Radon levels in a karst cave network in Shaanxi, China

Xinwei Lu
School of Tourism and Environment – Shaanxi Normal University, Xi'an, P.R. China
Loretta Y. Li
Department of Civil Engineering – University of British Columbia, Vancouver, BC, Canada
Xiaolan Zhang
School of Tourism and Environment – Shaanxi Normal University, Xi'an, P.R. China

ABSTRACT
Radon air concentrations in a karst cave network of Shannxi, China, were measured by continuous monitoring for an annual cycle. The measurement results show that radon air concentration in the cave ranged from 384 to 2020 Bq m^{-3}, with an annual average of 1120 Bq m^{-3}, which is similar to other caves in China. Distinct monthly and seasonal variations of radon air concentration inside the cave were observed. The monthly average radon air concentration in the investigated caves in April to October are higher than the upper bound of radon action level for underground space used in China (1000 Bq m^{-3}), whereas the radon level for the lest of the year is below the upper bound of radon action level. The monthly average radon air concentrations of the caves in July and August are also higher than the upper bound of radon action level recommended by the International Commission on Radiation Protection (ICRP) for workplaces (1500 Bq m^{-3}). The seasonal statistic analysis of radon air concentrations shows that the maximum concentration occurred in the summer, whereas the minimum radon concentration occurred during the winter. The radon concentrations in Xishui cave are lower than which in Lingyun cave. The difference of radon air concentration in the two studied caves and in different months appears to be caused by natural advection.

RÉSUMÉ
Les concentrations en Radon du réseau de grottes de Shannxi, Chine, ont été mesurées de façon continue pendant une année entière. Les résultats de ces mesures montrent que les concentrations en Radon contenues dans l'air de la grotte varient de 384 à 2020 Bq.m^{-3}, avec une moyenne annuelle de 1120 Bq m^{-3}, ce qui correspond aux valeurs obtenues dans d'autres grottes de la région. Des variations mensuelles et annuelles significatives de la concentration en Radon de la grotte ont été observées. La moyenne mensuelle pour les mois d'avril à octobre est supérieure que la valeur haute du niveau d'action utilisé en Chine pour le Radon pour les espaces souterrains (1000 Bq.m^{-3}) alors qu'elle est inférieure à cette même limite pour les autres mois de l'année. La valeur maximale recommandée (1500 Bq.m^{-3}) par la Commission Internationale de la Protection contre les Radiations pour les lieux de travail (ICRP, International Commission on Radiation Protection). Les analyses statistiques saisonnières des concentrations de Radon dans l'air indiquent que les plus fortes valeurs ont été mesurées en été alors que les valeurs hivernales sont les plus faibles relevées. Les concentrations mesurées dans la grotte de Xishui sont plus faibles que celles relevées dans la grotte de Lingyun. Les différences de concentration relevées dans les deux grottes sont probablement dues aux différentes ventilations de celles-ci.

1 INTRODUCTION

Radon is a naturally occurring odourless and colourless radioactive noble gas. The half-lives of the three isotopes of radon (^{222}Rn, ^{220}Rn and ^{219}Rn) are 3.82 days, 55.6 s and 3.96s respectively. They originate from the natural decay chains of ^{238}U, ^{232}Th and ^{235}U, respectively (Hafez and Hussein 2001). Amongst the three isotopes, ^{222}Rn has the most significant impact on the environment due to its relatively long half-life, enabling it to migrate significant distances within the geological environment before decaying.

Prolonged exposure to radon may cause a negative effect on human health. In high concentrations, radon has been shown in a number of studies to cause lung cancer and bronchial tissue damage in miners (Qureshi et al. 2000; Samet et al. 1991). Radon from soil, rock, sediments and water can concentrate in enclosed spaces such as, mines, caves, and the built environment. Build-up of radon and elevated radiation exposure levels in caves have been observed by researchers in several areas of China (Chen and Li 1995; Luo et al. 1996; Lu 2002) as well as in other countries such as Mexico, United Kingdom, Spain, Ireland, Solvenia, Yugoslavia and the United States (Kobal et al. 1986, 1987; Cunningham and LaRock 1991; Eheman et al. 1991; Jovanovič et al. 1992; Solomon et al. 1992; Duffy et al. 1996; Jovanovič 1996; Dueñas et al. 1999; Gillmore et al. 2000; Sperrin et al. 2000; Gillmore et al. 2001; Gillmore et al. 2002; Dueñas et al. 2005; Krewski et al. 2005; Lario et al. 2005). Radon can migrate over large distances and can concentrate in caves, chambers and corridors (Ball et al. 1991; Przylibski 1999; Lu 2002). The radon concentrations in karstic (i.e. limestone) cave systems depend on a complex inter-relation among several different factors, including outside-inside temperature differences, wind velocity, humidity, karstic geomorphology and porosity, and the radium content of the sediments and rocks (Lu 2002; Lario et al. 2005). The complex dynamics of radon in natural underground atmospheres makes continuous monitoring essential for protecting cave workers against radiation. However, studies and monitoring of radon in caves are limited in China. The aim of this work was to monitor radon air concentrations in one of the most visited karst caves in China and to determine radon air concentrations throughout a year. The measured radon air concentrations were then compared with Chinese standard, international standards and other previous studies. The results of this work could provide valuable safety guidance with respect to the radiation exposure of cave workers.

2 BACKGROUND OF THE STUDIED SITE

The Lantian karst cave, situated in the northern hillside of Qinling mountain about 60 km east of Xi'an (Fig. 1), was discovered in 1931 by the Taoists and exploited as a tourist cave since the mid-1980s. These are beautiful and famous caves, among the most visited tourist attractions in Shaanxi Province, China. Every year more than 50,000 tourists visit Lantian cave, especially from February 5th to 7th on the traditional Chinese calendar. Every year 10,000 pilgrims gather from a 100-km radius to join the religious activity. This cave contains two large sub-caves: Lingyun cave and Xishui cave. They were formed by water erosion of limestone. Xishui cave consists of a series of S-shaped passages and a very large hall (Xishui Hall) 370 m in total length. There are more than 40 polychromatic paintings and sculptures in the Xishui Hall showing the Chinese Taoism culture. Lingyun cave, with a total length of about 530 m, consists of two big chambers (Xiaoyao Hall and Lingyun Hall) and a series of narrow S-shaped corridors. A schematic plan of the studied caves system is shown in Fig. 1.

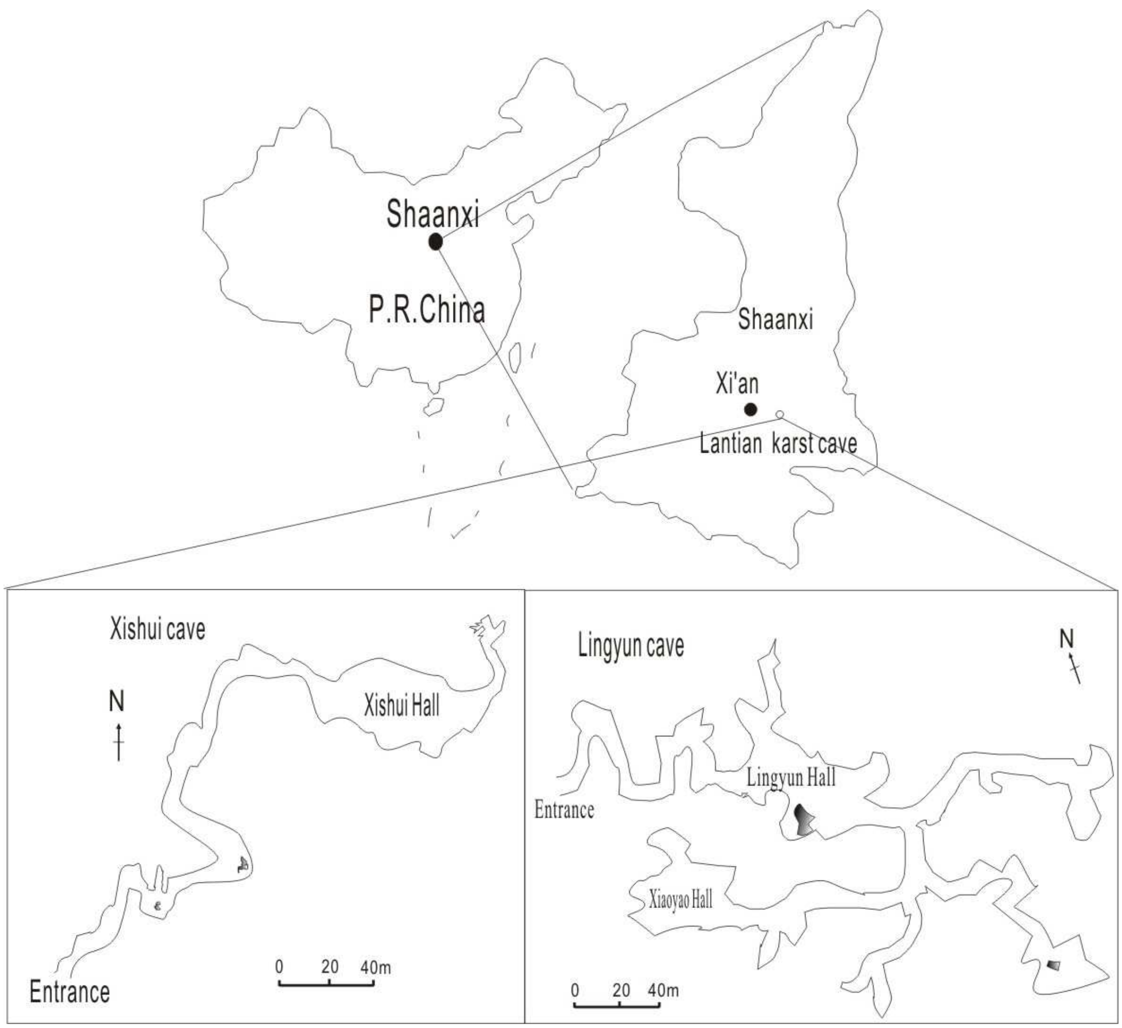

Fig. 1 Location and layout of Lantian karst cave.

3 METHODOLOGY

The radon air concentration was measured by a Model 1027 Professional Continuous Radon Monitor over a complete annual cycle (March 2004-February 2005). This Monitor is a patented electronic detecting device which uses a diffused-junction photodiode sensor to determine the concentration of radon gas. The principle underlying the Model 1027 Radon Monitor is that ambient air laden with radon diffuses into the detection chamber and alpha particles emitting from the decay of radon are detected by the photodiode. The Monitor has been evaluated and accepted by the U.S. Department of Environmental Protection (U.S. EPA). An automatic recording system was programmed to store records every hour during the entire monitoring period. Radon Monitor was installed approximately 1 m above the ground near the centre of Xishui Hall, Lingyun Hall and Xiaoyao Hall (Fig. 1). Data were recorded continuously and collected every 10 to 15 days for analysis.

4 RESULTS AND DISCUSSION

The continuous monitoring data of radon air concentration in the Lantian karst cave from March 2004 to February 2005 are presented in Fig. 2. The radon levels inside the Xishui Hall, Lingyun Hall and Xiaoyao Hall ranged from 384 to 2020, 404 to 2010 and 419 to 2010 Bq m^{-3}, respectively, with corresponding annual averages of 1100, 1110 and 1150 Bq m^{-3}. These radon concentrations are similar to other caves in China (Chen and Li 1995; Luo et al. 1996). The measurements indicate that the radon average levels in all three locations are similar. The small difference in the radon concentrations in the two caves and two Halls of Lingyun cave is likely related to the natural ventilation of the caves. Lingyun karst cave is longer than Xishui karst cave and the topography structure of Lingyun karst cave is more complex than Xishui karst cave. Xiaoyao Hall is located in the dead air zone of Lingyun cave, while Lingyun Hall is near the entrance of the cave (Fig.1). Therefore, the natural ventilation in the Xishui karst cave and Lingyun Hall could be better than those of the Lingyun karst cave and Xiaoyao Hall.

The daily average radon air concentrations in the studied caves are higher than the upper bound of radon action level (1000 Bq m^{-3}) for underground space proposed by China (GBZ116-2002, 2003) during May to September (Fig. 2). The monthly variation of radon concentrations in the two caves (Table 1 and Fig. 2) show that the lowest monthly average radon air concentration occurred in January, while the highest was observed in August. The monthly average radon air concentrations in the investigated caves between April and October are higher than the upper bound of radon action level. Amongst those high concentration months, July and August are higher than the upper bound of radon action level (1500 Bq m^{-3}) recommended by the ICRP65 for workplaces (ICRP 1994).

The seasonal variations of radon level in these two caves were calculated based on the continuously monitored values from March 2004 to February 2005. The average values for the spring (March to May), summer (June to August), autumn (September to November) and winter (December to February) were 1090, 1530, 1110 and 679 Bq m^{-3} for the Xishui karst cave, and 1100, 1570, 1130 and 706 Bq m^{-3} for the Lingyun karst cave, respectively (Fig. 3). Distinct seasonal patterns of radon concentration were observed in these caves with the highest concentrations in the summer and the lowest

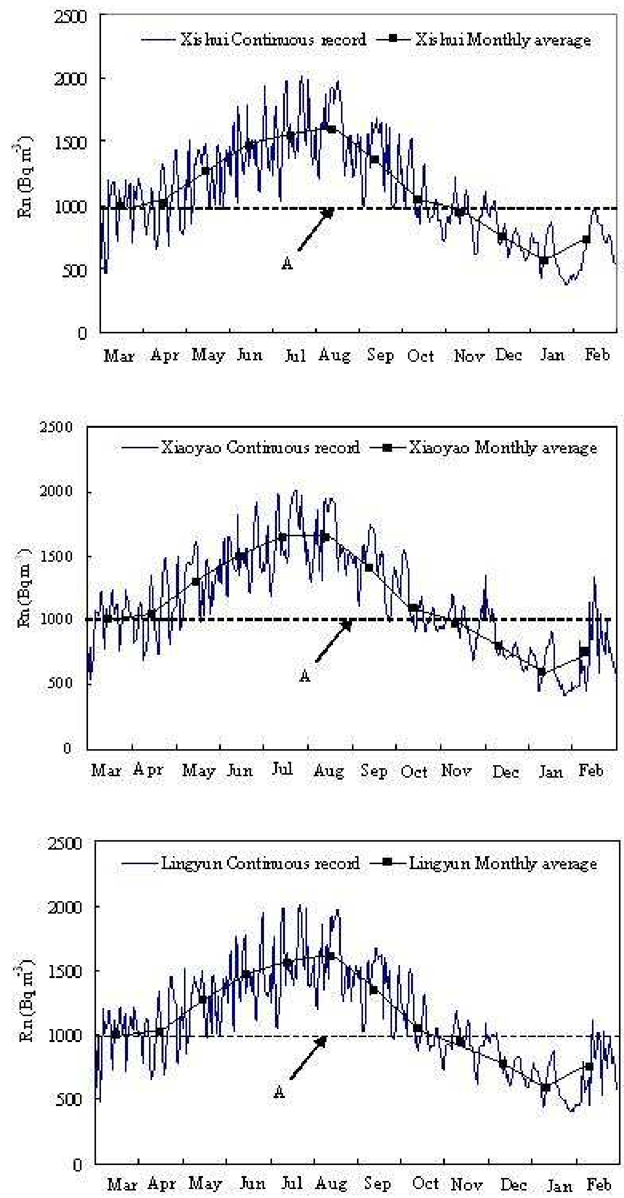

Fig. 2 Continuous monitoring data and monthly average of radon air concentration at the three sampling locations. A: the upper bound of radon action level for underground space in China

Table 1. Radon air concentration in Lantian karst cave of Shaanxi, China

Month	Rn concentration (Bq m^{-3})		
	Xishui cave	Lingyun cave	
	Xishui	Lingyun	Xiaoyao
Mar	468-1200 (988)	481-1210 (992)	531-1230 (999)
Apr	656-1440 (1020)	661-1450 (1030)	691-1480 (1050)
May	865-1490 (1270)	868-1500 (1270)	928-1610 (1300)
Jun	1030-1940 (1460)	1050-1950 (1460)	1190-1930 (1500)
Jul	1030-2020 (1550)	1060-2010 (1560)	1200-2010 (1640)
Aug	1220-1970 (1590)	1220-1970 (1600)	1300-1940 (1650)
Sep	976-1690 (1350)	967-1670 (1350)	987-1700 (1400)
Oct	720-1530 (1040)	728-1510 (1040)	906-1550 (1100)
Nov	615-1220 (931)	615-1190 (938)	695-1210 (970)
Dec	566-1030 (751)	586-1020 (770)	611-1090 (791)
Jan	384-864 (567)	404-879 (581)	419-914 (598)
Feb	437-985 (726)	452-1010 (740)	477-1060 (757)
Annual	**384-2020 (1100)**	**404-2010 (1110)**	**419-2010 (1150)**

Rn concentrations in two karst caves are presented in range and mean (in parenthesis).

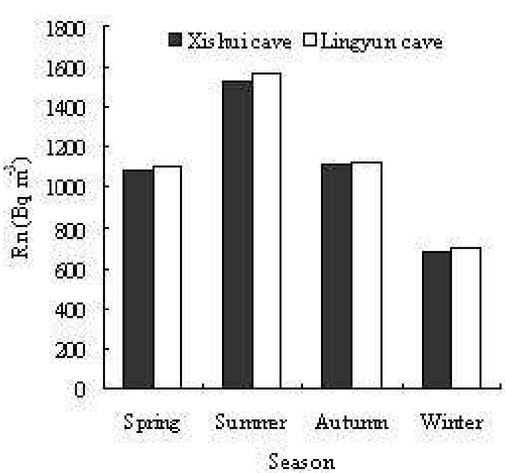

Fig. 3 Seasonal variations of radon air concentration (Bq m^{-3}) in the Xishui karst and Lingyun karst caves.

concentrations in the winter. The average ambient air radon concentration in the spring was similar to that in the autumn. A slow increase in concentrations in the spring and a gradual decrease in the autumn were observed (Fig. 2). Such seasonal variation of radon air concentration is consistent with other radon data for caves (Szerbin 1996; Dueñas et al. 1999; Przylibski 1999; Hafez and Hussein 2001; Przylibski 2001; Gillmore et al. 2002; Muramatsu et al. 2002). The seasonal variation of radon level in these caves could be due to the intensity of natural ventilation. The Xishui karst cave and Lingyun karst cave are poorly ventilated, and therefore radon may accumulate in such stagnant situation. This stagnation may be exacerbated by the relatively constant temperature inside the cave. The temperature inside Xishui and Lingyun karst caves, ~13 to 15°C, varies little over the year. However, the temperature outside the cave varies, 15 to 22, 28 to 40, 18 to 25 and –10 to +15°C in spring, summer, autumn and winter, respectively. The temperature inside the cave is normally lower than the outdoor temperature in the spring, summer and autumn, with the result that the cooler denser air keeps the radon emitted from the karst rocks in the cave, resulting in significantly higher radon concentrations. On the other hand in the winter, due to the natural convection, the warmer temperature in the cave relative to the atmosphere temperature, causes the air flow outside to carry radon continuously emitted from the rocks with it, resulting in a decrease in the radon concentrations in the cave.

The annual average radon concentration of the two caves is slightly greater than the upper bound of radon action level (1000 Bq m^{-3}) for underground space in China (GBZ116-2002, 2003) and less than the upper value of radon action level (1500 Bq m^{-3}) recommended by the ICRP65 for workplaces (ICRP 1994). The cumulative frequency distribution analysis of radon concentration in the two caves (Fig. 4) indicates that 56% of the concentration values in Xishui karst cave and 59% of radon concentration values in the Lingyun karst cave exceeded 1000 Bq m^{-3}, whereas 17% and 18% of radon values, respectively, in the Xishui and Lingyun caves exceeded 1500 Bq m^{-3}. Attention needs to be taken by the staff of the Lantian karst cave, especially in May to September that workers' hours inside the cave should be reduced.

5 CONCLUSIONS

The continuous monitoring of radon levels in a karst cave network of Shannxi, China indicates that the daily average radon air concentrations are higher than the upper bound of radon action level for underground space in China during May to September. The radon air concentration varied monthly and seasonally, with the highest level in August and the summer, while the lowest value is in January and the winter. Sharp increases and decreases occur in the spring and the autumn, could be caused by natural convection exchange of cave air. The annual average of radon air concentration in the investigated caves is slightly higher than the upper bound

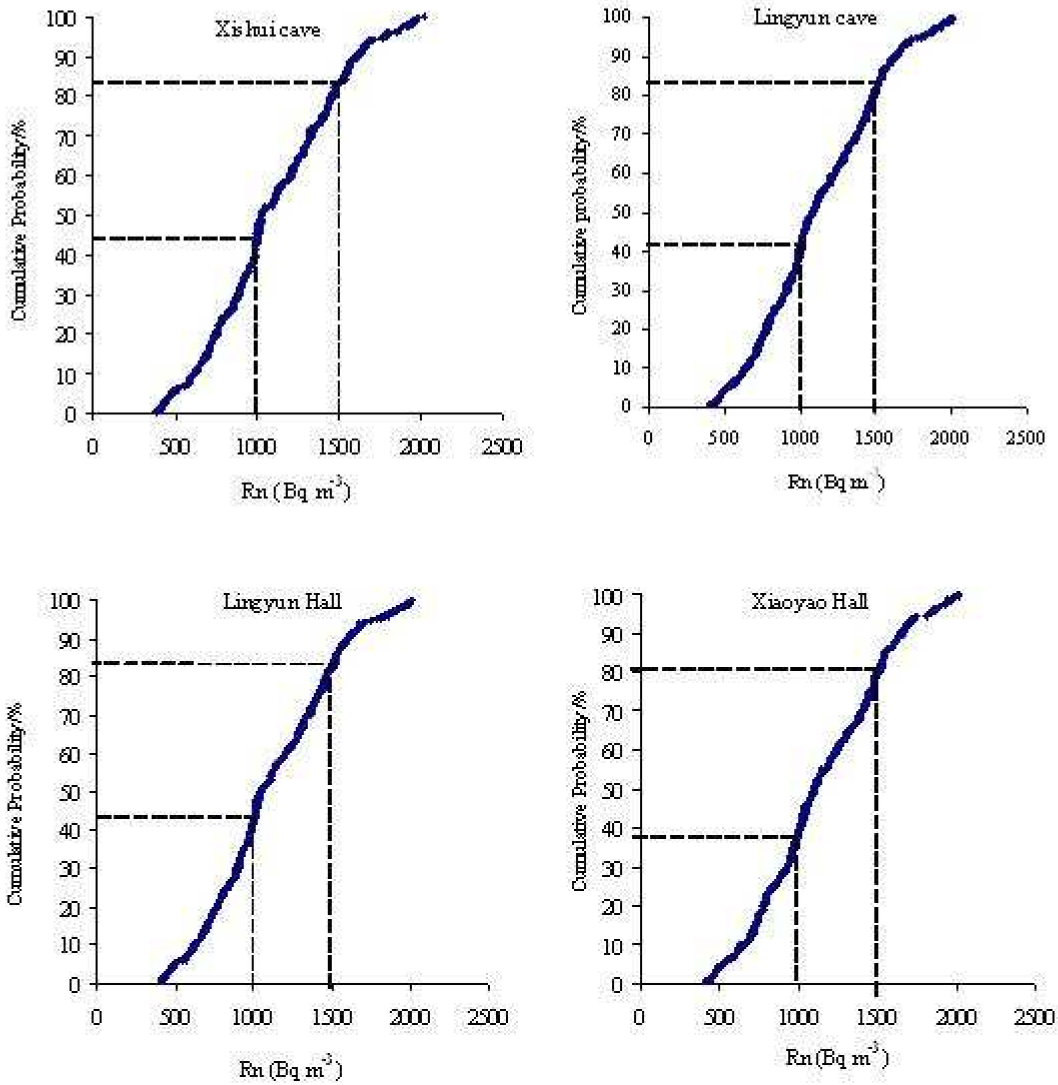

Fig. 4 Cumulative frequency distribution of radon air concentration (Bq m^{-3}) inside the Lantian karst cave.

of radon action level for underground space in China and less than the upper limit of radon action level recommended by the ICRP for workplaces.

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