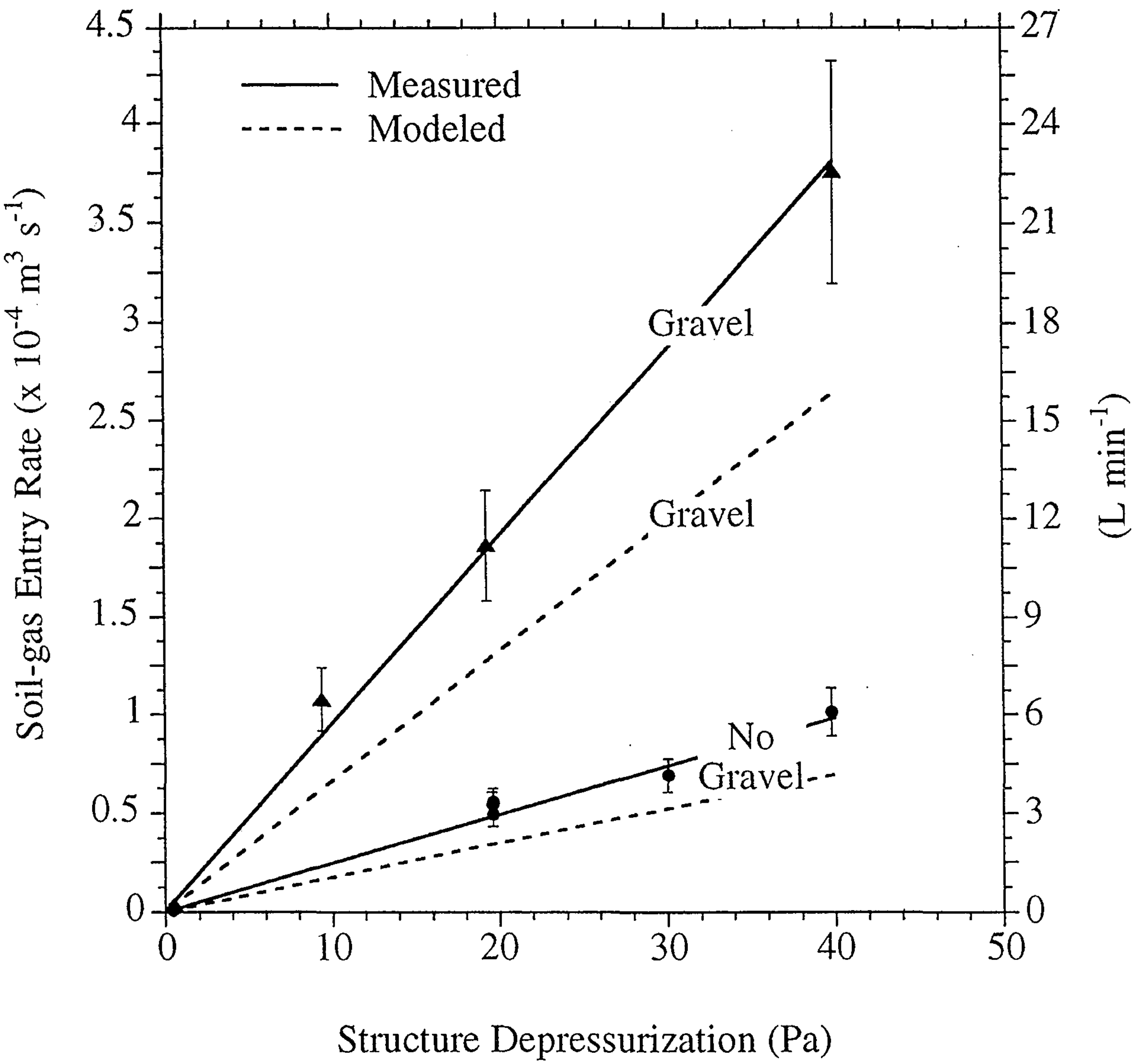

Fig. 2. A comparison of measured and modeled soil-gas entry rate into both structures as a function of structure depressurization. Lines through measured points are linear regressions weighted by uncertainties. The vertical bars represent measurement uncertainty.

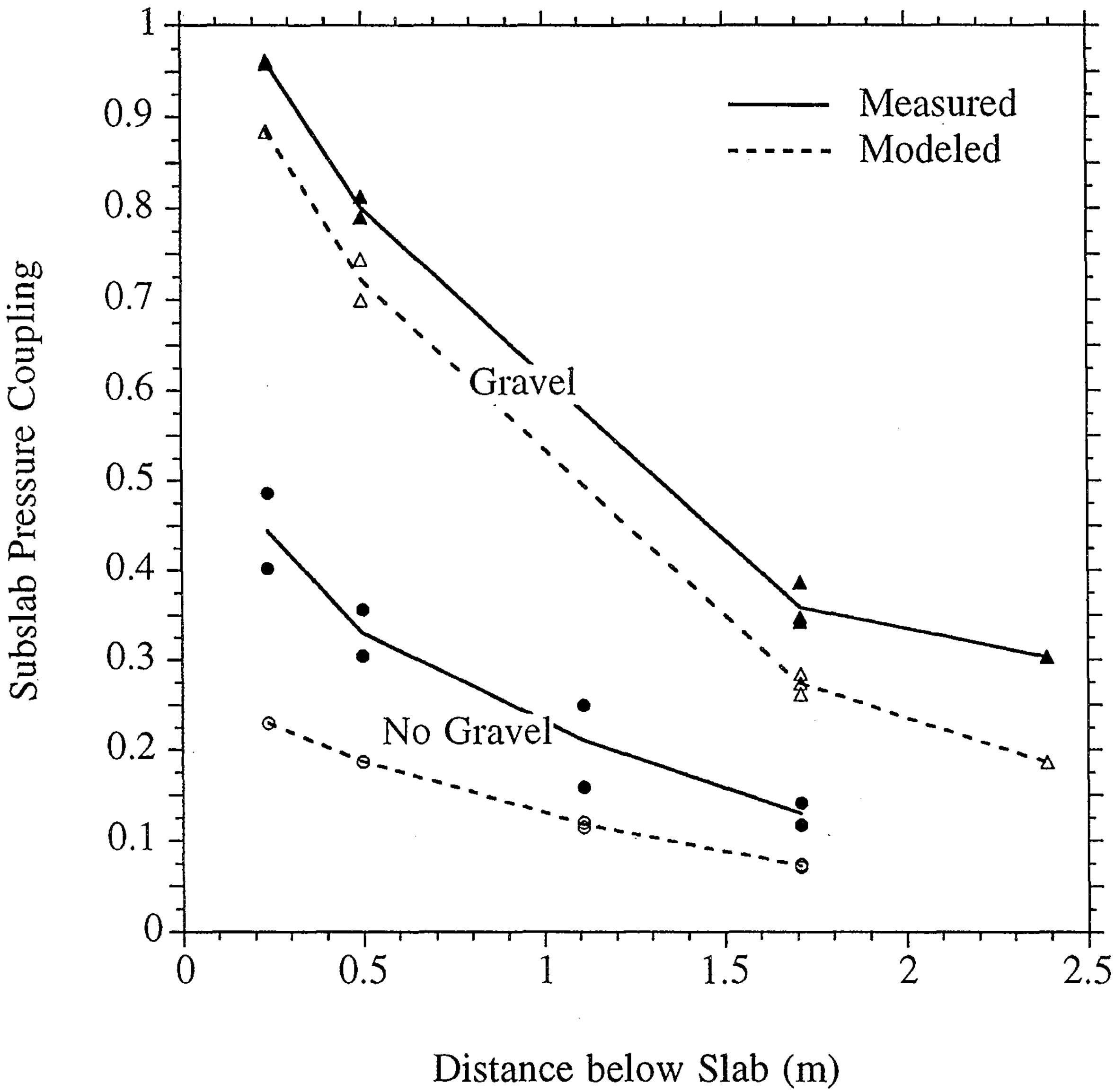

Fig. 3. A comparison of measured and modeled subslab pressure coupling underneath both structures with all six slots open. Lines connect average values for a each probe length and are intended for visual guidance only. Note there are no 1.11-m-long probes underneath the gravel structure, and no 2.39-m-long probes underneath the no-gravel structure. Measured values indicated by solid symbols; modeled values indicated by open symbols. The maximum uncertainty on the measurements is ±0.02 in the no-gravel structure, and ±0.03 in the gravel structure.

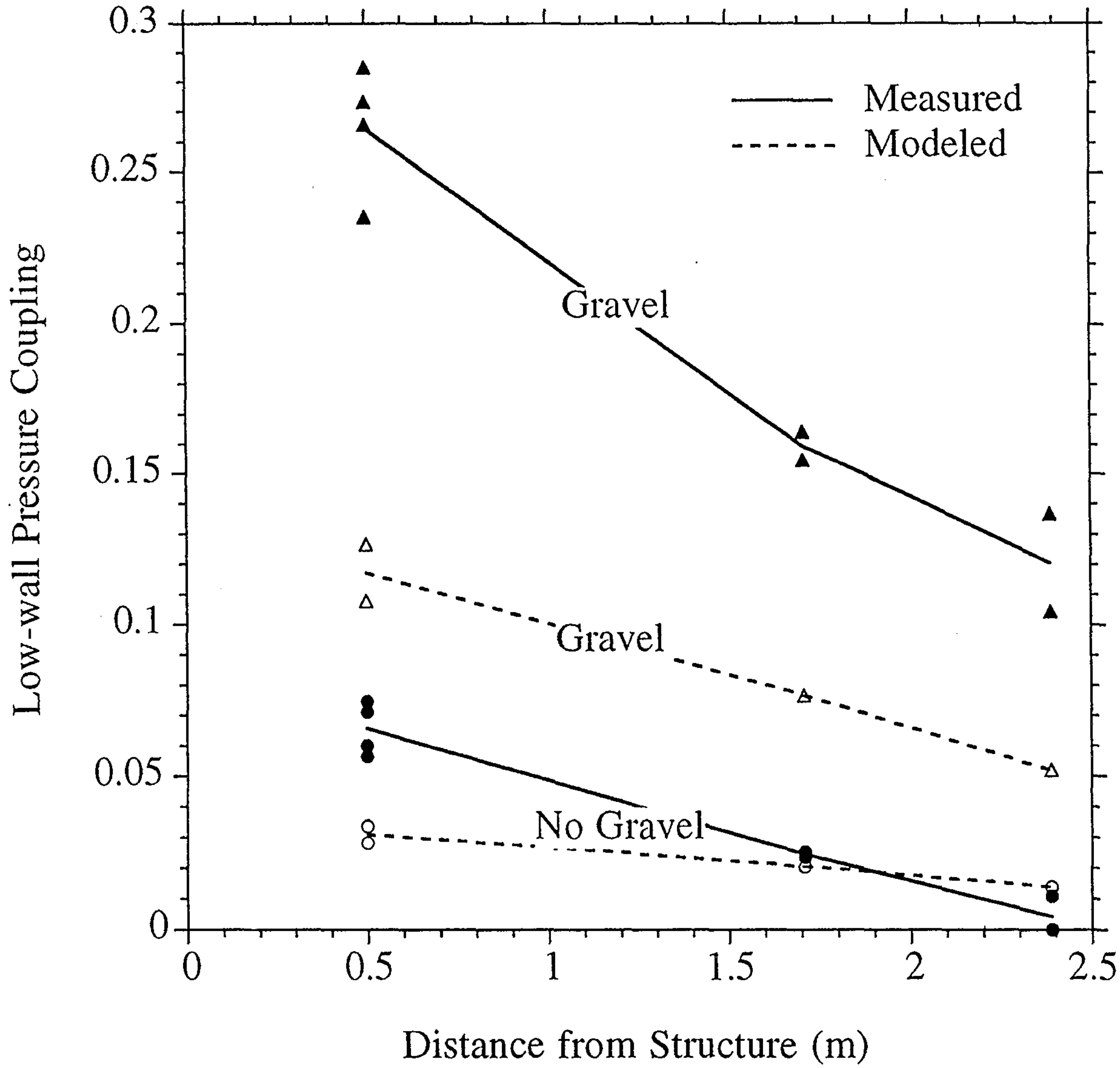

Fig. 4. A comparison of measured and modeled low-wall (1.6 m below grade) pressure coupling around both structures with all six slots open. Lines, symbols, and uncertainties are the same as in Fig. 3.

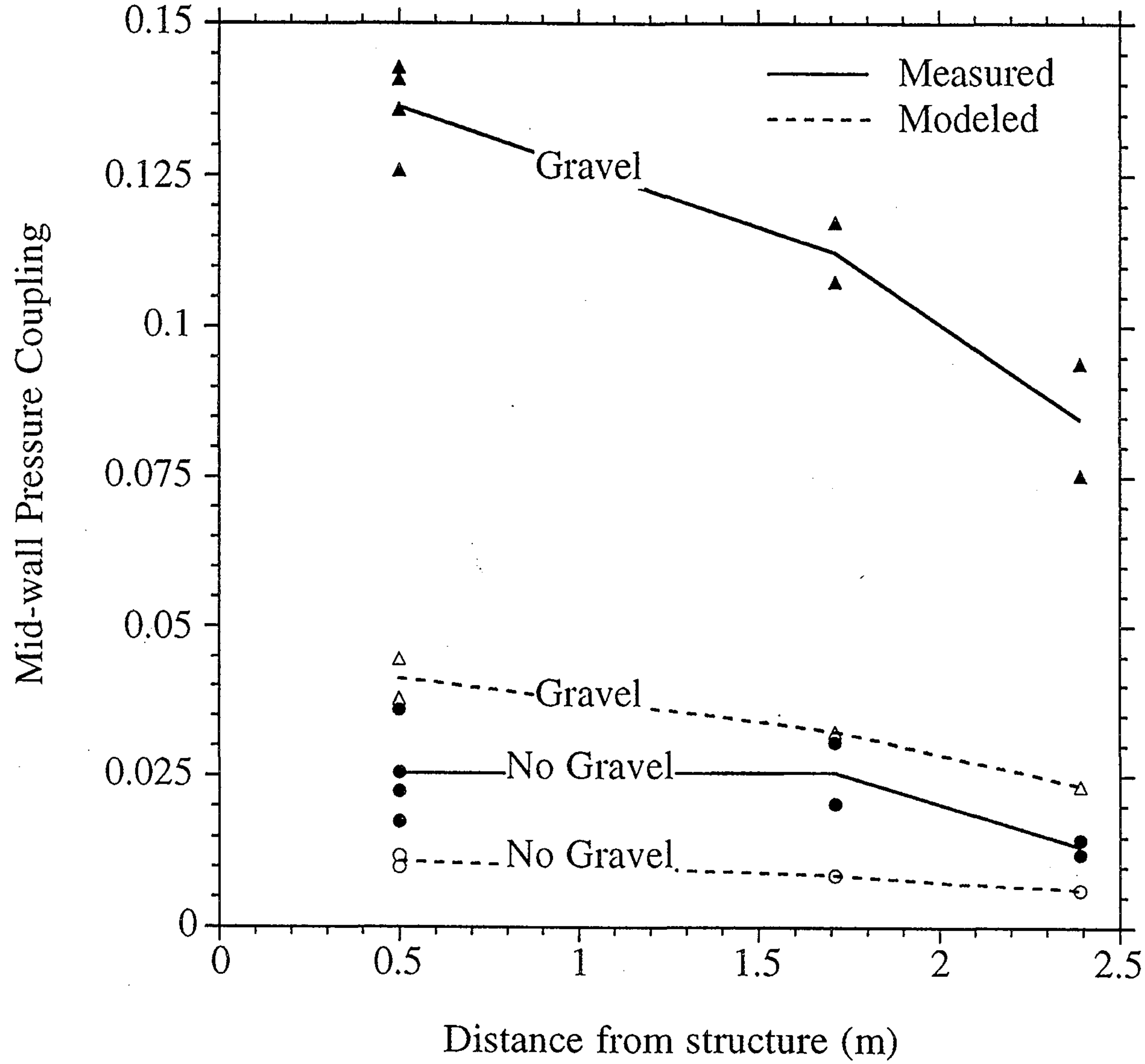

Fig. 5. A comparison of measured and modeled mid-wall (0.8 m below grade) pressure coupling around both structures with all six slots open. Lines, symbols, and uncertainties are the same as in Fig. 3.

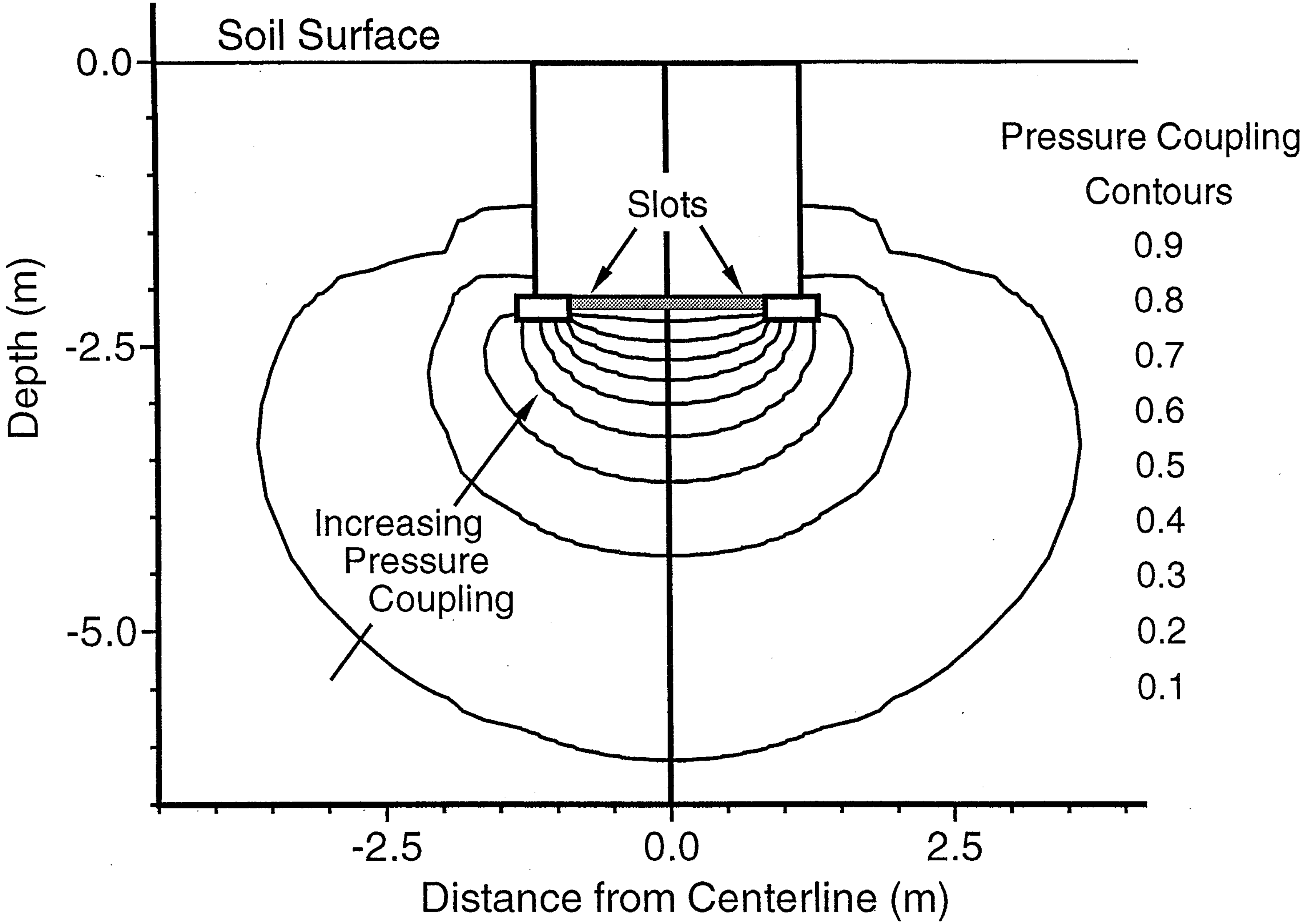

Fig. 6a. Model prediction of the pressure coupling field in the east-west cross-section around the gravel structure with all six-slots open. Lines are pressure coupling contours. The subslab gravel layer is represented by the shaded region underneath the structure floor. The cusp in the 0.1 pressure coupling contour near the structure wall occurs at the interface between the backfill and the undisturbed soil. The permeability changes by an order of magnitude at this interface (see Table 2). The line down center of the figure represents the model's plane of symmetry.

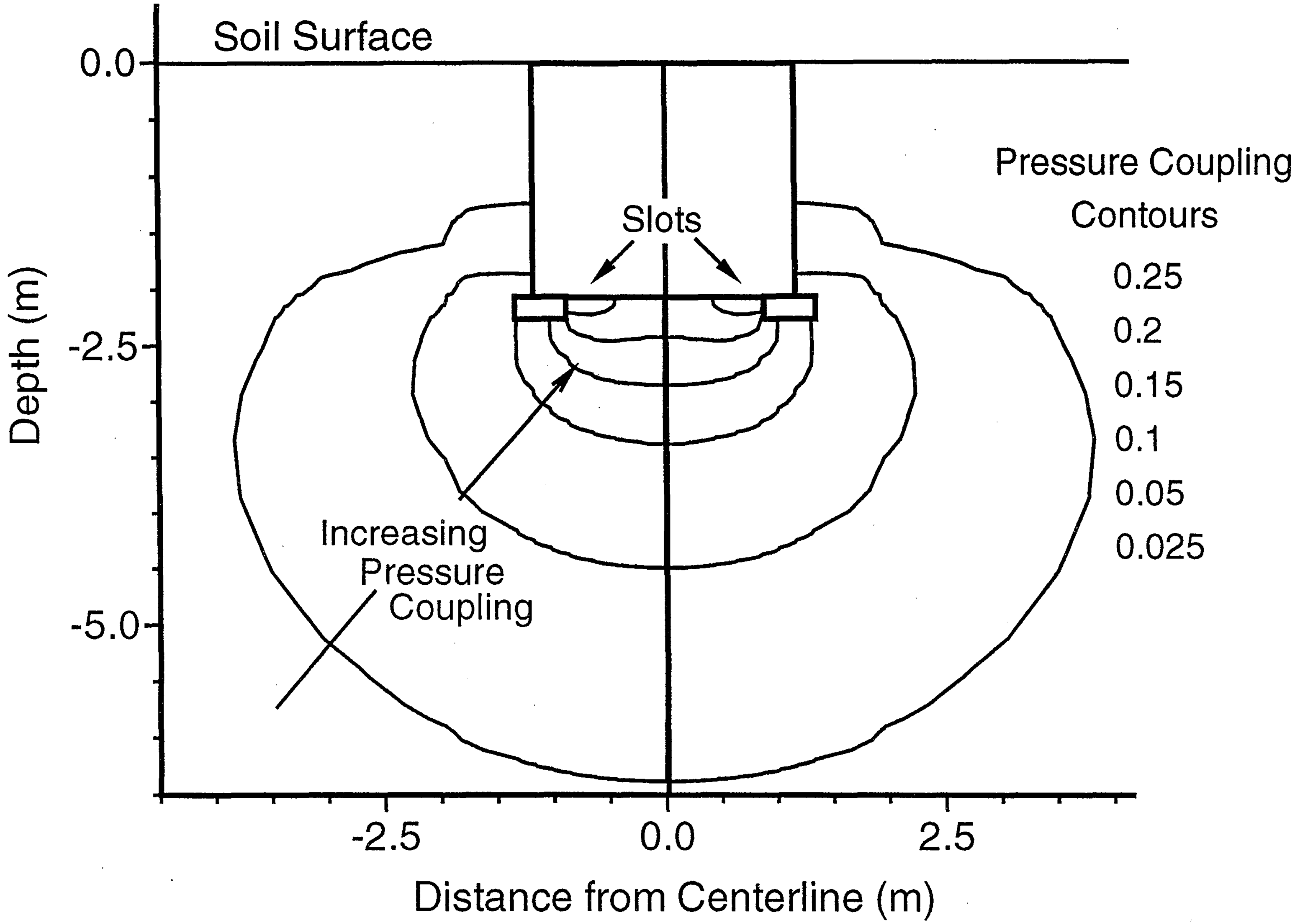

Fig. 6b. Model prediction of the pressure coupling field in the east-west cross-section around the no-gravel structure with all six-slots open. Lines are pressure coupling contours. The cusp in the 0.025 pressure coupling contour near the structure wall corresponds to the interface of the backfill and undisturbed soil. The permeability changes by an order of magnitude at this interface (see Table 2). The line down center of the figure represents the model's plane of symmetry.

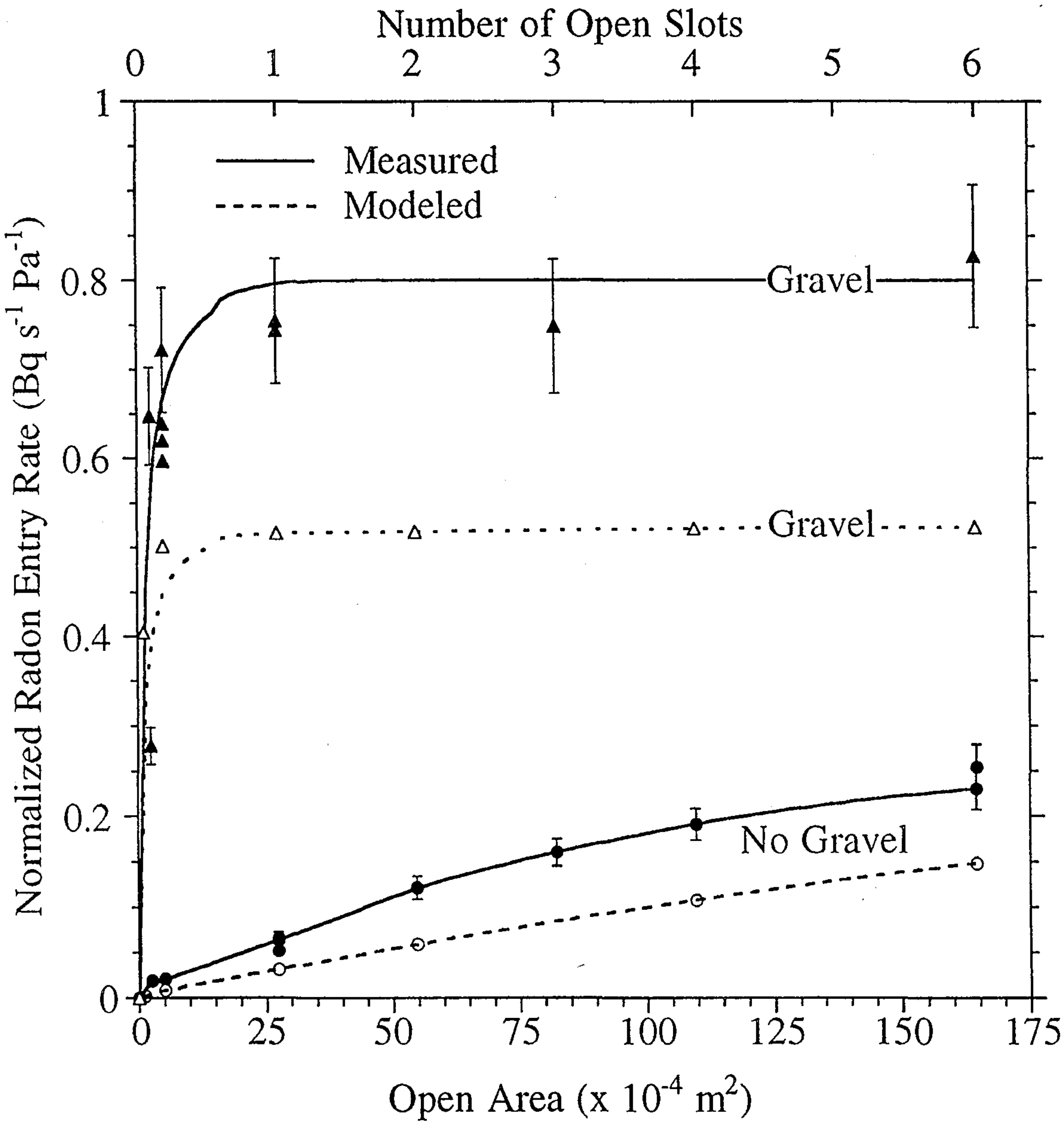

Fig. 7. A comparison of measured and modeled advective radon entry rate normalized by structure depressurization as a function of open area. Solid symbols indicated measured values; open symbols indicate modeled values. Lines are intended for visual guidance only. The vertical bars represent experimental uncertainty.

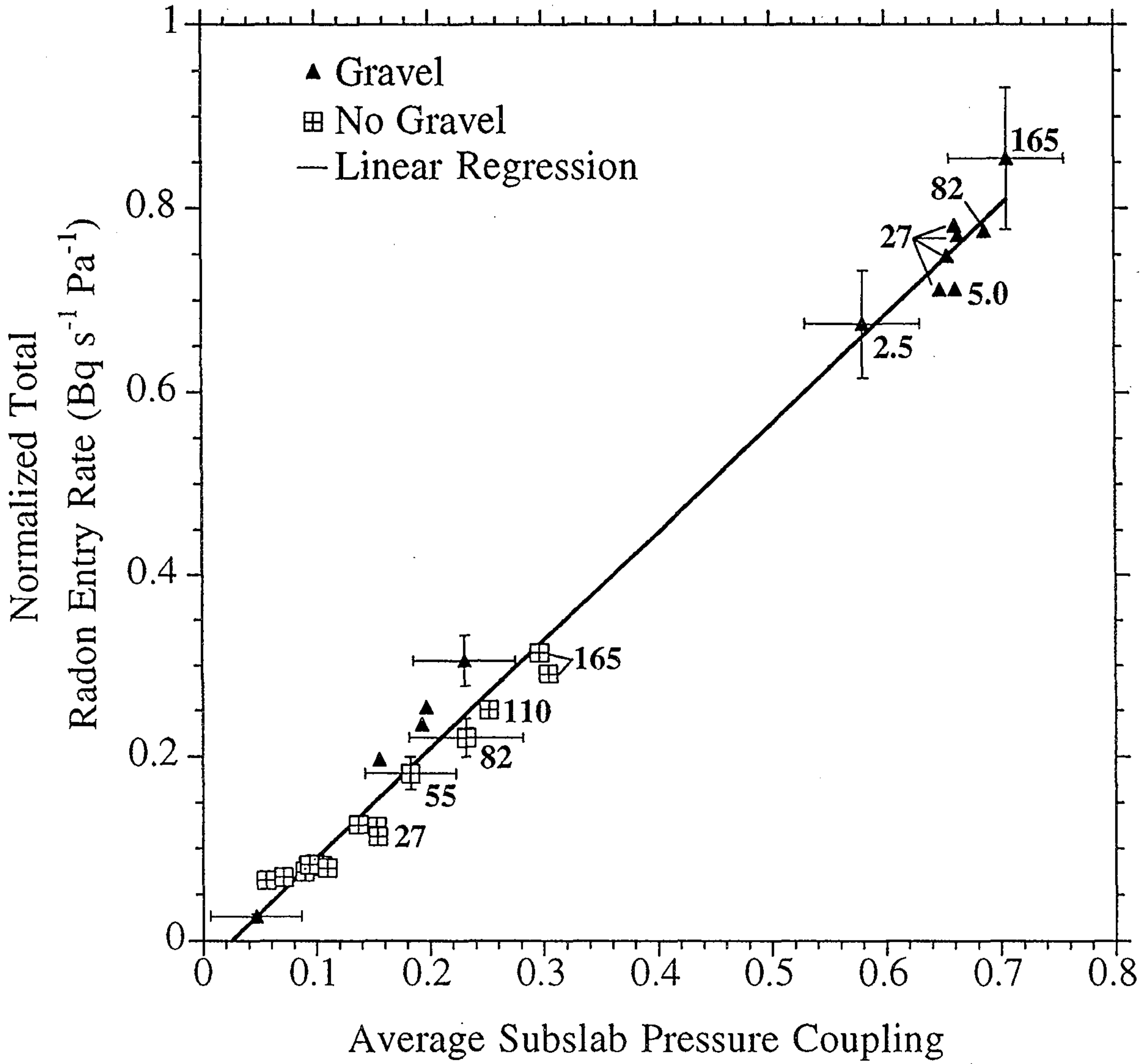

Fig. 8 Measured total advective radon entry rate into both structures normalized by structure depressurization as a function of average subslab pressure coupling. Numbers indicate open area in units of 10^{-4} m^2. Vertical bars indicate uncertainty of measured radon entry rate, a maximum of 12%; horizontal bars indicate uncertainty of average pressure coupling, a maximum of ±0.05. Error bars omitted on some points for visual clarity.