Radon Levels Inside the Caves of Bohol Island, Philippines

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Abstract. Radon concentration in various workplaces, including tourist caves, remains higher than the recommended action level by the International Commission on Radiological Protection, which may pose a significant health risk. However, there has been no endeavor to investigate radon concentration in Philippine caves. This work investigated radon concentration inside Hinagdanan Cave, Batungay Cave, and Princess Manan-aw Cave using a passive radon detector. Radiation dose assessment and health risk estimation were also performed using the determined radon levels. The radon concentration inside these caves was above the safety limit (300 Bq/m^3) and action limit (1000 Bq/m^3) recommended by the World Health Organization and International Atomic Energy Agency, respectively. The dose assessment and evaluation do not exceed the annual dose limit prescribed by the Philippine Nuclear Research Institute. Lastly, the results of the lung cancer risk estimation exceed the recommended limit of 130 - 270 lung cancer cases per million people per year by the International Commission on Radiological Protection, except for Hinagdanan Cave. Radon mitigation must still be prioritized since the safety and action limit is exceeded, and administrative controls must be put in place to control radon exposure.

Keywords: Radon, Philippine caves, CR-39, radiological risk, Bohol Island

1. Introduction

Caves are known for their unique geological formations and are popular tourist destinations. However, they can also pose a risk to human health due to high concentrations of radon, a naturally occurring radioactive gas present in cave environments, particularly in areas with high concentrations of uranium and other radioactive elements. Radon and its decay products comprise approximately 42% of human exposure to natural radiation sources (United Nations Environment Program, 2016). Moreover, it has been identified as the second leading cause of lung cancer after smoking (World Health Organization, 2009).

Various studies have reported that radon concentrations in caves are generally above the prescribed limits of the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) for the public and occupationally exposed individuals. Radon levels may vary from hundreds to tens of thousands of Becquerel per cubic meter of air (Gonzalez et al. 2010; Wang et al. 2019). It is mainly affected by different factors such as seasonal changes, temperature, humidity, and ventilation.

Additionally, continuous monitoring programs in several countries have shown that elevated radon levels in caves are prominent during the summer, whereas minimum radon levels are detected during the winter (Lu et al. 2009; Smetanová et al. 2014; Ambrosino et al. 2021). These observations are connected to the temperature difference between the inside and outside of the cave environment. Furthermore, spatial variation of radon in caves was observed to be at a maximum in areas further from the cave entrance and generally affected by ventilation (Dinu et al. 2017; Paz et al. 2019; Weng et al. 2021).

In the Philippines, extensive karst formations in a limestone environment can be found on the island of Bohol, with over 1,000 caves extending from the central part to the southwestern boundary (Delos Reyes et al., 2016, as cited by the Provincial Government of Bohol, 2018). However, there have been no studies that address radon levels in these caves. This paper aims to measure the radon concentration in selected caves of Bohol Island using passive radon detectors. Moreover, risk estimation was performed to provide preliminary information on the current radon levels in Bohol Island's caves and their potential impact on human health.

2. Materials and Methods

2.1. Study Area

Bohol Island is in the central part of the Philippines, forming part of Region VII and is located explicitly between 9°30' and 10°15' N latitude and 123°40' and 124°30' E longitude. Three caves were selected: the Hinagdanan Cave, Batungay Cave, and Princess Manan-aw Cave located in Dauis, Alicia, and Trinidad, respectively, as shown in Figure 1. These caves are underlain by limestone formations namely the Maribojoc limestone, Carmen Formation, and Sierra Bullones limestone, respectively (Hernandez et al., 1988 & Faustino et al., 2003).

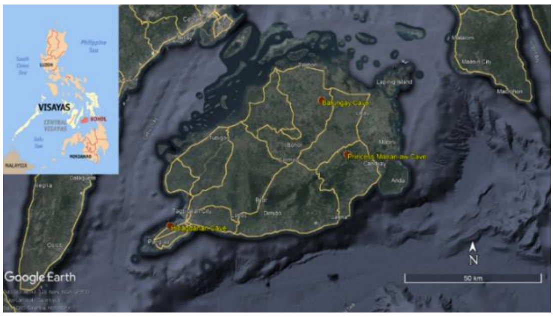

Figure 1. Location map of Bohol Island with the indication of study areas

2.2. Radon Measurement

The radon concentration inside the caves was measured using a solid-state nuclear track detector called the Raduet developed by Tokonami et al. (2005) and manufactured by Radosys Ltd. in Hungary. These detectors were placed 1.5 to 2.0 meters above the ground and in strategic locations, covering the most accessible parts of the caves.

Furthermore, these detectors were deployed for three months following the recommendation of the World Health Organization. The concentration of radon (C_{Rn}) was calculated using Equation 1, described in the study of Kranrod et al. (2020):

$$C_{Rn}=\left(d_L-b\right)\times\frac{f_{Tn2}}{t\times(f_{Rn1}\times f_{Tn2}-f_{Rn2}\times f_{Tn1})}-\left(d_H-b\right)\times\frac{f_{Tn1}}{t\times(f_{Rn1}\times f_{Tn2}-f_{Rn2}\times f_{Tn1})} \quad (1)$$

C_{Rn} is the mean concentration of radon during the exposure period in Bq m^{-3}. d_L and d_H are the total alpha track densities in track mm^{-2}, taken from Raduet's low and high air-exchange rate chambers. f_{Rn1} and f_{Tn1} are the radon and thoron calibration coefficients for the low air-exchange rate chamber in tracks m^3 mm^{-2} kBq h. f_{Rn2} and f_{Tn2} are the radon and thoron calibration coefficients for the high air-exchange rate chamber in tracks m^3 mm^{-2} kBq h. t is the exposure time in hours, and b is the background track density in tracks mm^{-2}.

After the retrieval of the Raduets, the CR-39 detectors inside the Raduets were collected and etched using 6.25 M of NaOH solution at 90^o C for 6 hours. After this, the CR-39 detectors were washed with ethanol and deionized water. The alpha track densities were counted using the Radometer 2000 RSV8 (Radosys Ltd., Hungary).

2.3. Dose Assessment

The annual effective dose (E) in the units of Working Level Month per year (WLM/y) was calculated using Equation 2:

$$E=\frac{C_{Rn}\times F\times t}{6.37\times10^5\ \text{Bq h m}^{-3}} \quad (2)$$

F is the equilibrium factor with a value of 0.4, as recommended by ICRP for tourist caves. Lastly, *t* is the time spent inside the cave, in hours per year.

Furthermore, the value of E was converted in units of millisievert (mSv) by multiplying it with a dose conversion factor of 24 mSv/WLM to compare it with the maximum allowable value of E for the public and workers in the Philippines as per existing regulations.

2.4. Lung Cancer Risk Estimation

The lung cancer risk was estimated following the work of Anderson et al. (2021) and Azhdarpoor et al. (2021). The process involves the estimation of the weighted equivalent dose due to the lung (H_{lung}) using the different doses of radiation absorbed (D) by the lung regions specified by the Human Respiratory Track Model of the International Commission of Radiological Protection (ICRP). A risk factor of 18 x 10^{-6} was multiplied by the determined H_{lung} value to calculate the lung cancer cases (LCC) per million people yearly.

3. Results and Discussion

The average radon concentration measured and their corresponding range inside Hinagdanan Cave, Batungay Cave, and Princess Manan-aw Cave were 689 Bq/m^3, 808 Bq/m^3, and 1489 Bq/m^3, respectively, as shown in Figure 2. The average radon concentration in all three caves was above the reference level of 300 Bq/m^3 as prescribed by the World Health Organization (WHO), which indicates a potential risk to the health of tourists and cave workers.

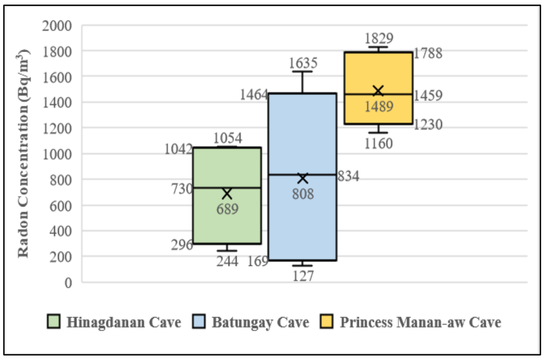

Figure 2. Boxplot of the measured radon concentration (✕ indicates the average value)

Currently, no specific regulation in the Philippines deals specifically with natural radiation sources in various workplaces. However, radiation doses received by workers from radiation sources are assessed following the Code of the PNRI Regulations (CPR) Part 3 (Philippine Nuclear Research Institute, 2021). Since cave workers are exposed to radon, they could also be considered radiation workers. The calculated annual effective dose received by tourists and cave workers given the specified time of occupancy and the corresponding lung cancer risk estimation is summarized in Table 1.

Table 1. Annual effective dose and lung cancer risk estimation for cave workers (W) and tourist (T)

Cave	**E (mSv/y)**		**Annual LCC (Per million people)**	
	W	**T**	**W**	**T**
Hinagdanan Cave	2.17	5.2×10^{-3}	35	0
Batungay Cave	22.9	2.4×10^{-2}	371	0
Princess Manan-aw Cave	14.1	2.2×10^{-2}	228	0

The time spent by tourists was based on the estimation of cave guides and was assumed to participate in a tour once per year. On the other hand, time spent by workers was based on the same estimation and adding the number of tours they guide in a single day. From the results, the annual dose received by tourists does not exceed the annual dose limit for the public, thus, no further adjustment is necessary for the length of tour inside these caves. Furthermore, the cave guides of Hinagdanan Cave and Batungay Cave receive an annual dose of less than the said limit.

Based on the current estimation of exposure time to the cave environment of tourist, the calculated average LCC for tourist was negligible. Considering the situation of cave workers, the estimated LCC values at Batungay and Princess Manan-aw cave were above the range of 170-230 per million people as recommended by the ICRP (Azhdarpoor et al., 2021). Hence, the measured radon concentration inside these caves can be considered a health hazard.

4. Conclusion

To conclude, the radon concentration inside the investigated caves of Bohol Island exceeds the safety limit of the World Health Organization and the action level of the International Atomic Energy Agency. Administrative controls, such as tour time management, must be strictly implemented in these caves because engineering solutions to mitigate radon could be harmful to the cave environment.

On the other hand, the annual radiation dose limit has not been exceeded considering the exposure situation of both tourists and cave workers. However, it is important to consider that the distribution of radon inside the caves is not uniform and may present higher elevated radon exposure as people traverses its deeper parts. The results of the lung cancer risk estimation show that radon exposure inside Batungay and Princess Manan-aw cave may pose a significant risk to the cave workers.

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