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The distribution of radon in tunnels with different geological characteristics in China

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ABSTRACT

In China, as the economy is developing and the population is expanding, some underground buildings have been used as supermarkets, restaurants and entertainment places. Tunnels in mountains are one type of underground building, and the radon (^{222}Rn) level in tunnels is an important issue. Radon levels in different type tunnels appear to differ, and relatively higher levels of ^{222}Rn are associated with particular types of bedrock. The ^{222}Rn levels in tunnels in five different geological characteristics were analyzed. Those built in granite had the highest ^{222}Rn levels with a geometric mean (GM) of 280 Bq m^{-3}, while those built in limestone (GM: 100 Bq m^{-3}) and andesitic porphyry (GM: 96 Bq m^{-3}) were lower. The sequence of ^{222}Rn concentrations was: granite > tuff > quartz sandstone > limestone > andesitic porphyry, and the ^{222}Rn in granite was statistically significantly higher than in limestone and andesitic porphyry. Tunnels built in granite, tuff, quartz sandstone, limestone tended to have higher ^{222}Rn concentrations in summer than in winter, while the reverse tendency was true in andesitic porphyry tunnels. Only the difference in limestone was statistically significant.

1. Introduction

Radon (^{222}Rn) is a radioactive gas arising from the uranium (U) decay chain, and is the largest single source of radiation exposure to many populations (Font et al., 1999). Inhalation of ^{222}Rn and its daughter products could cause a significant health hazard when they are present in enhanced levels (Porstendörfer, 1994; Singh et al., 2001). A large number of ^{222}Rn surveys have been carried out for estimating the health risk to ^{222}Rn in many countries (Srivastava et al., 2001; Kullab et al., 2001). Radon comes mainly from soil and bedrock, so ^{222}Rn has the highest levels in basements and underground spaces that are in contact with the soil or bedrock (Gillmore et al., 2001; Anastasiou et al., 2003). Radon levels in underground spaces such as tunnels, caves and mines have become an important issue (Gillmore et al., 2000; Grattan et al., 2004; Richon et al., 2004). In China, a survey of the air ^{222}Rn levels in 234 underground buildings in 23 cities was carried out by solid state nuclear detectors through the last two years. The study showed the distribution of ^{222}Rn in underground buildings of those cities, and the factors causing high ^{222}Rn levels as well as the daily and seasonal variations of ^{222}Rn concentrations (Li et al., 2006a,b).

Radon migrates through pores in soil, fractures in rocks and along other weak zones, such as shears, faults, and thrust (Ramola et al., 2006). Relatively high levels of ^{222}Rn emissions are associated with particular types of bedrock and unconsolidated deposits, such as some granite, U-enriched phosphatic rocks, and some permeable sandstone (Appleton, 2005; Ramola et al., 2006). This paper describes the distribution of ^{222}Rn in mountain tunnels with different geological characteristics. The seasonal variations of ^{222}Rn concentrations in these tunnels were also demonstrated.

2. Surveying method

2.1. Tunnels studied

The study involved 77 tunnels built in mountains. Of these, 57 tunnels could be classified by their rock characteristics including granite, limestone, tuff, andesitic porphyry and quartz sandstone. During the study period, tunnels in quartz sandstone were all occupied, while the occupation rates of tunnels in tuff were 20%, and that of other three types were 40%. The occupied tunnels were used as supermarkets, restaurants or entertainment places.

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Table 1
Radon concentration in different tunnels (Bq m^{-3}).

Rock	Sites	GM (GSD)	Occupied sites	Distribution
Granite	29	280 (2.9)	13	L
Limestone	10	100 (2.6)	4	L
Tuff	5	220 (2.1)	1	L
Andesitic porphyry	8	96 (2.5)	3	L
Quartz sandstone	5	210 (1.4)	5	N

Note: GM – geometric mean, GSD – geometric standard deviation, L – lognormal distribution, N – normal distribution.

2.2. Radon measurement

Measurements were carried out employing CR-39 detectors made from Allyl Diethylene Glycol Carbonate, which is sensitive to α particles and is used widely in accumulating ^{222}Rn measurements. The detectors were hung in the worst ventilation site in each tunnel and were exposed for three months in spring, summer and winter in one year. After the sampling was over, the detectors were retrieved from all sites and etched in 7 N KOH at 70 °C for 6 h. The detectors were made in China and 4.218 tracks cm^{-2} (kBq m^{-3} h)$^{-1}$ was obtained from calibrated by the Radon Laboratory, School of Nuclear Science &Technology, Nanhua University in Hengyang, China. Data were obtained by reading the detectors using an optical microscope at a magnification of 630×. The measured limit was 8.7 Bq m^{-3} if the detectors were exposed for three months. Detectors were also calibrated for ^{220}Rn in the same situation as ^{222}Rn, and 0.159 tracks cm^{-2} (kBq m^{-3} h)$^{-1}$ was obtained, accounting 3.8% of ^{222}Rn. Therefore the obtained data are mainly from ^{222}Rn (Li et al., 2006b).

3. Result and analysis

3.1. The distribution of radon in tunnels

There were different uses for the tunnels. Some were unoccupied and were closed normally, and others were occupied and used as warehouses, passages, summer resorts and were open some times. Radon concentrations in most tunnels were measured during spring, summer and winter, and the data were averaged to obtain the annual ^{222}Rn concentrations (Table 1). The K–S test was used to check the distribution of data and a probability level of Asymp.-Sig.(2-tailed) > 0.05 was considered to indicate the data followed normality. Radon concentrations in tunnels built in granite, tuff, limestone and andesitic porphyry were lognormally distributed, while ^{222}Rn concentrations in tunnels built in sandstone were normally distribution. The average value based on lognormally distributed data was suitable to represent a sample, and the ^{222}Rn arithmetic mean and geometric mean (GM) both were 210 Bq m^{-3}, so in this paper the GM were used to represent their ^{222}Rn levels in each type tunnels (Table 1). For a single tunnel, the annual ^{222}Rn concentration was obtained by averaging its ^{222}Rn concentrations across seasons.

Radon levels in different type tunnels appeared to differ. There were 29 tunnels in granite, with the highest GM of 280 Bq m^{-3}, and the single highest ^{222}Rn value (2482 Bq m^{-3}) occurred in this type of tunnel. With the equilibrium factor at 0.5 (Wang, 1994), the highest ^{222}Rn value is six times the safe limit for ^{222}Rn and its daughters for type I underground buildings (200 Bq m^{-3} in equilibrium equivalent concentration) (GB/T 17216-1998, 1998). Tunnels built in limestone and andesitic porphyry had relatively lower ^{222}Rn levels. The sequence of ^{222}Rn concentrations was: granite > tuff > quartz sandstone > limestone > andesitic porphyry and independent sample test based on the equality of GM showed that the ^{222}Rn level in granite was significant higher than in limestone and andesitic porphyry, with Sig.(2-tailed) of 0.014 and 0.015 ($P = 0.014$ and 0.015). Granite tunnels are mainly located in two places. Some are near coastal cities in Southeast China (Guangdong and Fujian province), and the others are near Qingdao, a coastal city in East China. Occupation rates of the tunnels in East China (50%) were slightly higher than that in Southeast China (43%). Tunnels in Southeast China had higher ^{222}Rn levels (GM: 340 Bq m^{-3}) than those in East China (GM: 140 Bq m^{-3}), which may mainly due to the fact that granite in Southeast China was produced in late Yanshan Period, and was in rich with radioactive elements.

Radon levels in occupied tunnels in granite (GM: 170 Bq m^{-3}) were significant lower than those in unoccupied tunnels (GM: 430 Bq m^{-3}) ($P = 0.012$). Higher ^{222}Rn exposure has a potentially adverse effect on human health, so it is necessary to pay attention to the ^{222}Rn in tunnels of occupied sites (Table 2). Among the 13 occupied granite tunnels, the ^{222}Rn concentration in the dead end

Table 2
The characteristics of the occupied granite tunnels.

Tunnel	Use	Characteristics	Ventilation condition	Annual radon (Bq m^{-3})
GO-1	Tea room	Uncoated, Granite appears, surface area is about 380 m^2, occupied only in summer.	Nature ventilation	400
GO-2	Leisure room	Uncoated, Granite appears, with a well in it, occupied only in summer.	Nature ventilation	410
GO-3	A hall showing root carving products	Coated with granite and concrete, surface area is about 500 m^2 with 9 m height.	Nature ventilation, using electric fan in summer.	170
GO-4	Audiovisual store	Coated with concrete	Nature ventilation, using electric fan in summer.	170
GO-5	Restaurant store	Coated with ceramic tile, located in the dead end of a tunnel.	Nature ventilation	500
GO-6	Fire control center	Coated with concrete	Artificial ventilation	80
GO-7	Alleyway	Coated with concrete	Artificial ventilation	110
GO-8	Book store	Coated with concrete	Artificial ventilation	130
GO-9	Water pump room	Uncoated wall, concrete-coated ground.	Artificial ventilation	280
GO-10	office	Coated with concrete	Artificial ventilation	110
GO-11	Room for duty	Coated with porcelain clay and anti-water paint. One person lived in it. Using tap water.	Artificial ventilation	58
GO-12	Restaurant	Coated with concrete and ceramic tile, there were about 50 people having lunch during 11:30–12:00 every day.	Artificial ventilation after having lunch.	120
GO-13	Office	Coated with concrete and terrazzo.	Artificial ventilation for 2 hours every day.	140

Note: sites 1–10 located in Southeast China, annual radon concentrations were obtained from averaging the radon in spring, summer and winter; sites 11–13 located in East China, annual radon concentrations were obtained from averaging the radon in summer and winter.

Table 3
Details of tunnels built in limestone.

Located city	Tunnels	Coating materials	Use	Summer radon (Bq m^{-3})	Winter radon (Bq m^{-3})	Average radon (Bq m^{-3})	Summer/winter ratio
Guiyang	L-1	Concrete, terrazzo	Unoccupied	1100	52	570	21
	L-2	Concrete	Banana store	70	51	60	1.4
	L-3	Concrete	Unoccupied	100	68	86	1.5
	L-4	Concrete, ceramic tile, terrazzo	Banana store	50	27	38	1.9
	L-5	Non-coated wall and concrete ground	Unoccupied	31	51	41	0.6
	L-6	Half-coated with concrete	Unoccupied	70	37	53	1.9
Guilin	L-7	Concrete, ceramic tile	Entertainment	620	71	340	8.7
	L-8	Granite, ceramic tile	Entertainment	410	67	240	6.0
	L-9	Non-coated	Unoccupied	61	29	45.2	2.1
	L-10	Gypsum board, concrete, wood	Unoccupied	210	97	150	2.2

of a tunnel was relatively higher (GO-5), followed by tunnels GO-1 and GO-2 which were uncoated and had high levels of ^{222}Rn. Ventilation also affected the ^{222}Rn concentrations . The GM ^{222}Rn concentration of five tunnels (GO-1–5) with nature ventilation was 300 Bq m^{-3}, significant higher than with artificial ventilation (GO-6-13, GM: 120 Bq m^{-3}) ($P = 0.006$).

Opposite to the results from the tunnels built in granite, ^{222}Rn was homogeneously distributed throughout tunnels built in quartz–sandstone. This could because they were all occupied.

Radon in limestone was relatively higher in part of due to the abundant fractures and cavities. Even though the overall concentration of U in the limestone was below 2 mg kg^{-1}, high ^{222}Rn emissions were probably derived from radium deposited on the surfaces of fractures and cavities (Appleton, 2005). In this survey, ten tunnels built in limestone (similar cavities) had modest ^{222}Rn levels (Table 3). These tunnels were situated in Guiyang and Guilin cities, and both cities are located in significant Karst regions in Southwest China. There were six tunnels in Guiyang city, and two of them were used as banana storage (L-2, 4), and the others were unoccupied. The tunnel L-1 had the highest average ^{222}Rn concentration, probably because of enriched groundwater. Groundwater was the main nature carrier fluid, and ^{222}Rn in water may be transported for distances of up to 5 km in streams flowing underground in limestone. Radon in the water could emit directly into the gas phase until a gas phase is introduced (Appleton, 2005). Besides tunnel L-1, the ^{222}Rn concentrations of the others (tunnels L-2–6) were all lower than that in Guilin city (tunnels L-7–10). Generally, it is apparent that dry and uncoated tunnels in Guilin city had lower ^{222}Rn levels. In four tunnels in Guilin, the non-coated tunnel (L-9) had the lowest ^{222}Rn concentration (45 Bq m^{-3}), while the other three tunnels had relatively higher ^{222}Rn, which was probably due to the emissions from coating materials which were concrete, ceramic tile, gypsum board, etc. The ^{222}Rn concentrations of the three tunnels 7, 8 and 10 were statistically significant higher than that of the dry tunnels in Guiyang (tunnels 2–6) ($P = 0.001$), so the difference of ^{222}Rn level between tunnels in the two cities was partly caused by the coating materials.

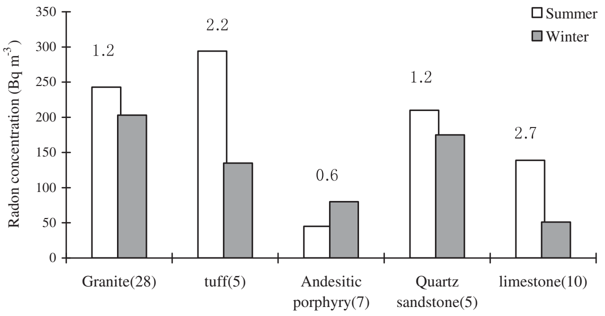

Fig. 1. Seasonal variation of radon in tunnels, the number in figure represents summer/winter ratio of tunnels, the number in parenthesis represents number of tunnels.

Table 4
Seasonal variation of radon in tunnels in andesitic porphyry.

Tunnel	Summer (Bq m^{-3})	Winter (Bq m^{-3})	Summer/winter ratio
A-1	46	110	0.4
A-2	58	37	1.6
A-3	58	78	0.7
A-4	130	300	0.4
A-5	57	60	1.0
A-6	13	60	0.2
A-7	25	60	0.4

3.2. *The seasonal variation of ^{222}Rn in tunnels*

The ^{222}Rn levels usually demonstrate seasonal variation between summer and winter (Ramola et al., 1998; Perrier et al., 2004). In this study, there are 55 tunnels with data for both summer and winter (Fig. 1). Radon levels in the different seasons appeared to differ. It is obvious that except tunnels built in andesitic porphyry, tunnels built in the other four types of rocks have higher ^{222}Rn levels (GM) in summer than in winter. Tunnels built in limestone had the highest summer/winter ratio (2.7), and the independent sample test based on equality of GM showed that the ^{222}Rn level in summer in limestone was significant higher than in winter ($P = 0.029$). A limestone tunnel (tunnel L-1, Table 3) had the highest summer/winter ratio (21), which was probably because the U-enriched groundwater enhanced the ^{222}Rn level in summer and caused a higher summer/winter ratio (Perrier et al., 2005).

There was no significant difference in temperature throughout the year in the tunnels with poor ventilation (about 20 °C, temperature data was obtained by investigation, some tunnels monitored temperature for insuring mushroom production). However, with ventilation the interior temperature was modified by the outside temperature and so varied from summer to winter. From Fig. 1, only tunnels built in andesitic porphyry appeared to have lower ^{222}Rn levels in summer than in winter (Table 4), which is reverse to the usual seasonal variation of underground buildings. Except for tunnel A-2, all other tunnels had summer/winter ratios lower than 1.0.

4. Conclusions

In five types of tunnels, tunnels built in granite had the highest ^{222}Rn levels (GM 280 Bq m^{-3}), and tunnels in Southeast China had higher ^{222}Rn levels than in East China. The ^{222}Rn concentration measured in the dead end of a tunnel was relatively high and the tunnel with more interior space was low. Tunnels built in limestone and andesitic porphyry had relatively lower ^{222}Rn levels. For tunnels built in limestone, dry and uncoated tunnels had relatively lower ^{222}Rn levels. The ^{222}Rn levels in limestone tunnels seemed to be mainly determined by their coating materials. The sequence of ^{222}Rn concentration by GM based on host rock was: granite $>$ tuff $>$ quartz sandstone $>$ limestone $>$ andesitic porphyry, and the ^{222}Rn levels in granite were statistically significant higher than in limestone and andesitic porphyry. Tunnels built in granite, tuff, quartz sandstone, limestone tended to have higher GM ^{222}Rn concentrations in summer than in winter, while reverse was true in andesitic porphyry tunnels. The difference in limestone was statistically significant.

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