3. Measuring radon concentration in soil gas

As the soil gas radon concentration may vary widely over a small distance, any evaluation based on a single measurement is not viable. Under the original method of classifying the radon risk of foundation soils (BARNET 1994), a minimum of 15 soil gas radon concentration measurements is required when a building site for a single family house is evaluated (MATOLÍN and PROKOP 1991). The measurement of larger areas should be made in a 10 × 10 m grid, or a 20 × 20 m in some cases.

This research was focused on the statistical evaluation of soil gas radon concentration data. The main goal was to reconfirm the requirements concerning the minimal set of soil gas radon concentration values and the grid of measuring points.

3.1. INPUT DATA

Most of the data used for the statistical testing came from the old records of the RADON corporation. These data were soil gas radon concentration values from commercial measurements. Only a few supplementary measurements were performed during this stage of the research.

Our detailed analysis involved thirteen large data sets in which the number of measurement points ranged from 61 to 200. The data were obtained during the radon surveys of large building areas in a 10 × 10 m grid, between 1993 and 2000. First, the basic statistical parameters were calculated for each of the13 original sets of data. Several subsets of values corresponding to a 20 × 20 m grid were then chosen from each of the original data sets, and the statistical analysis was repeated. Finally, two randomly chosen subsets from each of original data sets were also tested. Furthermore, 30 smaller data sets (each having either 18 or 25 measuring points) have been analyzed.

3.2. STATISTICAL EVALUATION

The 13 larger data sets (an example is given in Tab. 2) can be divided into several groups according to the prevailing distribution type. The distribution of several data sets was closely approximated by a log-normal model, while the distribution of other sets was found to be heterogeneous, being amenable to neither a log-normal nor a normal model. Normal distribution was also applicable in some rare cases. The general conclusion that neither a normal nor a log-normal model is generally applicable agrees well with the results of a previous study (NEZNAL et al. 1994a). Robust nonparametric estimates, such as the median or the

Table 2. Results of statistical evaluation

Data set No.	1591–96						
	original set of data "10 × 10 m"	choice "20 × 20 m" (1)	choice "20 × 20 m" (2)	choice "20 × 20 m" (3)	choice "20 × 20 m" (4)	random choice (1)	random choice (2)
N	197	57	50	47	43	60	40
mean	7.9	7.2	7.4	7.4	9.8	7.4	7.6
$mean_{10}$	6.3	6	5.9	6.2	7.6	6.1	6
median	5.2	5.1	5.1	5.3	5.4	5.1	5.1
Q_{75}	8.5	8.3	7.8	7.6	10.4	8.5	8.4
sigma	7.5	5.8	7.2	6.3	10.5	6.5	7.2
$sigma_{10}$	3	2.7	2.9	2.8	5	3.3	3.6
$(Q_{75} - Q_{25})/2$	2.3	2.2	2.1	1.8	3.2	2.6	2.5
minimum	1.1	1.1	1.4	1.4	1.4	1.4	1.4
maximum	58.5	27.7	38.3	33.4	58.5	30.4	30.4
sigma/mean	0.95	0.8	0.96	0.86	1.07	0.88	0.95
normality test	no	no	no	no	no	no	no
95 %CI: mean	(6.8;8.9)	(5.7;8.8)	(5.4;9.5)	(5.5;9.2)	(6.6;13.0)	(5.8;9.1)	(5.3;9.9)
95 %CI: median	(5.0;5.7)	(4.3;6.0)	(4.4;6.0)	(4.7;6.6)	(5.0;7.4)	(4.1;5.6)	(3.8;5.6)
95 %CI: sigma	(6.8;8.3)	(4.9;7.1)	(6.0;8.9)	(5.3;8.0)	(8.7;13.3)	(5.5;8.0)	(5.9;9.2)
95 %CI: Q_{75}	(6.9;10.9)	(6.0;11.2)	(6.0;12.7)	(6.5;14.3)	(7.3;21.5)	(5.6;12.3)	(5.3;17.9)

N = number of measuring points; mean = arithmetic mean; $mean_{10}$ = trimmed arithmetic mean (10 %); Q_{25} = the 1st quartile (the 25th percentile); Q_{75} = the 3rd quartile (the 75th percentile); sigma = standard deviation; $sigma_{10}$ = trimmed standard deviation (10 %); 95 %CI = 95% confidence interval third quartile, are more suitable for the description of soil gas radon concentration data.

One of the goals of this research was to test the agreement of the results using measuring point grids of 10 × 10 and 20 × 20 m, and to test the possibility of reducing the required minimal number of measuring points. The main problem is that the number of measurements is usually low for the purposes of statistical analysis. Any reduction in the number of measured values results in an enlargement of the relevant confidence intervals. In other words, if the number of measured values is low, the width of the confidence intervals is influenced more by the size of the data set than by the variability of data.

The minimum size of data sets that ensure acceptable relative errors of the standard deviation (10 %) is about 50 values if the distribution of the data set is normal. For a log-normal distribution, the minimum size of the data set is substantially higher. Radon surveys are usually performed in areas no larger than 100 × 100 m, with larger areas being measured only rarely. If measurements are made in a 10 × 10 m grid, an area of 100 × 100 m corresponds to 121 measuring points. When a 20 × 20 m grid is used, only 36 measuring points are taken. Such a low number is insufficient for a proper statistical evaluation, even if the data distribution is normal.

When data sets with larger variability are evaluated, substituting a 20 × 20 m grid for a 10 × 10 m grid causes a substantial enlargement of confidence intervals for the median and for the third quartile (see Tab. 2). Limit values that separate the medium and high categories of radon risk (radon index) are 10 and 30 kBq . m^{-3}, respectively, when the soil permeability is high. The confidence interval for the third quartile could thus cover all three intervals corresponding to three different risk categories.

For small data sets (15 soil gas radon concentration values corresponding to a building area for a single family house), the applicability of statistical evaluations is disputable at all.

It can be concluded that, from the statistical perspective, there are no good reasons for substituting a 20 × 20 m grid for a 10 × 10 m grid. This conclusion is valid also for reducing the minimum required number of measuring points when a building site for a single family house is evaluated.

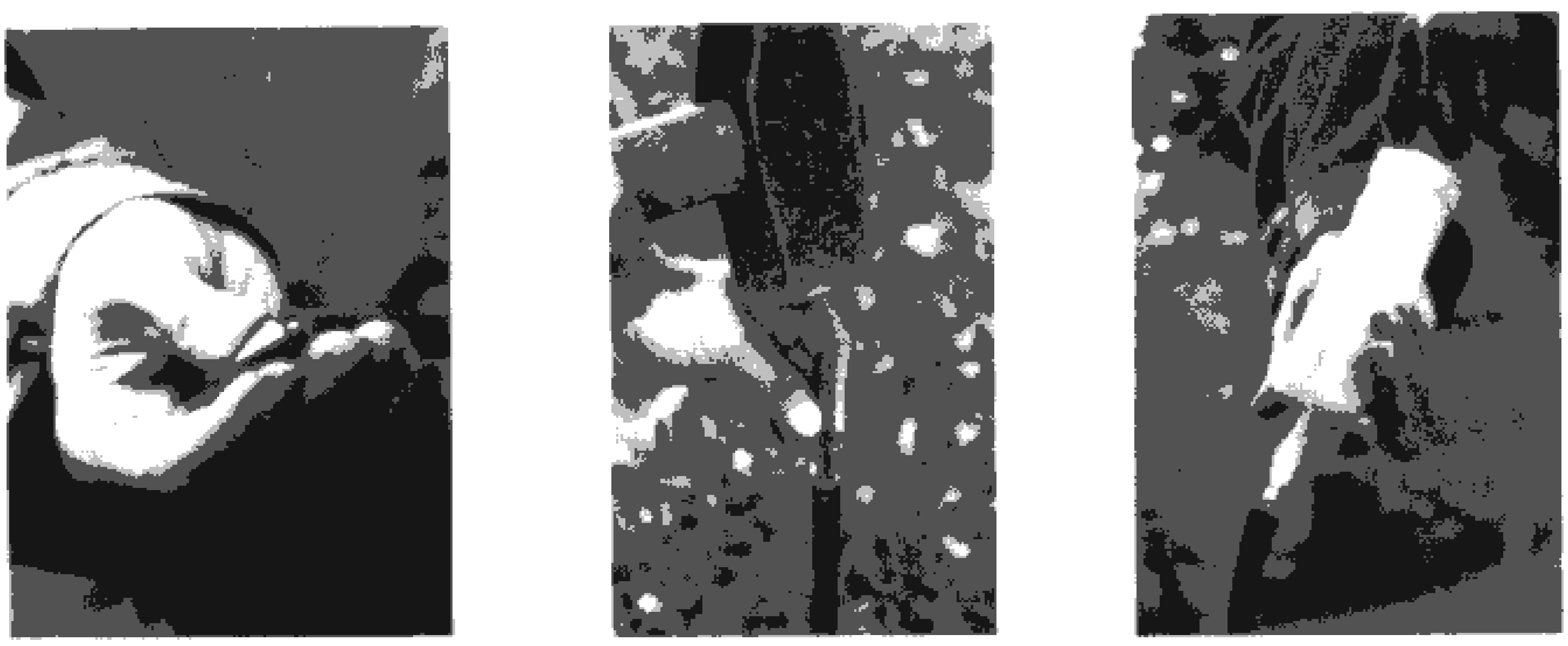
4. Soil gas sampling

The equipment for soil-gas sample collection commonly used in the Czech Republic consists of a small-diameter hollow steel probe with a free, sharpened tip at the lower end. The probe is pounded into the soil to a depth of 0.8 m. A punch wire is then inserted into the probe. The active area is created in the head of the probe by the extension of the tip, by means of the punch wire, to a distance of several centimeters. Samples of soil-gas are collected using a syringe or a pump, and are introduced into evacuated Lucas cells (see Fig. 3). A similar sampling technique was described by REIMER (1990).

Measurements of soil-gas radon concentrations carried out in previous years (MATOLÍN et al. 2000, NEZNAL et al. 1994b, NEZNAL et al.1996a) indicated the dependence of soil-gas radon concentrations on sampling depth, soil permeability, the dimensions of the cavity from which the soil-gas samples were taken, and the soil-gas sampling technique used. Soils of low permeability often require the enlargement of the sampling cavity (i.e. the enlargement of the active area).

4.1. SAMPLING GEOMETRY

The relationship between the soil-gas radon concentration and variable sampling geometry was studied at four test areas characterized by soils of low permeability and/or high soil moisture. The measurements were made at nine



(a) (b) (c)

Fig. 3. Soil gas sampling.
(a) Inserting the sharpened tip into the lower end of the probe.
(b) The sharp tip is moved a few centimetres lower – this action creates a cavity at the lower end of the probe.
(c) Soil-gas sample collection using a syringe.

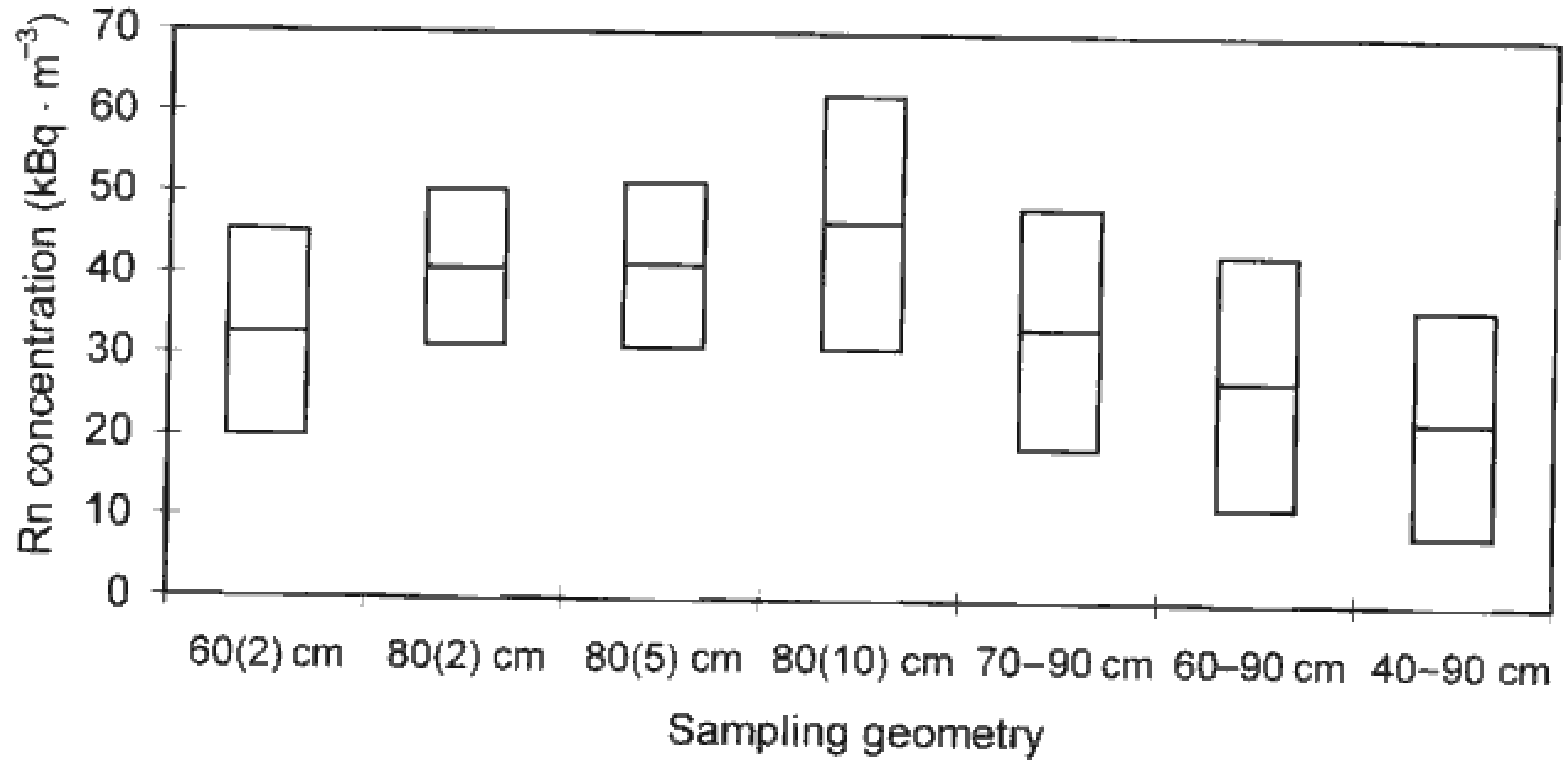


Fig. 4. Reference area Světice: Soil gas radon concentration (arithmetic mean ± standard deviation) vs. sampling geometry.

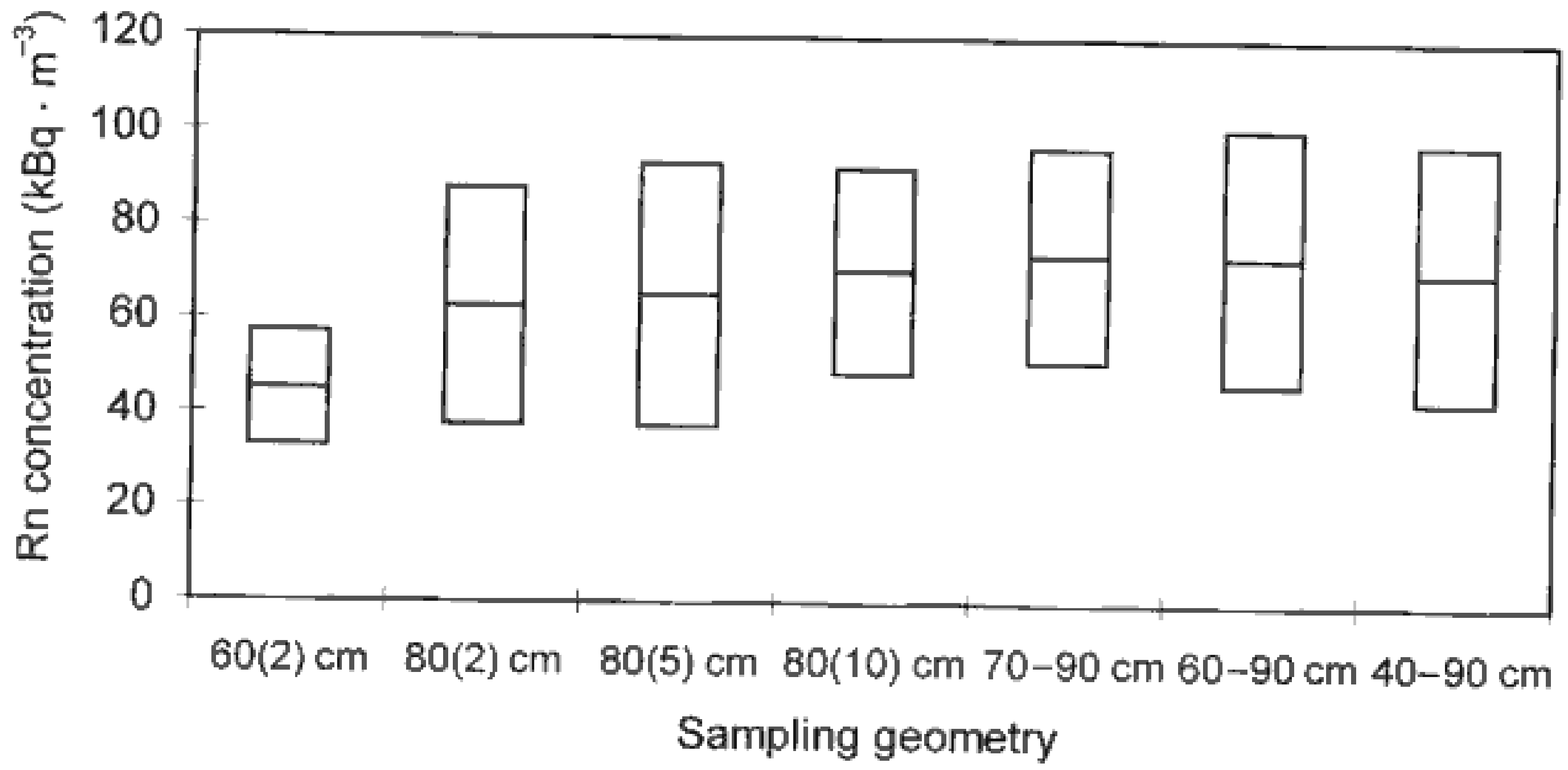


Fig. 5. Reference area Ptice: Soil gas radon concentration (arithmetic mean ± standard deviation) vs. sampling geometry.

measuring points at each test area. At each measuring point, the soil-gas samples were collected from different sampling depths and by using different active area dimensions:

- sampling depth 60–62 cm, height of the cavity 2 cm, referred to as "geometry 60 cm (2 cm)."
- sampling depth 80–82 cm, height of the cavity 2 cm, referred to as "geometry 80 cm (2 cm)."
- sampling depth 80–85 cm, height of the cavity 5 cm, referred to as "geometry 80 cm (5 cm)."
- sampling depth 80–90 cm, height of the cavity 10 cm, referred to as "geometry 80 cm (10 cm)."
- sampling depth 70–90 cm, height of the cavity 20 cm, (the probe was retracted back to the surface), referred to as "geometry 70–90 cm."
- sampling depth 60–90 cm, height of the cavity 30 cm, referred to as "geometry 60–90 cm."
- sampling depth 40–90 cm, height of the cavity 50 cm referred to as "geometry 40–90 cm."

4.2. FIELD MEASUREMENTS

Measurements were taken at three test areas: Světice, situated 20 km SE of Prague, bedrock formed by Ordovician shales, covered by loess loams; Dubnice in northern Bohemia, situated 20 km W of Liberec, bedrock formed by Cretaceous claystones and sandstones, covered by clayey sands or sandy clays; and Růžená in southern Bohemia, situated 90 km S of Prague, bedrock formed by durbachites (biotite syenite) of the Central Bohemian pluton, covered by fluvial sediments. The results obtained at these sites were similar. The soil-gas radon concentration readings were almost identical when geometry 80 cm (2 cm), geometry 80 cm (5 cm), or geometry 80 cm (10 cm) were used. Radon concentrations in the soil-gas samples collected using geometry 70–90 cm were slightly lower, but comparable with the previous ones. The results obtained using the geometry 60–90 cm were lower but similar to those from the geometry 60 cm (2 cm) trial (see Fig. 4).

Almost no dependence of soil-gas radon concentration readings on the dimensions of the active area was observed at the fourth test area in Ptice (situated 20 km W of Prague, bedrock formed by Ordovician shales, Quaternary cover by eolian clayey loams), characterized by a homogeneous vertical soil profile (see Fig. 5).

4.3. THE INFLUENCE OF VARIABLE GEOMETRY ON MEASUREMENT RESULTS

It can thus be concluded that the measured soil-gas radon concentrations do not depend on the sampling geometry if the soil layer is homogeneous and of low permeability.

A decrease of soil-gas radon concentration with increased dimensions of the active area (i.e. using geometry 70–90 cm, geometry 60–90 cm, or geometry 40–90 cm) indicates that the vertical soil profile is not homogeneous and that the soil permeability is higher at shallow depths.

The perfect sealing of all parts of the equipment is required when soil-gas samples are collected in soils of low permeability.

5. Permeability determination

The original method for classifying the radon risk of foundation soils used direct in situ measurements of permeability or particle size analyses (in which the permeability is derived simply from the weight percentage of the fine fraction in a soil sample). The main disadvantages of particle size analyses are that it does not consider other factors influencing soil permeability, such as the natural moisture, density, and effective porosity of the soil. The results of direct measurements are strongly dependent on small-scale variations in the character of the soil. Moreover, the equipment commonly used in the Czech Republic does not enable exact measurements in soils of extremely low or high permeability (results vary by several orders of magnitude). No rules for the statistical evaluation of permeability values, the minimum number of measurements, or for the evaluation of changes in vertical profiles were included in the original method.

This part of the research focused mainly on selecting the most suitable method for determining soil permeability, and on the influence of spatial and seasonal variations on radon risk classification. More detailed information on the results from this research is given in NEZNAL and NEZNAL (2003). For better understanding of factors influencing the permeability and the reasons for changes of the uniform method, it is repeated in this section.

5.1. COMPARING THE METHODS FOR PERMEABILITY DETERMINATION AND FIELD MEASUREMENT

As the first step, a wide range of approaches used in Czech Republic and other countries for determining the gas permeability of soils and rocks were considered for further investigation (TANNER 1994). These consist mainly of single probe measurements (DAMKJAER and KORSBECH 1992), dual probe measurements (GARBESI et al. 1993), and the derivation of permeability from factors such as by aqueous permeability (ROGERS and NIELSON 1991) and grain size analysis. Methods used in fields other than radon risk mapping were also included (ASHER – BOLINDER et al. 1990, MORRIS and FRALEY 1994). After comparing the advantages and disadvantages of these systems from the professional and economic perspectives, three direct measurement prototypes were prepared. The main goal was to avoid or at least decrease the disadvantages experienced with the RADON JOK equipment.

These three prototypes and the RADON JOK system were tested under various geological conditions. The tests confirmed the expected limitations of the particular methods. The single probe system was chosen for the testing of temporal and spatial variations due to its simplicity and based on its previous results. The measurements were performed at two test areas with distinct geological characteristics: Světice, situated 20 km SE of Prague, with bedrock formed by Ordovician shales, covered by loess loams; and Klánovice, situated in the eastern part of Prague, with bedrock formed by Cretaceous sandstones, covered by sands. The tests were performed monthly during a one-year period. The gas permeability of soils and rocks was measured at 15 points at a depth of 0.8 m (the same depth at which soil gas samples are collected for radon concentration measurements).

Other important parameters, mainly soil gas radon concentration and soil moisture, were also determined in the interest of considering any correlations that might arise between the various influencing factors. Data gathered from the Kocanda and Lysá nad Labem test areas (section 8.1.) were also used in the final assessment.

Detailed measurements from 21 other areas have been used for comparing the results of direct in situ permeability measurements with those derived from particle size analysis. The assessments based on the description of the variability of several factors in the vertical profile were compared with those based on the results of direct *in situ* measurements and derived from particle size analysis.

5.2. RESULTS OF FIELD MEASUREMENTS

In general, a good correlation between the measured parameters was obtained at areas with homogeneous and highly permeable soils. Conversely, correlations between radon concentration and permeability, as well as between permeability and soil moisture, were very weak in environments of medium or low permeability. This conclusion was valid even for highly permeable environments, where relatively high saturation of the upper horizons occurred (Fig. 6).

Concerning the statistical evaluation, it is possible that the individual permeability values are substantially affected by the small-scale of the measured soil volume, especially in areas of medium to low permeability. The statistical evaluation can be affected by the occurrence of

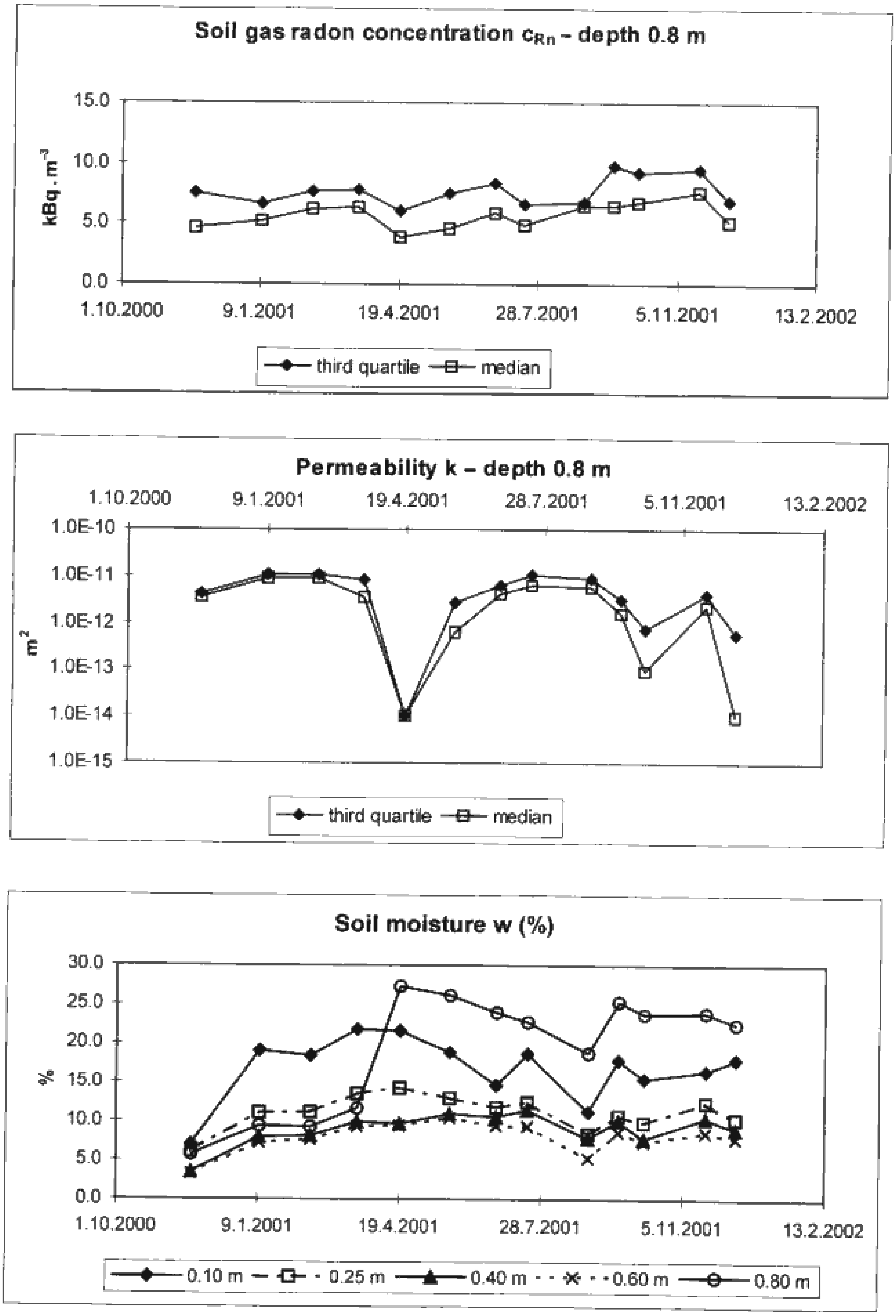


Fig. 6. Results of measurements at area Klánovice.

high permeability outliers, and by inexact values under the lower limit in cases of extremely low permeability. Thus, a large number of measurements should be required for evaluating direct measurements of permeability.

At most of the 21 areas the final classification based on the vertical profile assessment was consistent with the results of direct measurements, and partly with the data derived from particle size analysis. Where the permeability derived from particle size analysis is contradictory, the underestimation of permeability is caused mainly by low soil moisture and/or by the occurrence of significant macro- and micro-fissures. Overestimated permeability can be observed especially in fine-grained sands with relatively high soil moisture.

5.3. EVALUATION OF PERMEABILITY

For improving the method for radon risk classification, it is recommended that the permeability of soils be determined by means of a large number of direct in situ permeability measurements and/or by the expert evaluation of permeability.

Direct in situ permeability measurements should be performed at a depth of 0.8 m under the ground surface. It is recommended that the permeameters based on measuring air flow during suction from the soil, or the pumping of air into the soil under a constant pressure, be used.

For direct in situ permeability measurements, the requirements for the number of measurements are the same as for those for soil gas radon concentration, i.e. at least 15 measurements for a single building (with the building site $\leq 800\ m^2$), or measuring in a 10×10 m grid for larger areas (building sites $> 800\ m^2$). The third quartile of the data set, which diminishes the influence of outliers and of local permeability anomalies, is used as a decisive value for the assessment.

In such cases it is not necessary to describe the vertical soil profile. However, the person responsible for the assessment and final classification must consider the local permeability anomalies and variations, and the data spread.

The expert evaluation of soil permeability is necessary when in situ permeability measurements are not performed at all soil gas sampling points. This expert evaluation, which results in classifying the permeability of a site as low, medium, or high, is based on the description of vertical soil profile to a minimum depth of 1 m. This evaluation must be accompanied by at least one of the following methods:

- ⇒ Macroscopic description of samples from a depth of 0.8 m, with the classification of its permeability (low – medium – high). The estimation of the fine fraction (f, particle size < 0.063 mm) is used for this classification.
- ⇒ Evaluation of the resistance during the suction drawing of soil gas samples for the radon concentration measurements at all sampling points, and estimating the overall permeability category (low – medium – high).

During this evaluation, which strongly depends on personal experience (i.e. on expert, yet subjective knowledge), it is necessary to describe the changes in vertical profile from the surface down to the assumed depth of the building foundation, or to the depth of the assumed contact between the building and the soil.

6. Radon exhalation rate from the ground surface

More detailed information about the research on measuring the radon exhalation rate from the ground surface, as well as a detailed analysis of measurement results, has been presented by NEZNAL and NEZNAL (2002).

A uniform method used in the Czech Republic for determining the radon potential of foundation soils is based on measuring the radon concentration in soil gas, and on determining soil permeability. The samples of soil gas are collected at a depth of 0.8 m below the ground surface. When the thickness of soil cover is very low, or when the soil pores are saturated with water, the sample collection at that depth can be complicated or almost impossible. We must therefore ask whether there is another way to assess the soil gas radon concentration.

The radon exhalation rate from the ground surface is one of the factors that characterizes the radon potential of soils, or radon potential of waste materials contaminated by natural radionuclides. Various techniques for determining radon exhalation rates are available, such as the simple accumulator method (HINTON 1985, ANDĚL et al. 1994, NEZNAL et al.1996b, MERTA and BURIAN 2000). However, a serious disadvantage connected with this method is that the ground surface is strongly affected by changing meteorological conditions. Large temporal variations of the radon exhalation rate can therefore be expected.

6.1. THE SIMPLE ACCUMULATOR METHOD

The determination of radon exhalation rate using the simple accumulator method is based on measuring the increasing radon concentration in a cylindrical canister placed on the measured surface. During the field survey, cylindrical canisters having a base of $0.08\ m^2$ and a height of 0.2 m were used. A single measurement of the radon exhalation involved the determination of rising radon concentrations in four air samples collected from the accumulator in regular 40 or 60 minute intervals. For the determination of other parameters, samples of soil gas for the measurement of soil gas radon concentration were collected from a depth of 0.8 m below the ground surface. Direct in situ measurements of soil permeability were made using the RADON-JOK equipment. This latter method is based on a soil-gas withdrawal by means of negative pressure. Soil moisture was determined by comparing the weight of the soil samples before and after drying. Temporal changes in soil moisture were determined using an indirect method based on measuring the di-electric constant of the soil.

6.2. TEST SITES

The majority of field measurements were performed at four test areas characterized by different geological conditions: Dubnice in northern Bohemia, situated 20 km W of Liberec, with bedrock formed by Cretaceous claystones and sandstones, covered by clayey sands or sandy clays; Stráž, situated in northern Bohemia near the town Stráž pod Ralskem on the uranium mill tailings; Růžená, situated in southern Bohemia 90 km S of Prague, with bedrock formed by durbachites of Central Bohemian pluton, upper horizons formed by weathering crust; and Žibřidice, situated in northern Bohemia 18 km W of Liberec, with bedrock formed by Cretaceous sandstones, covered by fluvial sands and clays. Radon exhalation rates, soil permeability and soil gas radon concentrations were determined at ten measuring points during a single day. Soil moisture was measured in six probes at different depths below the ground surface. Temporal changes of all factors were monitored at four test areas from summer 2000 to summer 2001. The measurements were repeated every second month, i.e. seven times at each area during the testing period.

Two different ways of placing the canisters on the measured surface were tried at the test areas of Dubnice and Stráž: (a) the canister is placed on an undisturbed soil surface and sealed with clay or sandy clay (this method will be referred to as the "surface" method); (b) the upper soil layer is removed and the canister is placed about 10 cm below the ground surface (this method will be referred to as the "–10 cm" method).

In September 2001, supplementary measurements of the radon exhalation rate, soil permeability, and soil gas radon concentration were made at the Zdiměřice test area (situated about 5 km SE of Prague, bedrock is formed by Proterozoic shales, upper horizons by clays). This site is characterized by an extremely low soil permeability and by water saturation of the upper soil layer.

6.3. APPLICABILITY OF THE METHOD

A detailed analysis of measurement results has been presented by NEZNAL and NEZNAL (2002). The spatial variability of radon exhalation rates was comparable or slightly higher than that of soil-gas radon concentrations. A higher variability was observed when measurements were made under extreme meteorological conditions (such as when the soil surface was frozen or saturated with water, or when strong winds occurred).

The temporal variability of radon exhalation rates were significantly higher than that of soil-gas radon concentration when the soil gas samples were collected from a depth of 0.8 m below the surface. Two different methods of placing the canisters on the surfaces to be measured (the "surface" and the "–10 cm" methods) were tested at two test areas. It was expected that the latter of the two would be less sensitive to changes in meteorological conditions, but this assumption was not confirmed. The temporal variability of the results obtained by both methods was similar.

In general, the correlations between the radon exhalation rate from the surface and the soil-gas radon concentration, and between the radon exhalation rate and soil moisture, were very weak. This conclusion was valid even for the soil moisture measured at a depth of 0.1 m.

It is therefore concluded that measured values of radon exhalation rate are substantially affected by the conditions of the soil surface. Significantly lower values were observed when the soil surface was frozen or covered by water. Furthermore, a decrease in radon exhalation rate was found at the Růžená test area following compression of the upper soil layer.

Supplementary measurements that were taken at the Zdiměřice area have confirmed that the use of radon exhalation rate is not suitable for the determination of radon potential of soils at building areas with soils that are saturated or of low permeability. If the water saturation of the upper soil layers is connected with a soil's low permeability, the radon exhalation rate from the surface is very low even when the measurements of radon concentration in the soil gas indicate a high radon potential.

For these reasons the radon exhalation rate method cannot be recommended as a standard supplementary method for assessing the radon risk of foundation soils.

7. Instantaneous, integral, and continual measurements of soil gas radon concentration

Evaluating the radon potential of foundation soils is based on the instantaneous values of soil gas radon concentrations measured using Lucas cells. This part of the research focused on integrated and continual measurement techniques, in which we analyzed the applicability of continual and/or integral measurements of soil gas radon concentration for the classification of radon potential.

7.1. LABORATORY AND FIELD TESTS

Following a review of available reports, laboratory tests on the influence of high and low temperatures on the measurement were performed. The response of the scintillometer to a controlled radiation source (alpha emitter) was determined repeatedly at temperatures ranging from –6 to +35 °C. A field test comprised the third step of this research. Short-term temporal variations of the radon concentration in soil gas have been studied by various measuring techniques, including instantaneous methods (grab sampling) using Lucas cells, continuous monitors, and integrated nuclear track-etch detectors.

A detailed description of measurement techniques that were compared, and the results, is given in NEZNAL et al. (2004).

7.2. EVALUATION OF THE RESULTS

The laboratory tests have confirmed that the instrument's response is temperature dependent, especially if the setting of a working high voltage of the photomultiplier is not optimal. During the field measurements, a relatively low variability of soil gas radon concentration appeared during a 72 hour trial period. Different temporal changes were observed when using different methods (an example of the results obtained using two different continual monitors is given in Fig. 7). Much of these changes was probably caused by fluctuations and errors connected with measuring methods themselves and it did not reflect real variations in the measured parameter.

As long as measurements are not performed under extreme meteorological conditions, all of the tested methods are generally applicable for the determination of soil gas radon concentrations. The only significant disadvantage of the continual and integral methods is their substantially higher cost.

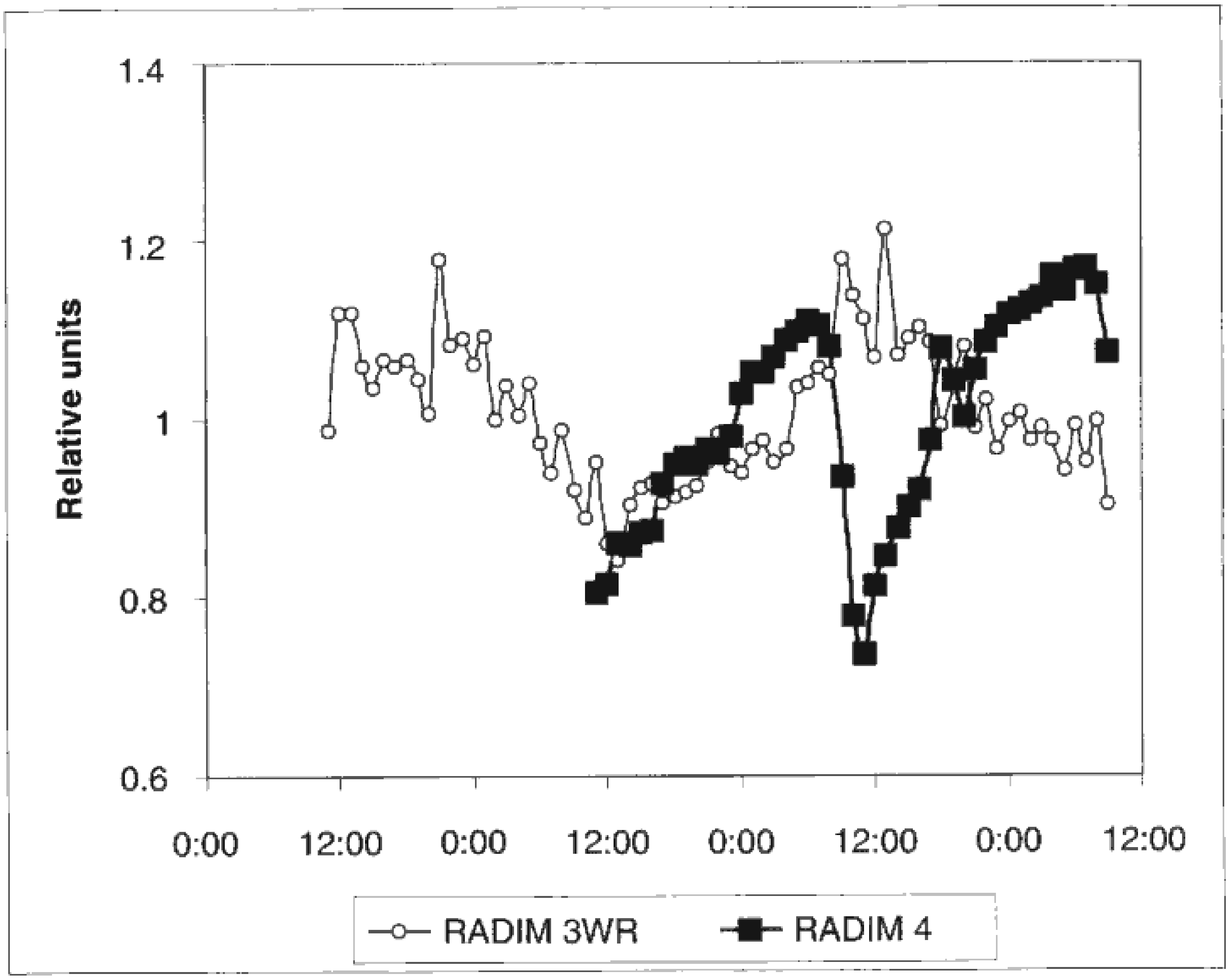


Fig. 7. Relative temporal variations of soil gas radon concentration – continual monitors (RADIM).

8. Geological parameters and their impact on the final assessment of radon potential of soils

The method that had been used for radon risk classification in the Czech Republic since 1994 (BARNET 1994) is based on the assessment of the radon concentration in soil-gas and on the degree to which the soil and rocks are permeable to gasses. Thus, permeability is one of the main factors for the final radon risk classification of building sites.

The final assessment of permeability can be very difficult in some cases, especially when the spatial variability of permeability is very large (BALL et al. 1981, TANNER 1991). It is therefore of interest to search for other factors that are similarly effective in describing the radon potential, and to attempt to substitute them for permeability. We have therefore studied the advantages and disadvantages of using various factors (such as soil moisture, saturation, effective porosity, porosity, density, and bulk density) for the purpose of radon risk classification. This research considers vertical and horizontal changes in the soil profile, the seasonal variability of conditions, and the availability of measuring methods and equipment.

8.1. TESTED PARAMETERS

For comparing the advantages and disadvantages of using various parameters toward radon risk classification, we have performed measurements at two test areas with different, yet homogeneous, geological conditions: Lysá nad Labem, situated at the eastern part of the town, 40 km E of Prague, bedrock formed by Cretaceous sediments, Quaternary cover by fluvial sands; and Kocanda, situated 50 km E of Prague, bedrock formed by Proterozoic paragneiss, covered by loess and loess loam.

When selecting the parameters and measuring methods for testing, economic issues were considered to be very important, as the measuring methods should be used in commercial practice. We therefore concentrated mainly on in situ measurements. The following parameters were chosen for consideration: permeability, soil moisture, porosity, water saturation, and the mass percentage of various size fractions. These factors were measured, along with soil gas radon concentrations, at 15 points at various depths each month during a one-year period. Some data from measurements at the Klánovice and Světice areas (section 5.1.) were also used.

8.2. APPLICABILITY OF VARIOUS PARAMETERS

In general, a good correlation between the measured parameters was obtained at areas with homogeneous and highly permeable soils. The correlation coefficients between median values at the Lysá nad Labem test area (with homogeneous upper soil layers, characterized by low soil gas radon concentrations and high permeability) are as follows:

$c_{Rn}(0.8m)/c_{Rn}(0.4m) = 0.92$	$k(0.8m)/k(0.4m) = 0.83$
$c_{Rn}(0.8m)/k(0.8m) = -0.68$	$c_{Rn}(0.4m)/k(0.4m) = -0.60$
$c_{Rn}(0.8m)/w(0.1m) = 0.70$	$k(0.8m)/w(0.1m) = -0.52$
$c_{Rn}(0.8m)/w(0.25m) = 0.88$	$k(0.8m)/w(0.25m) = -0.66$

Note: Values in brackets represent the depth below the surface; $\mathbf{c_{Rn}}$ is soil gas radon concentration, **k** is permeability, **w** is soil moisture.

Conversely, the correlations between soil-gas radon concentration and soil permeability, and between permeability and the soil moisture and other parameters, were often very weak in environments of medium or low permeability. An example from the Kocanda test area is illustrated in Fig. 8. Although this area can be described as having homogeneous upper soil layers, the large spatial and vertical changes in permeability and other factors do not allow any correlations between the measured parameters. Permeability values are strongly affected by small scale variations in the character of the soil. A similar situation occurred even in highly permeable environments, where there was relatively high saturation of the upper soil horizons (such as at the Klánovice test area).

These results were followed up by repeated measurements of soil gas radon concentrations and soil permeability in the area of Prosek in Prague 9, where there is substantial variability in the upper soil horizons (the upper horizons are formed of loess, while the bedrock is of Cretaceous sandstone). Lower soil gas radon concentrations corresponding to higher permeability before a process of compaction and lime stabilization occurred at this site, and the higher concentrations corresponding to lower permeability following these changes resulted in the same classification of radon potential.

For improving the method of radon risk classification, it is recommended that all factors be evaluated, including their variation within the vertical profile from the surface down to the assumed level of the building's foundations, or to the assumed level of the contact between the building and the soil. It is necessary to describe the following parameters: permeability, grain size, soil moisture, degree of saturation, effective porosity, porosity, density, bulk density, compactness, thickness of Quaternary cover, weathering character of the bedrock, and any modification of the soil layers by anthropogenic activities.

9. Radon availability

The two main factors used in classifying the radon risk of foundation soils are soil gas radon concentration and soil permeability. The evaluation of these factors was semi-quantitative (see Tab. 1 in section 2.5.2.) in the original method commonly used in the Czech Republic (BARNET 1994). The classification of permeability is based on the description of the vertical soil profile. For assessing the soil gas radon concentration, the third quartile (= the 75th percentile) of the set of measured values is the decisive value.

For the practical application of radon survey results toward selecting optimum building technology, it would seem useful to define a single parameter for characterizing the radon potential of soils. This parameter is usually called radon availability, though for the transition to the new method we used radon potential of the building site (RP). This parameter should enable the more exact characterization of radon risk, especially when the measured values are close to the limits that separate the different risk categories. Different approaches and models for assessing radon availability have been studied and tested.

9.1. TESTED MODELS

Based on a review of the available scientific papers, five different radon availability models were studied in detail. However, several problems appeared in connection with finding a common procedure for testing the different models.

Another complication is that there is no system of standardizing soil permeability measurements, and thus the comparison of permeability data obtained by using different methods is difficult.

Finally, three radon availability models were chosen for testing. The approach originally proposed by SURBECK et al. (1991), and modified later (SURBECK and JOHNER 1999), is based on the determination of soil gas radon concentration and soil permeability. Radon availability is then expressed as $\mathbf{RA = c_{Rn} . k}$, or $\mathbf{RA = c_{Rn} . (k)^{1/2}}$, where $\mathbf{c_{Rn}}$ is soil gas radon concentration, and **k** is permeability. An approach that is similar to the Czech one was proposed by KEMSKI et al. (1996). In this system, soil gas radon concentration and soil permeability are measured, and radon availability is expressed as a radon index, ranging from 0 to 6. The measuring methods and the limits separating the radon risk categories (radon index) in this model are little different than in the Czech system. The last radon availability model that we tested (NEZNAL et al. 1995) is described in detail in section 2.5.1. (as radon potential).

In the interest of minimizing the errors caused by the lack of standardization of soil permeability measurements, the permeability limits of all models were modified to be comparable to the Czech ones. Two versions of all the above mentioned models (referred to as Surbeck I, Surbeck II, Kemski I, Kemski II, Neznal I, and Neznal II) were tested using existing data on soil gas radon concentrations

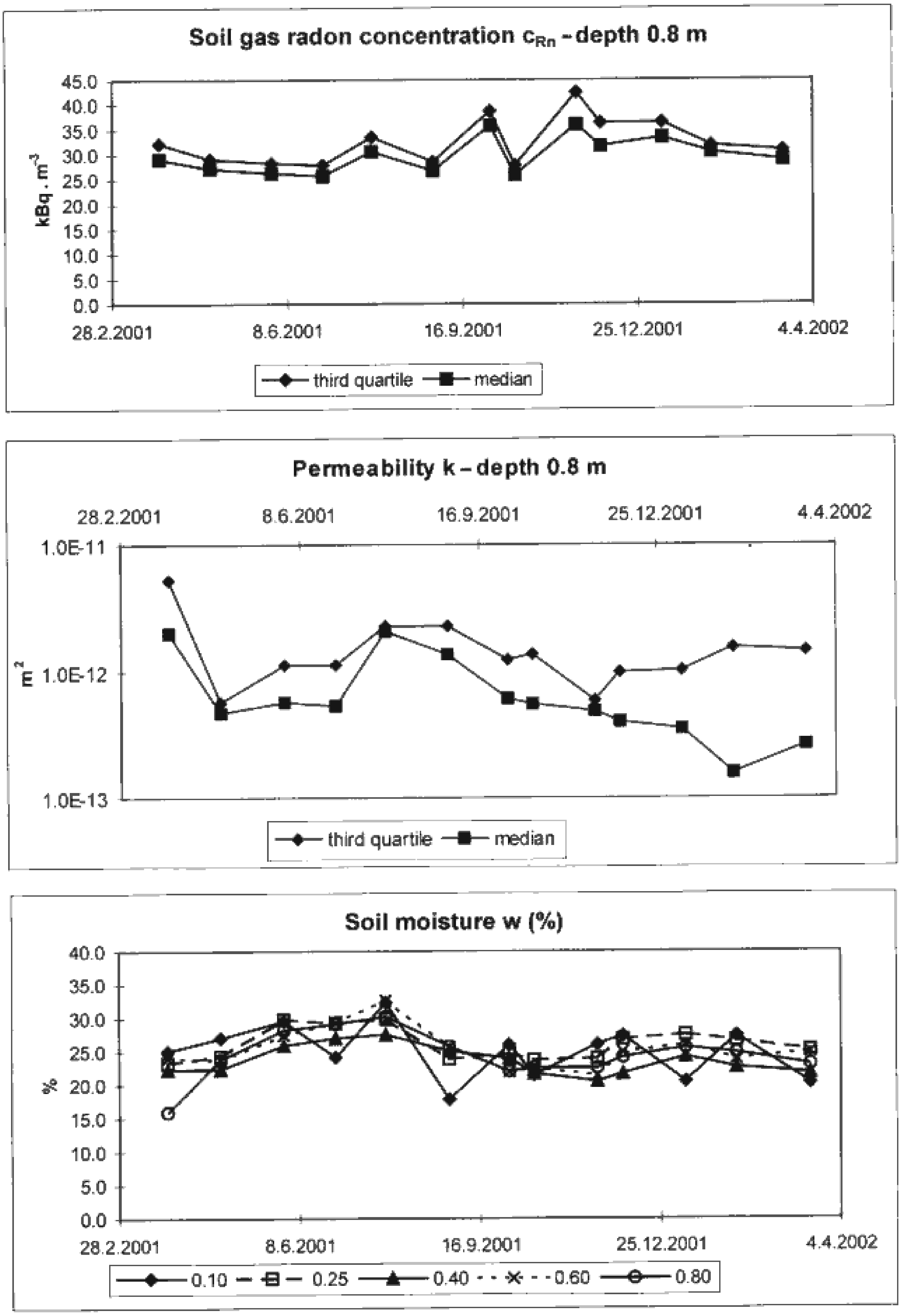


Fig. 8. Results of measurements at area Kocanda.

and soil permeability from the records of the RADON corporation. These measurements had been made at 25 building sites. The Surbeck I version is based on multiplying the soil gas radon concentration by the permeability, whereas Surbeck II involves the multiplication of the soil gas radon concentration by the square root of the permeability. Both versions of the Kemski model use the same limits of soil gas radon concentration for separating the categories of radon risk (10 kBq . m^{-3}, 30 kBq . m^{-3}, 100 kBq . m^{-3} and 500 kBq . m^{-3}), but use different permeability limits (Kemski I: 4.10^{-12} m^2 and 4.10^{-13} m^2; Kemski II: 4.10^{-12} m^2 and 4.10^{-14} m^2). The Neznal I model describes the limits and the RA parameter in the following form:

$$-\log k = 1/10 \,.\, c_A - (\,1/10 + \log 1E{-}10\,) = 0.1\, c_A + 9{,}9$$

$$-\log k = 1/35 \,.\, c_A - (\,1/35 + \log 1E{-}10\,) = 0.0286\, c_A + 9{,}971$$

$$RA = (-\log k - 10\,) / (c_A - 1).$$

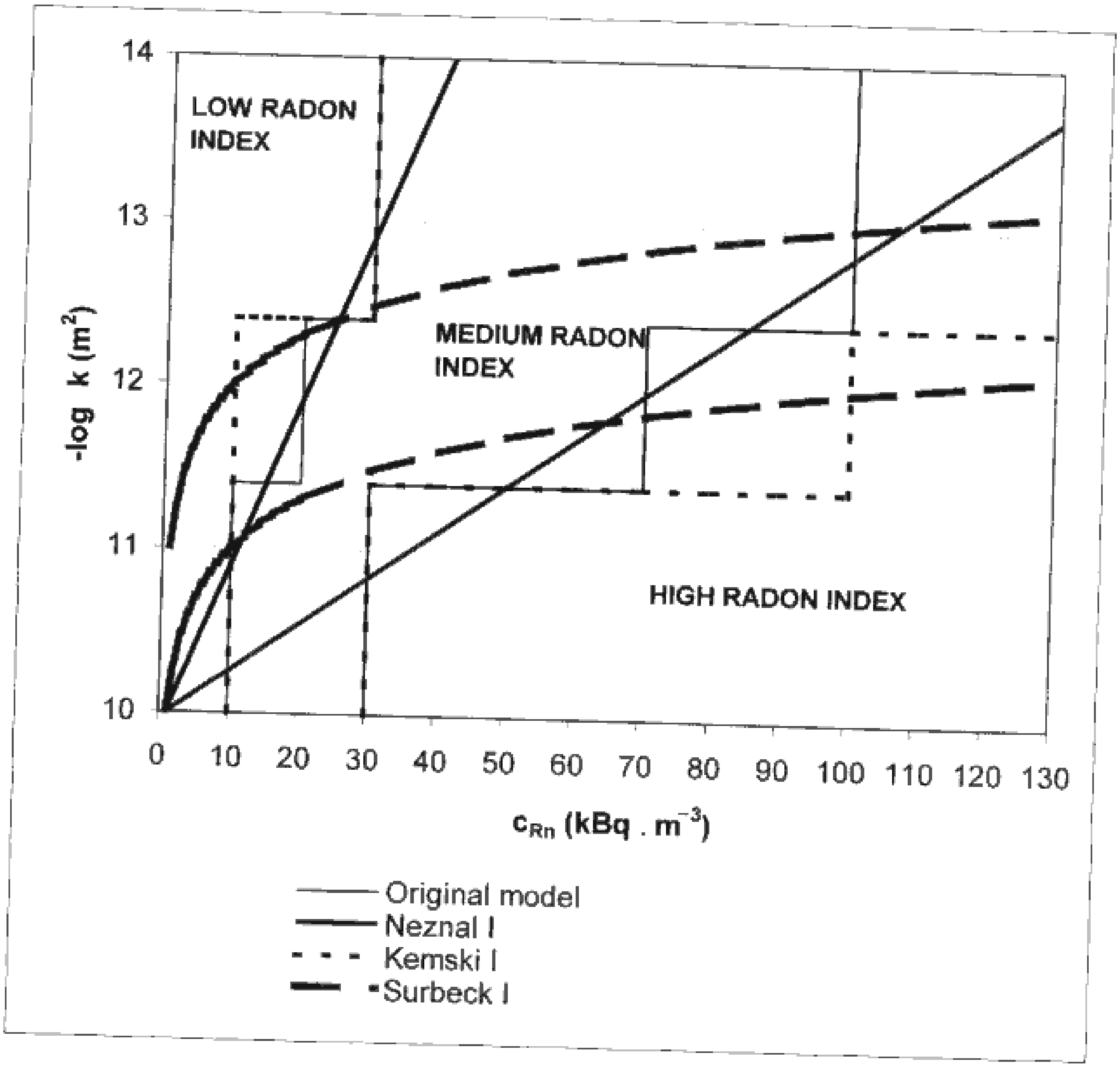


Fig. 9. Different models of radon availability.

The slopes of the lines are given by the values 1/10 and 1/35, and their intersection corresponds to the values of c_A = 1 kBq . m^{-3}, and k = 1E–10 m^2.

The Neznal II model has a larger interval for medium permeability. The equations describing the limits and the RA parameter are as follows:

$-\log k = 2/10 . c_A - (2/10 + \log 2.524E{-}9) = 0.2\, c_A + 8.398$
$-\log k = 2/35 . c_A - (2/35 + \log 2.524E{-}9) = 0.0571\, c_A + {} + 8.540$
$RA = (-\log k - 8.598) / (c_A - 1).$

The slopes of the lines are given by the values 2/10 and 2/35, and their intersection corresponds to the values of c_A = 1 kBq . m^{-3}, and k = 2.524E–9 m^2.

The maximum values or the third quartiles were chosen as the decisive values for sets of soil gas radon concentration data. For soil permeability, the median values or the third quartiles were used. Radon index values obtained using different models were compared to those determined in accordance with the original Czech method. A comparison of the models is illustrated in Fig. 9. We also tested the reproducibility of the classifications, for which the results of repeated measurements at several test areas were used.

9.2. COMPARISON OF THE DIFFERENT APPROACHES

Significant agreement between the results obtained using the original method and the Neznal and Kemski models was observed. This is due to the similarity of the boundary values in these models (see Tab. 3). The assessment from the Surbeck models was a little different. In the majority of cases, the best agreement was found for the third quartile of the soil gas radon concentration values and for the third quartile of soil permeability values.

Disparity between the results of the various methods mainly concerned building areas whose assessments were close to the boundaries of the radon index classes. These discrepancies are usually due to the variable classification of soil permeability by different assessment methods (in situ measurements vs. description of vertical soil profile). The reproducibility of the classifications was relatively good for all models. By comparing the different radon availability models, we conclude that they are all generally applicable. Variable evaluation results were caused mainly by the inconsistent classification of soil permeability (at some areas, the soil permeability derived from the description of the vertical soil profile was lower than the soil permeability measured in situ).

Table 3. Comparison of evaluation results obtained using different radon availability models with results of the original model at 25 areas

	Surbeck I		Surbeck II		Neznal I		Neznal II		Kemski I		Kemski II	
Decisive values	A	D	A	D	A	D	A	D	A	D	A	D
maximum c_{Rn}; median **k**	11	14	12	13	22	3	21	4	20	5	21	4
maximum c_{Rn}; 3rd quartile **k**	11	14	13	12	18	7	22	3	20	5	21	4
3rd quartile c_{Rn}; median **k**	9	16	14	11	18	7	21	4	21	4	24	1
3rd quartile c_{Rn}; 3rd quartile **k**	13	12	15	10	21	4	21	4	24	1	24	1

A – agreement, D – disagreement, c_{Rn} – soil gas radon concentration, **k** – permeability

In the interest of maintaining continuity in classifying the radon risk of foundation soils, the Neznal I model is recommended for use in the improved radon risk assessment method. This model is general and amenable to modification; for example, in defining additional boundary regions between the low and medium, and between the medium and high radon indices.

10. The establishment of radon reference sites for testing soil gas radon concentration in the Czech Republic

Radon reference sites serve for the comparative measurement of the concentration of radon (^{222}Rn) activity in soil gas, and for verifying the consistency of results. Organizations that professionally determine the radon indices of building sites in the Czech Republic must undergo testing at radon reference sites as a prerequisite for earning an official permit for this activity from the State Office for Nuclear Safety (Act No. 18/1997). Radon reference sites are selected natural sites exhibiting distinct levels of radon in the soil, a homogeneous radon distribution, and suitable soil thickness and permeability enabling soil gas sampling at the depth of 0.8 m. Furthermore, the geological structure at the sites is known, and the concentrations of natural radionuclides of K, U and Th in the soils, and the temporal changes of radon activity in the soil gas have been investigated. An additional requirement for these sites is that they must be accessible by car, and the distances between them should be small. More information about this research is available in MATOLÍN 2002.

10.1. RADON REFERENCE SITES IN THE CZECH REPUBLIC

The selection and investigation of radon reference sites were based on radon detection, gamma-ray spectrometry, geoelectrical measurement, shallow seismic measurement, shallow drilling, and the in situ measurement of soil permeability.

Three new radon reference sites have been established 60 km SW of Prague, in the area of the town of Milín. These radon reference sites are situated in meadows, and each has 15 fixed stations within a 5 × 5 m grid. The Cetyně reference site, situated 5 km SE of Milín, lies in an area of leucocratic biotite orthogneiss covered by sandy loams and loamy sands. The mean values of activity concentration of radon (31.6 kBq . m^{-3}) and thoron (44.7 kBq . m^{-3}) are based on repeated field measurements throughout a period of one year. The permeability of the soil at the reference site is variable.

The Bohostice reference site, situated 7 km SE of Milín, lies in an area of leucocratic biotite orthogneiss covered by sandy loams and loamy sands. The mean value of radon activity concentration is 51.8 kBq . m^{-3}, and that of thoron is 39.7 kBq . m^{-3}. Soil gas sampling is easy at this site.

The Buk reference site, situated 2 km NNE of Milín, lies in an area of medium grained biotite and amphibole-biotite granodiorite of the Central Bohemian pluton. The surface cover is formed by eluvial sandy soil from the basement rocks. The mean value of radon activity concentration at this site is 154.7 kBq . m^{-3}, while that of thoron is 119.5 kBq . m^{-3}. The soil cover exhibits a high permeability, making soil gas sampling easy. The characteristics of radon reference sites in the Czech Republic are given in Tab. 4.

10.2. TEMPORAL VARIATION IN THE CHARACTERISTICS OF THE REFERENCE SITES

The range in temporal variations at the reference sites has been estimated from repeated measurements. Radon (^{222}Rn) and thoron (^{220}Rn) activity concentration in the soil gas, the permeability of the soils, the degree soil moisture, and the temperature of atmospheric air were monitored within the one-year period from 2000 to 2001. The resulting data show the range in temporal variations of these factors, and illustrate the effects of climate at each site.

10.3. TESTING THE RELIABILITY OF RADON MEASUREMENTS IN SOIL GAS

The reliability of measuring the concentration of radon activity in soil gas is tested by comparative measurements at radon reference sites. The resulting radon data collected by the official testers during a single day is compared with that of the site administrator, and with the data set of all preceding measurements at the particular reference site. An official tester from a radon testing organization measures the

Table 4. Signatures of radon reference sites in the Czech Republic

Parameter	Reference area		
	Cetyně	Bohostice	Buk
^{222}Rn, mean of medians/year (kBq · m^{-3})	31.6	51.8	154.7
^{222}Rn, distribution/reference site, coefficient of variability V	0.39	0.17	0.27
^{220}Rn, mean of medians/year (kBq · m^{-3})	44.7	39.7	119.5
^{220}Rn, distribution/reference site, coefficient of variability V	0.31	0.29	0.23
U (ppm eU)	2.0	2.3	3.6
Th (ppm eTh)	8.9	7.0	13.8
permeability of soil	low, (medium), high	(low), (medium), high	high
moisture content of soil (%)	16.8–24.4	15.1–21.5	9.7–14.8

radon concentration at 15 fixed stations at each reference site. The resulting ^{222}Rn data, expressed in kBq . m^{-3}, is subjected to a statistical analysis by the TestMOAR computer program (compiled by M. Bartoň). This analysis entails three individual data treatment procedures.

Test 1 compares the radon data collected by an official tester at each station of three reference sites, with the median value of the radon data reported by other participants on the same day at the same station. The level of confidence applied to this test is $\alpha = 1$ %.

Test 2 determines the tightness of the regression between the radon data reported by an official tester at each station of the reference sites and the median values reported by other participants on the same day. The test is run at the level of confidence $\alpha = 1$ %.

Test 3 calculates arithmetic means from the radon concentration values reported by the participants for particular reference sites, and normalizes these data in two steps. First, the data are normalized to the mean radon values determined by the administrator of the reference sites. Secondly, these normalized values are compared to the mean values of all preceding measurements of each parameter at a particular reference site in the past. The ideal normalized value is 1, though values within the range of 0.7–1.3 are acceptable. Test 3 eliminates temporal changes in the measurements, and is run separately for each reference site.

The results generated by the Test MOAR program give the calculated radon data and the critical values of the applied tests.

The new radon reference sites (MATOLÍN et al. 2001) have been functional since the year 2000. They are important for confirming the accuracy of radon data collected in the field, and thus play a crucial role in radon risk mapping at building sites and toward the global radionuclide data standardization (IAEA, in print).

11. Verification of the new methodology for radon risk mapping

The previous method of radon risk assessment (BARNET 1994) was also used for the measurement of test areas for radon risk mapping. These data serve as the basis for compiling radon risk forecasting maps on the scale of 1 : 50 000, which are useful for prioritizing the distribution of the indoor radon detectors and for efficiently detecting areas at which higher concentrations of indoor radon activity frequently occur (BARNET et al. 2003).

After the formulating the new method, it was necessary to verify its applicability for this purpose. The reliability of these maps was analyzed at the same time.

11.1. USE OF NEW METHODOLOGY FOR RADON RISK MAPPING

Different approaches to radon risk mapping are used at present (APPLETON and MILES 2002, KEMSKI et al. 2002). Since 1999 the CGS has been publishing radon risk maps in printed form and on CD-ROM using its own data or that from the Radon Risk Association. By the end of 2003, 154 map sheets were finished from a total coverage of 214 maps. The construction of radon risk maps is based on vectorized geological maps (of 1 : 50 000 scale) published by the CGS. The procedure is described in the paper by MIKŠOVÁ and BARNET (2002). The radon risk-index category in particular rock types is determined by measuring soil gas radon concentration and soil permeability at test sites. On each map sheet, a minimum 20 measured sites are selected in different geological units, and at every site 15 random points are measured. At present, 9000 test sites are stored in a database. Four different categories of radon index are used in the maps: low, intermediate, medium, and high.

The results obtained from a single test area with 15 sampling and measuring points serve as the basis for the formation of radon maps. The differences between the new method and the previous one are minor from the perspective of mapping, as the extent of the minimal set of measurements and the decisive statistical parameters are the same. The risk assessment is based on the determination of radon potential (the radon index of a building site), and the radon indices of buildings are not relevant to mapping. The newly modified method can be used toward constructing radon risk forecast maps, i.e. for field measurements at test sites and for adding to extant databases.

11.2. RELIABILITY ANALYSIS OF THE RADON RISK FORECAST MAPS 1 : 50 000

The reliability of radon risk prediction maps was analysed by comparing data from detailed radon surveys with data from the corresponding radon maps of the geological bedrock. The following cases were used in this comparison:

a) Areas at which all radon index categories are found, with major occurrences of the higher categories (map sheet Říčany, 13-31, 1 : 50 000). The results of 37 randomly chosen radon surveys were compared. The reliability of the map sheet was 62.2 %, for the low, intermediate, and medium radon index categories. The discrepancies between the results of the surveys and the radon index category assumed from the map were caused by local geological conditions, especially the presence of Quaternary sediments.

b) Areas at which the low to intermediate categories of radon index were predicted (map sheet Štětí, 02-44, 1 : 50 000). The results from 19 areas were compared. In this case the areas were chosen with respect to morphology and other factors. The expected higher radon index was confirmed at most of these sites. The occurrence of relatively large areas of low radon index categories, which were reliably assigned to these areas, is due mostly to homogenous geological conditions. There is no way to specify and describe detailed geological structure in geological maps of 1 : 50 000 scale.

c) Areas at which local and regional geological data were compared for the purposes of radon index category assessment (map sheet Beroun, 12-41, 1 : 50 000, Chaby area). An area of about 400 × 400 m was surveyed in a 10 × 10 m grid, which involved 1689 soil gas radon concentration measurements. Differences between the indications from the map and the data from the survey were substantial. The spatial distribution of radon was induced by variations in the geological conditions, which can only be characterized after a thorough geological survey. A geological map of 1 : 50 000 scale cannot register such details.

d) Areas at which homogeneous geological conditions and homogeneous radon indices of the building site were expected (map sheet Mělník, 12-22, 1 : 50 000, Kly area). Judging from the data derived from the 1 : 50 000 scale map, a highly permeable environment with intermediate radon index was assumed. A total 150 samples of soil gas were taken in a 10 × 10 m grid, and the entire area was classified as having a low radon index. When enough information on the local geological conditions is available, the radon potential can be more accurately predicted.

The newly modified method can be widely used for evaluating measurements at selected sites for the construction of radon risk forecast maps.

The analysis of the reliability of these maps also addressed the possibility of preparing predictive maps, the reliability of which would be high enough so as to define areas where radon risk assessment would not be necessary (i.e. where the degree of radon risk could be derived from the map). The analysis has shown that variations between local and regional geological structure, and of particular lithological units throughout the entire Czech Republic, are very substantial. It is not possible to make predictive maps that can define areas with 100 % low radon index. Neither can we establish a minimum number of required measured areas for assessing the radon risk at particular geological units, even when their dimensions are known. The number of such areas is proportional to the inhomogeneity of geological conditions.

The method of constructing radon risk maps is based on the generalization of data acquired within the Czech Republic. Due to the map scale constraints, these maps cannot include detailed descriptions of the geological structure, and thus cannot be used for directly predicting the radon risk of particular building sites.

Acknowledgement

This survey was supported by the State Office for Nuclear Safety, Prague, Research and Development project No. R/2/2000.