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Radon Risk Mapping using Indoor Monitoring Data – A Case Study of the Lahti Area, Finland

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Abstract

An empirical statistical model is described for the use of indoor radon monitoring data as an indicator of the areal radon risk from soil and bedrock. The percentages of future homes expected to have radon concentrations exceeding the design level of 200 Bq/m³ unless constructed to provide protection against the entry of radon were assessed. The radon prognosis was made for different subareas, soil types and foundation types. This kind of report is used by the health and building authorities.

In this study, 2689 indoor radon measurements were made in one of Finland's most radon-prone areas, consisting of eleven municipalities with a total area of 4600 km² and a population of 186,000. Radon concentrations were seasonally adjusted. Data on the location, geology and construction of buildings were determined from maps and questionnaires. The measurements covered different kinds of geological units in the area.

The radon risk is highest in the gravel-dominated subarea in an ice-marginal formation and lowest in the northern half of the area in buildings constructed on bedrock. In these two areas, the design level of 200 Bq/m³ would be exceeded in 99% and 39% of new houses with slab-on-grade.

KEY WORDS:
Radon, Indoor, Geology, Esker, Modelling, Building

Introduction

Various methods differing in scale and precision have been developed for assessing the radon risk at building sites. Methods for specific-site risk analysis entail on-site measurements of the radon in soil gas or external radiation, or laboratory analysis of the radon production in soil samples, or a combination of all these together. In Finland, the cost of these measurements for one building site might be almost the same as the extra cost involved in building a radon-resistant construction.

Costs can be reduced by providing a regional classification of areas with different levels of radon risk. In most radon-prone areas it is clear even without site-specific investigations that radon-resistant constructions are needed. In contrast, areas with a very low radon risk need neither radon-resistant constructions nor investigations. Areas not classified in either of these two, however, may need more detailed investigations. In Finland the final decision on the measures required rests with local authorities.

The Finnish Centre for Radiation and Nuclear Safety (STUK) has an indoor radon database of 30,000 measurements made systematically in houses, of which we know the exact position coordinates, the type of soil and bedrock at the building site, and details about construction. The latter were collected from questionnaires. The local health authorities had distributed dosimeters to households as recommended in STUK's measurement plan. The main purpose of these plans is to find houses exceeding the action limit. In general, the plan covers different geological units in an administrative area such as a municipality. Thus, relatively representative indoor radon monitoring data are available for different research purposes (Castrén et al., 1992). Data of this nature are also the most reliable for classifying the radon risk in an area. To use indoor radon concentrations in existing houses

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as an indicator of the radon risk from soil and bedrock, the concentrations have to be adjusted for construction and meteorological factors. The former we did with an empirical variance analysis model (Mäkeläinen et al., 1992), and the latter with a numerical physical model (Arvela and Winqvist, 1989).

To date, we have used this method to compile radon prognosis maps for seven municipalities or joint municipal boards. One example is the radon prognosis for the city of Tampere (Voutilainen and Mäkeläinen, 1991). The municipal health and building authorities use these maps when deciding whether they should make preventive measures against radon obligatory or not. Additional investigations are made in some municipalities. In Finland the design level for new houses is 200 Bq/m^3.

Materials

Indoor Radon Concentrations

We have been measuring indoor radon concentrations in the study area since 1982. For this study we used data on 2689 houses. We excluded houses which had either radon-resistant constructions or had been mitigated. Solid-state nuclear track dosimeters were used in the lowest residential storey of the houses during a two-month period in winter. A single measurement per house was used to cover as many dwellings as possible. We applied a physical numerical model to adjust the effect of temperature and wind speed to obtain comparable annual averages (Arvela and Winqvist, 1989, Castrén et al., 1992). As a conservative modification to the model, we assumed that annual means are never less than the radon concentrations measured during the cold season. In the event that the model yielded a lower annual mean than the concentration in winter, we let the annual mean be equal to the actual result of the winter measurement.

Study Area

The study area consists of eleven municipalities located in one of the areas with the highest radon concentrations in Finland. The 4600 km^2 area has a population of 186,000, and the biggest city, Lahti, a population of 93,000. The location of the area is shown in Figure 1, which also depicts the geographical distribution of indoor radon concentrations in Finland.

The most radon-critical landforms in Finland are usually eskers. These long and narrow, steep-sided ridges formed by glacial rivers are composed of stratified sand and gravel, making them permeable to water and air. In the study area there are abundant eskers and two extensive long ice-marginal formations (Salpausselkä I and II). The ice-marginal formations consist mainly of glaciofluvial material such as thick sand and gravel layers. In some places the proximal side of the formations also consists of till layers and the distal side of silt and fine sand layers. The internal structure is more complex than that of eskers. Elsewhere in the area, the pattern of different soil types resembles a jigsaw puzzle, with large areas of glacial till interspersed with small outcrops of bedrock. The low-lying areas are usually covered with clay and silt. Thin sand deposits cover small areas on slopes.

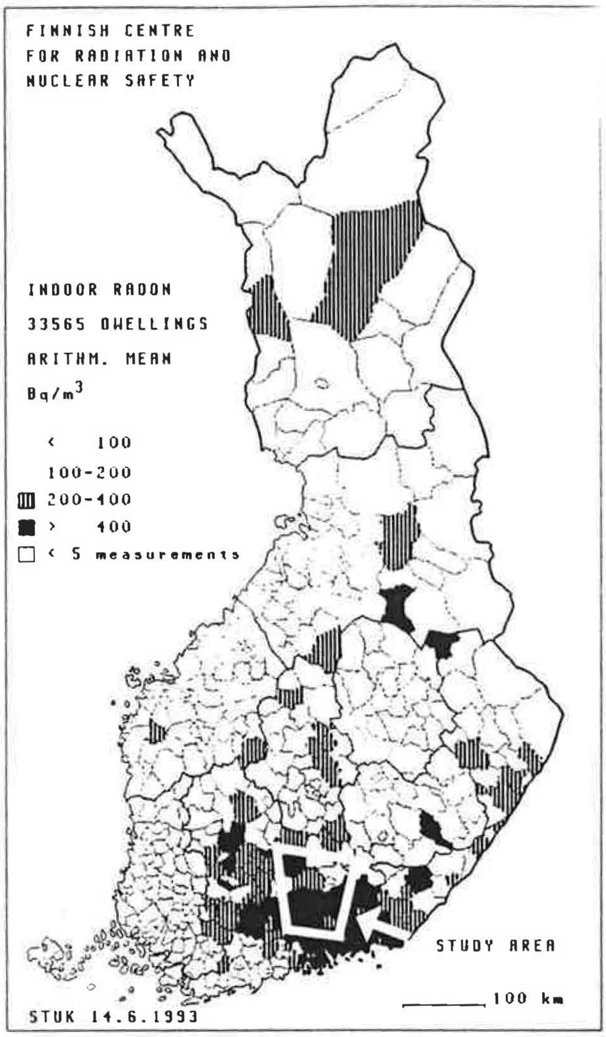

Fig. 1 The indoor radon concentration measured in 33,565 dwellings in Finland. The map shows the arithmetic means of the annual concentrations in municipalities. Measurements were made in single-family houses, two-family houses and rowhouses. The study area is marked on the radon map and consists of the city of Lahti and ten surrounding municipalities. Lahti lies 100 km north-northeast of Helsinki.

Geology of the Building Sites

The local health authorities had marked the house sites on basic or topographic maps ranging in scale from 1 : 5000 to 1 : 100,000. At STUK we determined the coordinates from these maps and the geological characteristics from geological maps using our mapping system.

The type of soil at the building site indicates the permeability of the ground. Gravel-dominated eskers and ice-marginal formations are the most permeable, and clay and unbroken bedrock the least permeable. The type of bedrock was assumed to indicate the uranium concentration of the ground. Aeroradiometric uranium maps were not available for the whole area.

The soil and bedrock types for each house were established from geological maps at 1 : 100,000 scale. For houses built on sand and gravel the soil type was ascertained from detailed maps of sand and gravel resources at 1 : 20,000 scale. The replies to the questionnaires indicated whether or not the house was built on bedrock. Accordingly, 14% of the houses were built on bedrock, 12% on till, 12% on clay or silt, 41% on sand and gravel in eskers or ice-marginal formations, and 21% on sand or gravel in other deposits. These deposits are usually sand-dominated littoral deposits around eskers or ice-marginal formations.

Permeability depends on the grain size and shape. For some of the houses built on sand and gravel, the grain size was established from detailed maps at 1 : 20,000 scale. The grain sizes were classified into three groups: gravel, sand and fine sand.

Construction Data of Houses

Airflow from the ground into a house is affected by the underpressure inside a house and the resistance of the foundation and soil to the leakage of airflow. According to Arvela et al. (1992), the use of permeable, light-weight concrete blocks in foundation walls and open stairwells between the basement and ground floor has led to an increase in the radon concentration of houses built in Finland during the last fifteen years. Thus, by classifying foundation types in an appropriate way, we have a factor that describes the radon leakage to the house. Data on the construction of buildings were collected from questionnaires completed by the residents.

The houses were divided into eight types according to the foundation type and the year of construction. The houses with slab-on-grade laid inside the foundation walls were divided into three age groups and those with a basement into two. The other three types were houses built on a slab with thickened edges, and those with crawl space with foundation walls made of either stone or concrete.

Methods

Statistical Method

We used a simple variance analysis model to calculate the construction factors for adjusted radon concentrations. The radon concentration was assumed to be

$$C_{ik} = a_0 \cdot a_i \cdot \epsilon_{ik} \qquad (1)$$

where C_{ik} is the radon concentration, a_0 the constant, a_i the foundation type coefficient and ε_{ik} the relative error. The coefficients a_i describe ratios of the resistance of the different foundation types to the leakage airflow. From the logarithmic transformation

$$\log(C_{ik}) = \log(a_0) + \log(a_i) + \log(\epsilon_{ik}) \qquad (2)$$

the parameter estimates $\log(a_i)$ and $\log(a_0)$ can be calculated by variance analysis. The adjusted concentrations were calculated for each house as

$$C_{ik} = \exp(r_{ik}) \cdot a_0 \cdot a_l \qquad (3)$$

where r_{ik} is the residual for a house in formula (2) and a_l the foundation type coefficient associated with the highest radon levels, which according to former studies is either slab-on-grade or a house with a basement, both built during the last fifteen or twenty years. The highest radon levels were used because the analysis applies to future homes in which precautions against radon have not been taken.

Delineating Subareas

To describe the radium concentration of the ground, we used subareas as a surrogate factor for radium concentration. The subareas were assumed to be homogeneous to some extent within a certain soil type. They were delineated separately for 1) sand and gravel, 2) bedrock, 3) till, and 4) clay and silt.

Houses built on sand and gravel were divided into two classes according to the formation type. Radon enters the house by diffusion and by pressure difference driven airflows caused by the stack-effect. As regards eskers and ice-marginal formations, the airflow generated by the macro-size stack-effect inside an esker or ice-marginal formation can greatly enhance the radon flow into the house. Thus, we classified sand and gravel into 1) sand and gravel in eskers and ice-marginal formations and 2) sand and gravel outside these formations. The former are thought to be more radon-prone than the latter. The situation of a house on an esker or ice-marginal formation is described by a dichotomous factor with a coefficient b_j. The subarea is described by the third factor c_k and thus the model is

$$C_{ijkl} = a_0 \cdot a_i \cdot b_j \cdot c_k \, \epsilon_{ijkl} \qquad (4)$$

Bedrock, till, clay and silt are less permeable. Their subarea coefficients contain information not only of the radium concentration but also of permeability. The differences in permeabilities between other soil types are smaller than in the case of sand and gravel.

The first approximation was that different bedrock types differ in the abundance and mode of occurrence of uranium. For example, in some granites the uranium is enriched and homogeneously dispersed whereas in some mica gneiss areas it is enriched in younger, migmatizaing granite veins. First, the adjusted indoor radon concentrations in houses built on bedrock were plotted on a map. The boundaries of different bedrock types were delineated, but it was found that the anomalous indoor radon concentrations did not correlate with the bedrock types, possibly because the occurrence of uranium did not follow the boundaries of the bedrock type in this study area. Granite and pegmatite veins are found to form migmatites with all bedrock types, and in certain areas these veins are enriched in uranium and in other areas not. The final delineation of the subarea boundaries for houses built on bedrock and till were made mainly according to adjusted radon concentrations and in a few minor cases according to bedrock type boundaries. The subarea boundaries for houses built on clay or silt were delineated using only the adjusted radon concentrations. The subarea boundaries for houses built on sand and gravel were first delineated according to the formation type (eskers, ice-marginal formations and others). The subareas in ice-marginal formations were formed on the basis of the adjusted radon concentrations. Finally, adjacent subareas with similar coefficients were put together for each of the four soil types.

Soil and subarea coefficients and foundation type coefficients were calculated according to formula (4). Using these models, which assumes lognormal distribution, we calculated the percentages of houses with different foundation types likely to have radon concentrations exceeding 200, 400 or 800 Bq/m^3 in each subarea. The whole analysis was made using the SAS program (SAS Institute Inc., 1989), with the GLM procedure.

Results

The boundaries of nine subareas for sand and gravel areas are shown in Figure 2. The subarea boundaries for bedrock (five areas), clay and silt (two areas) and till (four areas) are shown in Figures 3, 4 and 5. It is emphasized that conclusions of the model for a subarea can be applied only to houses built on the soil in question, not to other soil types that may occur inside the subarea boundaries.

The coefficients a_i and c_k of formula (4) are shown in Tables 1 and 2. The coefficient b_l and its 95% confidence interval which applies when a house is built on an esker or ice-marginal formation is 1.81

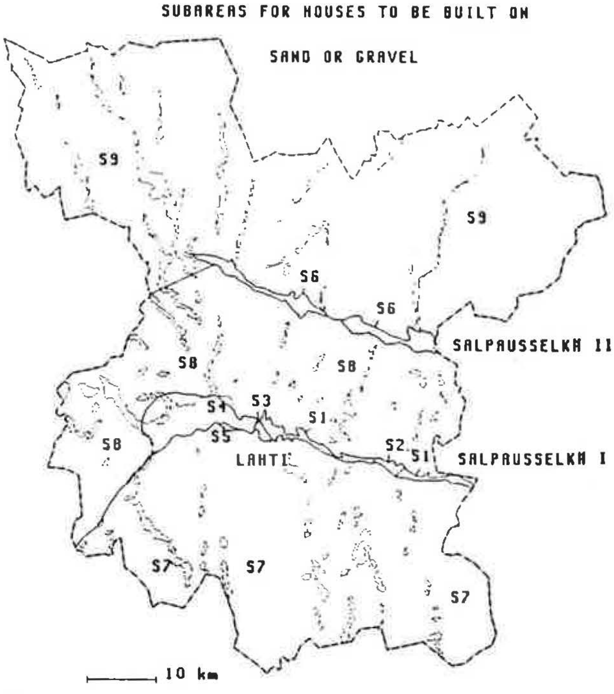

Fig. 2 The subareas (S1–S9) for houses to be built on sand and gravel. Salpausselkä I is divided into subareas S1–S5. Subarea S1 consists of the ice-marginal formation from Lahti eastwards, and S4 from Lahti westwards. Other subareas, S2 (Nastola centre), S3 (Kärpänen, Lahti) and S4 (Soramäki, Hollola) are small but the number of indoor radon measurements is so high that they were divided into their own subareas. Salpausselkä II forms subarea S6. Sand and gravel areas south of Salpausselkä I constitute subarea S7. Sand and gravel areas between Salpausselkäs I and II form subarea S8. Subarea S9 consists of sand and gravel areas north of Salpausselkä II.

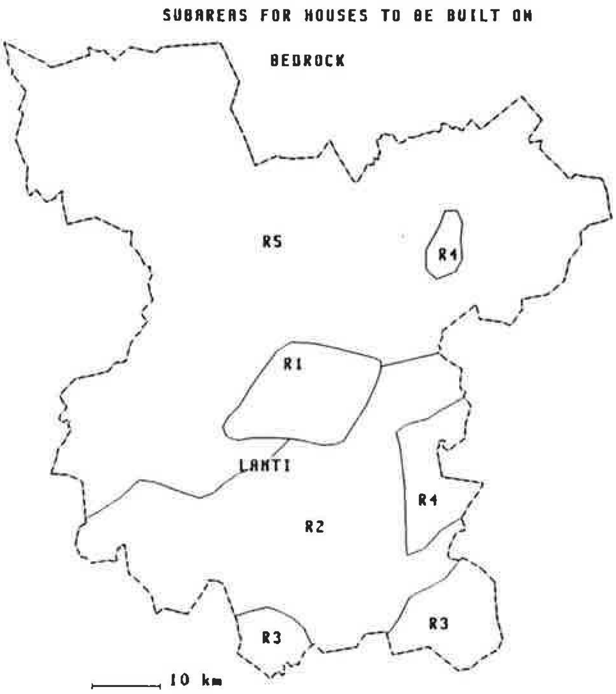

Fig. 3 The subareas (R1–R5) for houses to be built on bedrock.

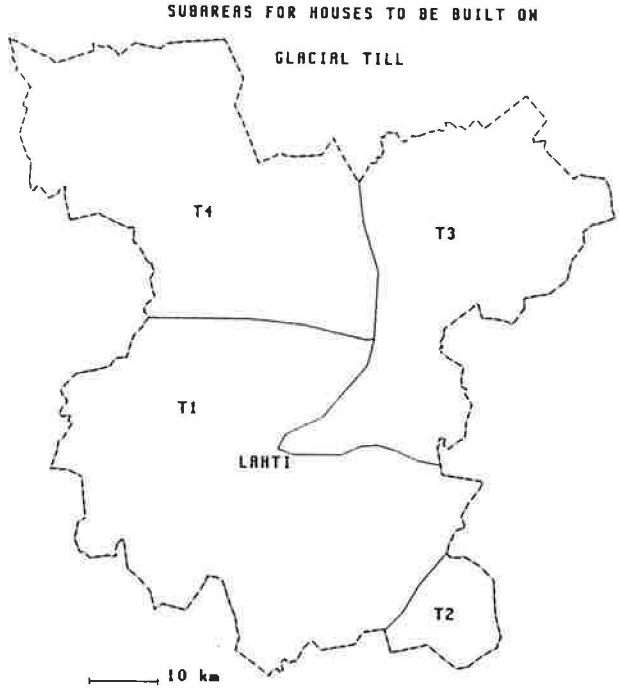

Fig. 4 The subareas (T1–T4) for houses to be built on glacial till.

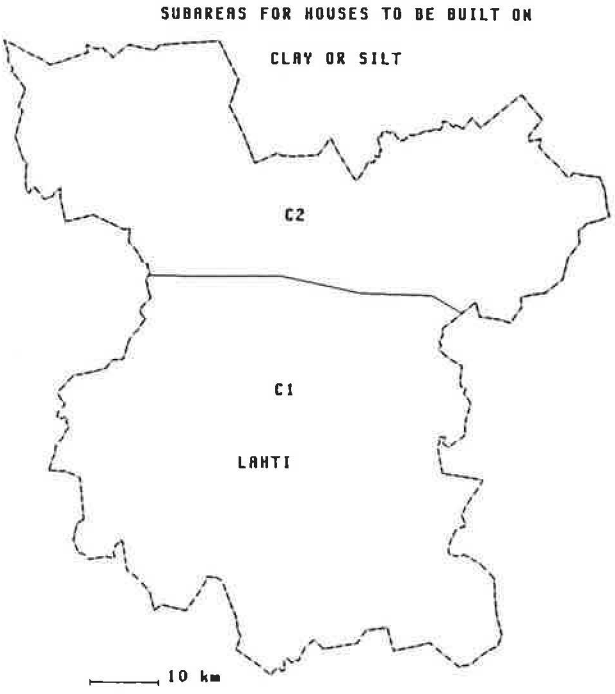

Fig. 5 The subareas (C1–C2) for houses to be built on clay or silt.

(1.63, 2.02) compared with 1.00 for b_2 of other soil types. The coefficients of foundation types a_i are shown in Table 1 and the coefficients c_k for subareas where houses are built on bedrock, clay, till, sand or gravel in Table 2. The square of the multiple correlation coefficient R^2 for the model is 0.35. The estimated value of σ_g is 2.28. The constant term (intercept) with its 95% confidence limits is 113 (83, 155) Bq/m^3.

Applying the model with the parameters of Tables 1 and 2 to a house built on slab with thickened edges on clay in the northern part of the area results in a predicted mean concentration of $0.94 \times 1.00 \times 113$ Bq/m$^3 = 106$ Bq/m^3. The 95% confidence intervals for an individual prediction are 60 and 551 Bq/m^3. Similarly, a new house with a slab-on-grade foundation built on gravel in the area of highest radon concentration in Lahti (subarea S3) has a predicted concentration of $1.60 \times 1.81 \times 4.00 \times 113$ Bq/m$^3 = 1310$ Bq/m^3. The 95% confidence intervals for an individual prediction are 258 and 6647 Bq/m^3.

The percentages of houses with radon concentrations exceeding 200, 400 and 800 Bq/m^3 and for different building sites and foundation types were assessed. The radon risk is lowest in houses built on bedrock in subarea R5, in the northern parts of the study area. This is a very large area, covering over half of the whole study area. In area R5, 15–39% of new houses built on bedrock would exceed 200 Bq/m^3, 3–13% would exceed 400 Bq/m^3, and only 0.3–2.5% would exceed 800 Bq/m^3. The interval of percentages depends on the foundation type.

Table 1 Estimates and 95% confidence limits for the foundation type coefficients in the multiplicative model for predicting indoor radon concentrations.

Foundation type	Estimate and 95% confidence limit	Foundation type	Estimate and 95% confidence limit
Slab-on-grade[a] < 1960	0.96 (0.83, 1.11)	Slab with thickened edges[b]	0.94 (0.83, 1.06)
Slab-on-grade[a] 1960–1979	1.34 (1.21, 1.48)	Crawl space (concrete)	0.87 (0.74, 1.02)
Slab-on-grade[a] ≥ 1980	1.60 (1.44, 1.77)	Crawl space (stone)[c]	0.67 (0.54, 0.81)
House with basement, < 1975	0.70 (0.61, 0.80)	Not known[d]	1.00
House with basement, ≥ 1975	1.35 (1.13, 1.61)		

[a] Slab-on-grade laid inside foundation walls
[b] House on slab with thickened edges
[c] Crawl space with foundation walls made of stone are no longer built
[d] Houses with several foundation types or those with unknown foundation type

Table 2 Estimates and 95% confidence limits for the subarea coefficients in the multiplicative model for predicting indoor radon concentrations.

Subareas[a] on bedrock, till and clay	Estimate and 95% confidence limit	Subareas[a] on sand and gravel	Estimate and 95% confidence limit
ROCK R1	1.85 (1.29, 2.65)	SAND S1	1.48 (1.05, 2.09)
ROCK R2	1.59 (1.14, 2.21)	SAND S2	1.82 (1.27, 2.60)
ROCK R3	1.45 (0.98, 2.15)	SAND S3	4.00 (2.82, 5.69)
ROCK R4	1.10 (0.75, 1.61)	SAND S4	2.26 (1.63, 3.14)
ROCK R5	0.87 (0.60, 1.27)	SAND S5	1.08 (0.74, 1.58)
TILL T1	0.95 (1.40, 2.68)	SAND S6	0.73 (0.50, 1.07)
TILL T2	1.39 (0.85, 2.29)	SAND S7	1.67 (1.22, 2.30)
TILL T3	0.96 (0.66, 1.39)	SAND S8	1.51 (1.09, 2.10)
TILL T4	1.44 (0.93, 2.25)	SAND S9	1.13 (0.79, 1.60)
CLAY C1	1.52 (1.10, 2.09)		
CLAY C2	1.00		

[a] Subarea codes used for different soil types: R = bedrock, T = till, C = clay and silt, S = sand and gravel

The radon risk is highest in subarea S3 in Lahti. This area is situated on the ice-marginal formation, Salpausselkä I. If conventional building constructions were used, 94–99% of the houses would have an indoor radon concentration of over 200 Bq/m^3 depending on the foundation type. The radon level 400 Bq/m^3 would be exceeded in 76–92% of the new houses, and that of 800 Bq/m^3 in 45–73% of houses. Figure 6 gives an example of some of the subareas in the city of Lahti.

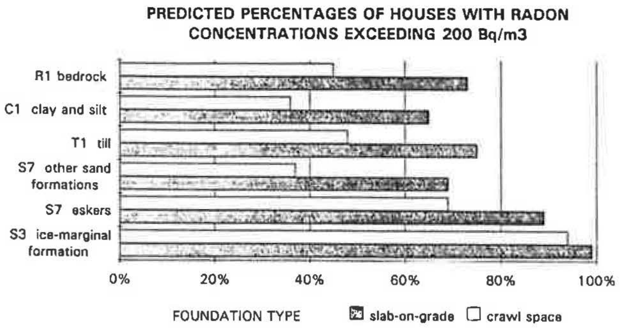

Fig. 6 Predicted percentages of houses with radon concentrations exceeding 200 Bq/m^3 calculated for different building sites and for two different foundation types. The subareas cover the city of Lahti and parts of surrounding municipalities.

The grain size itself was not as significant a factor as was the classification of sand and gravel into two deposition groups according to colour code from the soil maps at 1 : 100,000 scale. Grain size was significant only on the ice-marginal formations, where the radon concentrations in houses built on gravel would be 30% higher than in houses built on sand.

Discussion

This kind of subarea classification based on indoor radon measurements and geology is a source of information about the radon risk on an areal scale. It is most reliable when it refers to construction near or within an existing settlement. There is, of course, some variation in the radon risk within a subarea, particularly as the uranium concentration in bedrock can vary considerably within quite a small area. The uranium concentration is normally more homogeneous in building sites other than those on bedrock.

In the data available, the parameter best corresponding to permeability is the classification based on soil maps at 1 : 100,000 scale. On these maps the dark green of eskers, deltas and ice-marginal formations and the light green of other sand and gravel formations correspond roughly to the grain size and thickness of the formations. If the shape of the sand and gravel formations had been determined, the assessments for "eskers" could have been more detailed. Steep-sided, high and narrow eskers are the most radon-prone formations and flat and low landforms the least radon-prone because of the macro-size stack-effects inside the formations.

The oldest measurements date from 1982 and the most recent from 1992. We have revised our questionnaire many times during this period, and the classification of house type, foundation type, etc. is now more accurate than it was initially.

The radon risk report is a useful tool for health and building authorities when they have to decide whether an area requires radon-resistant constructions or not. The way in which the report is actually used depends on the municipality in question. This study has not yet come into use in municipalities. At present, in the city of Lahti and some neighboring municipalities the authorities require radon-resistant constructions only on the ice-marginal formation, Salpausselkä I.

The local authorities in the city of Tampere received our prognosis report (Voutilainen and Mäkeläinen, 1991) three or four years ago. The only areas where they have required radon-resistant constructions are the top and upper parts of eskers, where 80–90% of houses would exceed 200 Bq/m^3 and 40–50% 800 Bq/m^3. Elsewhere they have notified individual builders, building companies and geotechnical planning companies of the radon risk. In these areas radon-resistant constructions are not required even though on certain soil types and in certain subareas more than 50% of new houses would exceed 200 Bq/m^3 and 3–6% 800 Bq/m^3.

This method cannot be validated by radon measurements in houses to be built. Many future houses will be protected against radon because of recommendations made by local authorities in accordance with this study. We intend to make the validation in the near future by using random sampling of houses built prior to publication of this report.

Because the geological factors were determined from maps varying in scale, the data are not very accurate for individual building sites. To assess the radon risk for individual building sites within these larger areas, field measurements must be conducted.

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