Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Investigation of the relationship between earthquakes and indoor radon concentrations at a building in Gyeongju, Korea

Jae Wook Kim, Han Young Joo, Rinah Kim, Joo Hyun Moon*

Department of Nuclear & Energy Engineering, Dongguk University-Gyeongju, Gyeongju, Republic of Korea

ARTICLE INFO

Article history:
Received 26 June 2017
Received in revised form
19 December 2017
Accepted 20 December 2017
Available online 16 January 2018

Keywords:
Earthquakes
Gyeongju
Indoor Radon Concentration
RAD7
Radon Anomaly

ABSTRACT

This article measured and analyzed the indoor radon concentrations at one university building in Gyeongju, Republic of Korea, to investigate if there is any relationship between earthquakes and indoor radon concentration. Since 12 September 2016, when two 5.1 and 5.8 magnitude earthquakes occurred, hundreds of aftershocks affected Gyeongju until January 2017. The measurements were made at the ground floor of the Energy Engineering Hall of Dongguk University in Gyeongju over a period between February 2016 and January 2017. The measurements were made with an RAD7 detector on the basis of the US Environmental Protection Agency measurement protocol. Each measurement was continuously made every 30 minutes over the measurement period every month. Among earthquakes with 2.0 or greater magnitude, the earthquakes whose occurrence timings fell into the measurement periods were screened for further analysis. We observed similar spike-like patterns between the indoor radon concentration distributions and earthquakes: a sudden increase in the peak indoor radon concentration 1–4 days before an earthquake, gradual decrease before the earthquake, and sudden drop on the day of the earthquake if the interval between successive earthquakes was moderately longer, for example, 3 days in this article.

1. Introduction

Radon is a natural radioactive gas produced by radioactive decays of radium-226, which is found in uranium ores, phosphate rock, shale, igneous and metamorphic rocks such as granite, gneiss and schist, and, to a lesser degree, in common rocks such as limestone [1]. In the last decade, several studies have concluded that elevated concentrations of radon gas in soil or groundwater could be signs of an imminent earthquake. It is believed that the radon is released from cavities and cracks as the Earth's crust is strained prior to the sudden slip of an earthquake [2].

Sac et al. monitored the radon concentration of an active tectonic zone in western Turkey and found that there was a linear correlation between the radon emission rate and the seismic activity in the area under investigation [3]. Wakita et al. observed precursory changes in the radon concentration of groundwater prior to the Izu-Oshima-Kinkai earthquake, of 7.0 magnitude, on 14 January 1978 [4]. Omori et al. observed anomalous emanation of radon preceding large earthquakes and considered it to be linked to preseismic electromagnetic phenomena such as great changes of atmospheric electric field and ionospheric disturbance [5]. Kim et al. observed considerable variations of radon concentrations before the occurrence of earthquakes [6].

Previous studies have focused on anomalies in radon concentrations in outside environments such as soil and groundwater before earthquakes, but few studies have investigated the relationship between the indoor radon concentration and earthquakes. In this article, hence, we measured and analyzed the indoor radon concentrations at one university building in Gyeongju, where there have been hundreds of aftershocks since 12 September 2016; the study was performed to check if there were indicative changes in the indoor radon concentrations prior to earthquakes.

2. Materials and methods

2.1. Radon measurement device and procedure

We used a RAD7 detector to measure the indoor radon concentrations because this detector allows continuous measurements. As shown in Fig. 1, the RAD7 has a 0.7 L hemisphere coated on the inside with an electrical conductor; a silicon alpha detector is at the center. Samples of air drawn through a fine inlet filter enter

* Corresponding author.
E-mail address: jhmoon86@dongguk.ac.kr (J.H. Moon).

https://doi.org/10.1016/j.net.2017.12.010

the silicon alpha detector, and alpha radiation is directly converted to an electrical signal. The RAD7 can detect radon concentrations between 0.1 pCi/L and 20,000 pCi/L, with an uncertainty range of ±5 % [7].

The measurements of the indoor radon concentrations were on the basis of the US Environmental Protection Agency protocols [8]. Before the measurement, the RAD7 was purged for more than 10 minutes outside of a building to remove the remaining radon gas inside the chamber. Then, the air inlet of the RAD7 was placed 1.5 m above the floor, considering the breathing zone of a Korean adult. The indoor radon concentrations were continuously measured every 30 minutes over the measurement periods each month. The measurements were made in the corridor near the main entrance on the first floor of the Energy Engineering Hall of Dongguk University in Gyeongju. In the corridor, there was no forced air-conditioning, just natural ventilation through the entrance door as it was opened and closed by visitors. The measurement data were recorded and analyzed by using the program embedded in RAD7.

2.2. Data analysis method

Gyeongju is located in the southeastern area of the Korean peninsula, approximately 360 km away from Seoul. In Gyeongju on 12 September 2016, 5.1 and 5.8 magnitude earthquakes occurred one after another at a 48-minute interval. Since then and until 23 January 2017, 572 aftershocks have followed [9].

The indoor radon concentrations were measured on the ground floor of the Energy Engineering Hall of Dongguk University in Gyeongju, which is 10 km away as the crow flies from the epicenter of the 5.8 magnitude earthquake, as shown in Fig. 2, over a period between February 2016 and January 2017. The building is 5-story building and was built in 2008.

We applied an empirical relationship proposed by Hauksson and Goddard [10] to screen earthquakes, including aftershocks, to find the relationship between earthquakes and the indoor radon measurements. The empirical magnitude–distance relationship is

$$M = 2.4log_{10}D - 0.43 \quad (1)$$

where M is the earthquake magnitude on the Richter scale and D is a distance (km) from the epicenter. Eq. (1) indicates that an earthquake of magnitude M could be preceded by a radon anomaly at a distance of less than or equal to D (km).

Replacing D in Eq. (1) with 10 km gives $M = 1.97$. With the magnitude value rounded off, therefore, we used $M = 2.0$ as the screening criterion of earthquakes for further analyses. Applying the screening criterion, we reduced the number of earthquakes to 172 from 572. Among those, we finally chose 15 earthquakes for scrutiny, those whose occurrence times fell into the span of the indoor radon measurements. Table 1 shows statistics for the 2.0 magnitude or greater earthquakes that occurred in Gyeongju over the period of 12 September 2016 to 23 January 2017.

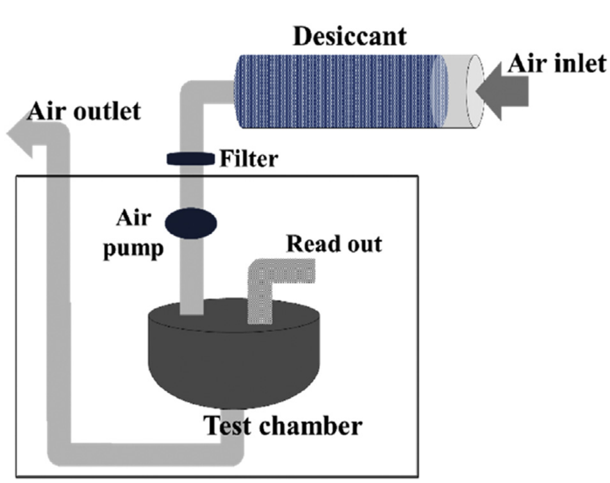


Fig. 1. Structure of RAD7 detector.

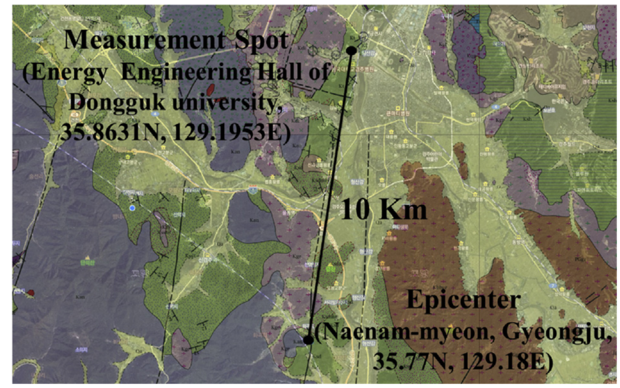


Fig. 2. Locations of epicenter and measurement spot.

A radon anomaly is defined as a significant deviation from the mean value. A very common practice in determining radon anomalies is the use of standard deviation (σ). The periods when radon concentration deviates by more than ±2σ from the related seasonal value are considered radon anomalies that are possibly caused by earthquake events and not by meteorological parameters [11]. Consequently, to check if radon anomalies in the indoor radon concentration occur prior to earthquakes, we examined if and how many indoor radon concentrations exceeded 2σ above the seasonal average before earthquakes occurred.

3. Results

3.1. Measurement results

Fig. 3 and Table 2 show monthly averages of the indoor radon concentration measurements from February 2016 to January 2017, except for September 2016, during which month the measurements were not made because of maintenance of the RAD7.

As shown in Fig. 3, the annual average was 13.4 ± 15.5 Bq/m^3. The indoor radon concentration in August 2016 was much higher than other months' concentrations and the seasonal average for summer, 12.6 ± 22.3 Bq/m^3. The measurement dates for August were about one month earlier than those for September, when the 5.1 and 5.8 magnitude earthquakes occurred. Unfortunately, we could not measure the indoor radon concentrations during September 2016

Table 1
Statistics for 2.0 magnitude or greater earthquakes that occurred in Gyeongju over the period of 12 September 2016 to 23 January 2017.

Month	Seismic magnitude			
	2.0–3.0	3.0–4.0	4.0–5.0	≥5.0
2016.09	120	15	1	2
2016.10	13	2	0	0
2016.11	7	0	0	0
2016.12	7	2	0	0
2017.01	2	1	0	0
Sum	149	20	1	2

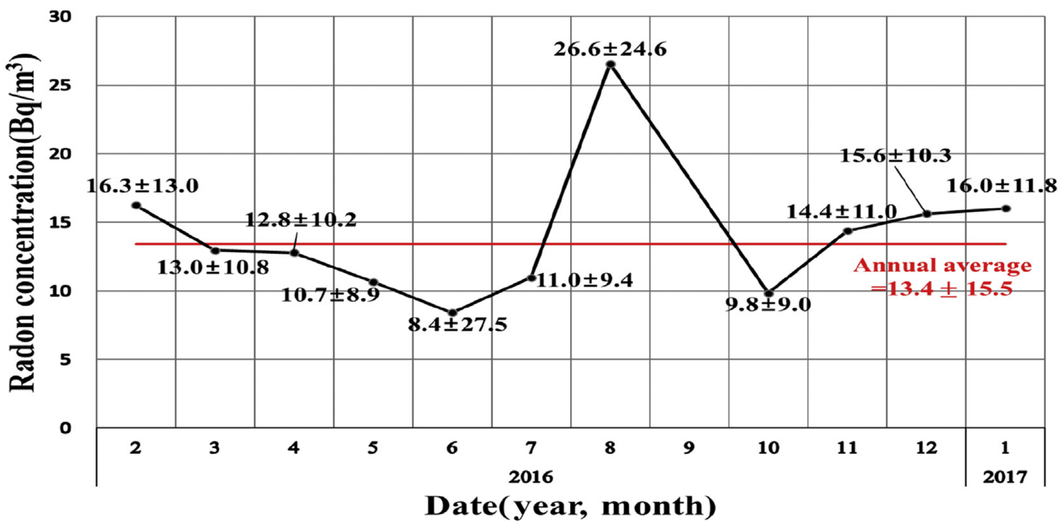


Fig. 3. Monthly averages of the indoor radon concentration (2016.02–2017.01).

Table 2
Monthly and seasonal indoor radon concentrations (2016.02–2017.01).

Season	Month (measurement period)	Monthly average temperature in Gyeongju (°C)	Monthly rainfall in Gyeongju (mm)	Monthly average indoor radon concentration (Bq/m^3)	Seasonal average indoor radon concentration (Bq/m^3)
Winter	2016.02 (2.23–2.29)	2.9	4.7	16.3 ± 13.0	16.3 ± 13.0
Spring	2016.03 (3.1–3.9, 3.17–3.31)	7.6	7.2	13.0 ± 10.8	12.3 ± 10.3
	2016.04 (4.1–4.7)	13.7	14.5	12.8 ± 10.2	
	2016.05 (5.11–5.21)	19.0	10.1	10.7 ± 8.9	
Summer	2016.06 (6.21–6.23)	22.4	3.4	8.4 ± 27.5	12.6 ± 22.3
	2016.07 (7.11–7.31)	25.7	12.9	11.0 ± 9.4	
	2016.08 (8.1, 8.10–8.18)	26.7	6.3	26.6 ± 24.6	
Autumn	2016.09	21.3	22.6	N/A[a]	13.5 ± 10.8
	2016.10 (10.19–10.26)	16.0	12.2	9.8 ± 9.0	
	2016.11 (11.1–11.30)	8.4	2.2	14.4 ± 11.0	
Winter	2016.12 (12.1, 12.29–12.31)	4.1	7.5	15.6 ± 10.3	16.0 ± 11.8
	2017.01 (1.1–1.23)	1.0	0.3	16.0 ± 12.0	

[a] No measurement due to maintenance of the RAD7.

due to maintenance of the RAD7. Hence, we reviewed the measurements from August 10 to August 18. Fig. 4 shows that the daily peak concentrations over the five consecutive days from August 10 to August 14; the peak concentration for two consecutive days from August 16 to 17 exceeded 57.2 Bq/m^3, which was the seasonal average + 2σ. Even the peak concentrations on August 11, 12, and 13 exceeded 110 Bq/m^3, which was about nine times higher than the seasonal average.

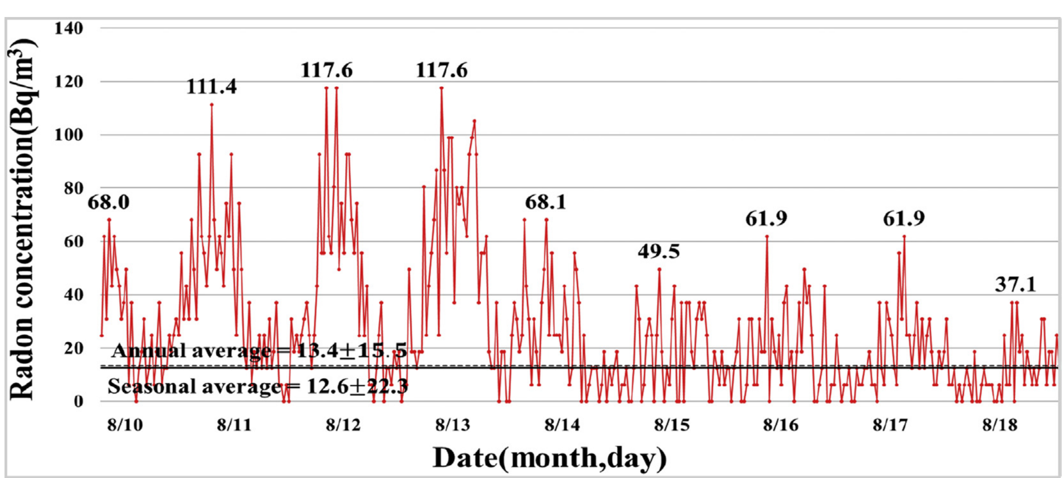


Fig. 4. Distribution of the indoor radon concentrations on August 2016.

Table 3
Comparison between the daily highest temperature, rainfall, humidity and radon concentration on August 2016 and 2017.

Date		Highest temperature (°C)		Rainfall (mm)		Humidity (%)		Daily peak radon concentrations (Bq/m^3)	
2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
8/10	8/21	38.2	31.2	0	1.0	69.9	85.9	68.0	33.9
8/11	8/22	37.7	34.0	0	0.5	69.8	84.0	111.4	33.9
8/12	8/23	39.4	32.0	0	0	68.9	—	117.6	33.9
8/13	8/24	39.3	34.8	0	0	61.3	71.8	117.6	22.6
8/14	8/25	39.2	33.0	0	20.5	65.4	77.8	68.1	28.3
8/15	8/26	35.4	31.3	0	0	75.3	71.0	61.9	33.9
8/16	8/27	33.3	30.5	0.2	0	75.6	74.0	55.7	33.9
8/17	8/28	34.6	33.0	0	0	75.1	74.8	61.9	22.6
8/18	8/29	34.1	30.1	0	1.0	73.5	82.6	30.9	33.9

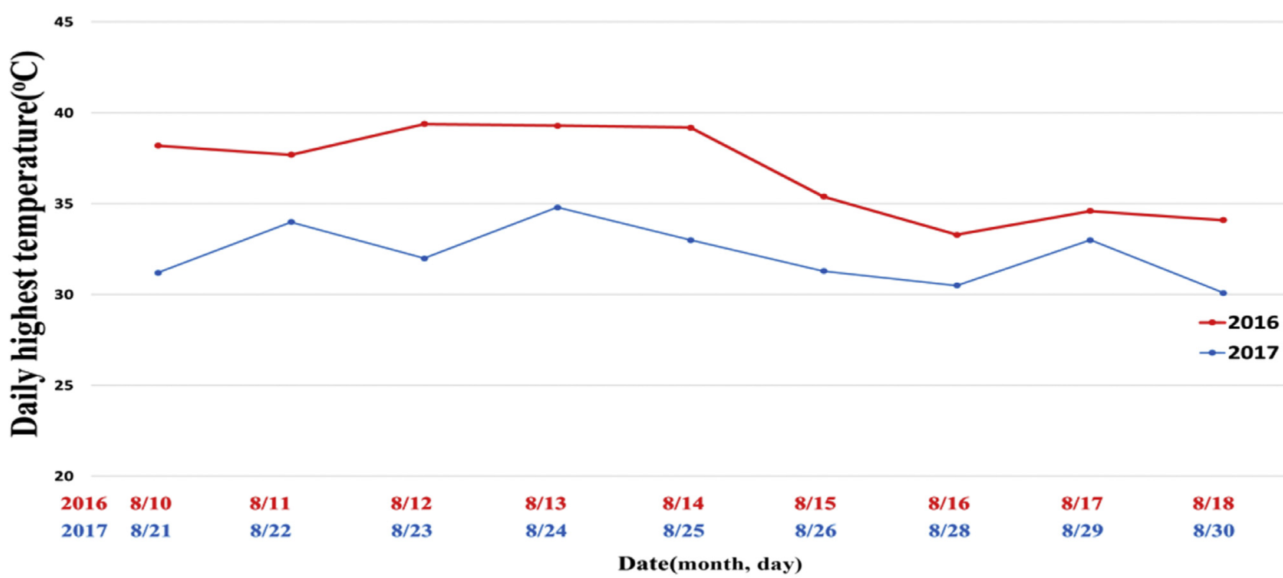


Fig. 5. Comparison between the daily highest temperature on August 2016 and 2017.

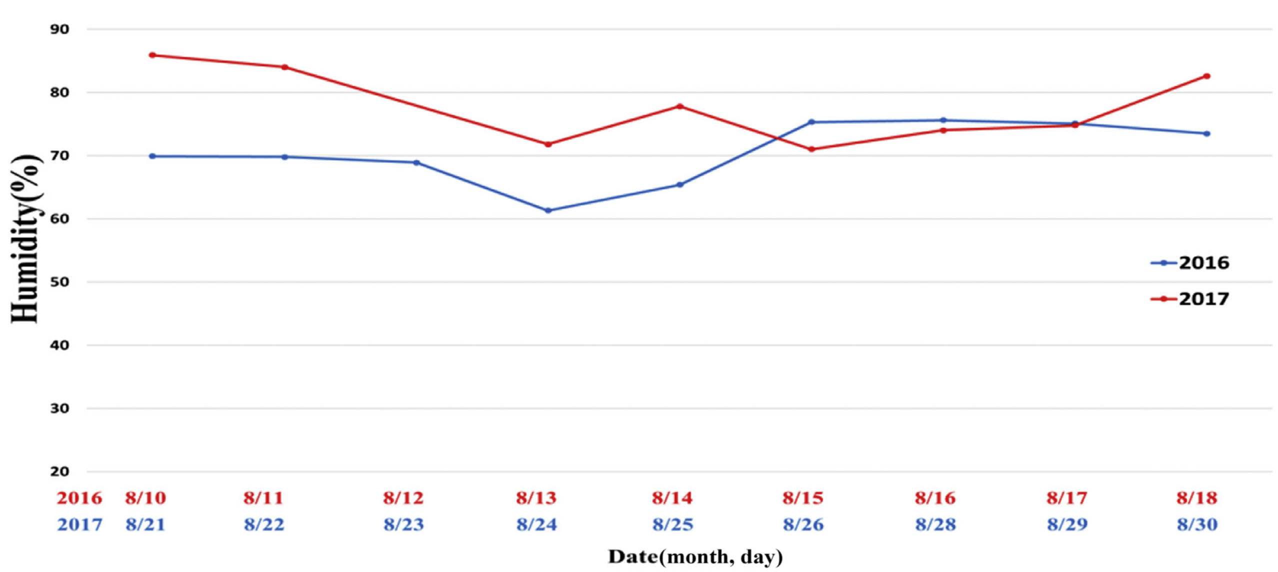


Fig. 6. Comparison between the daily humidity on August 2016 and 2017.

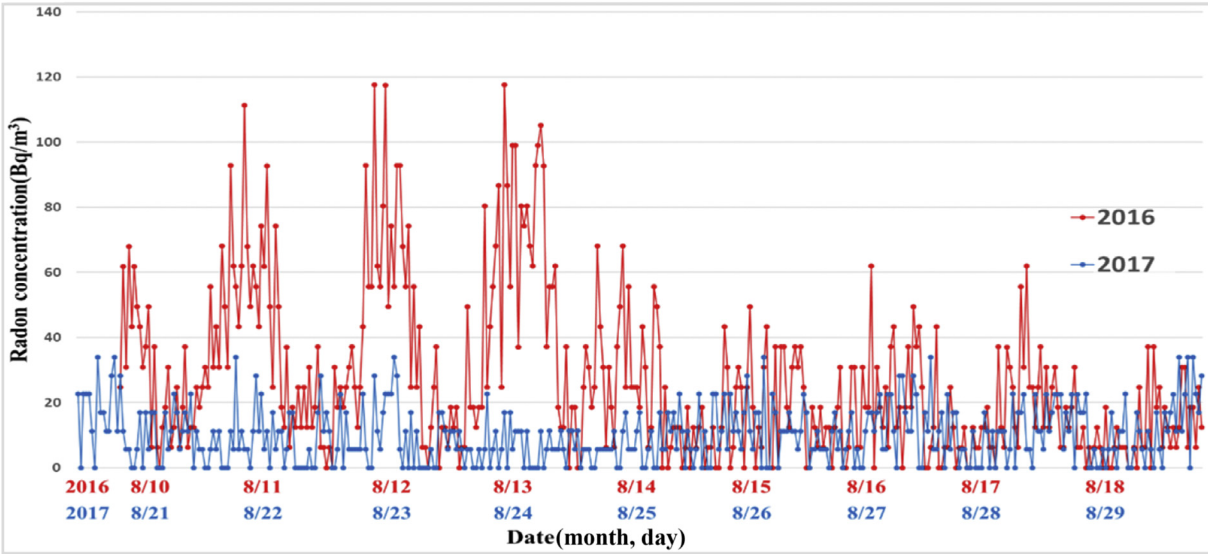


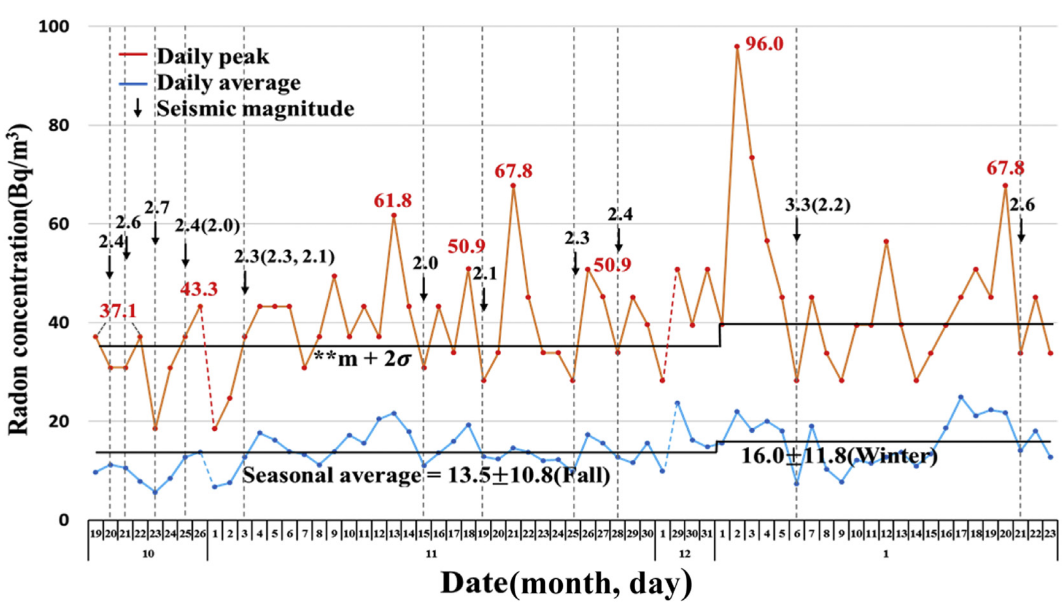
Fig. 7. Comparison of the indoor radon concentrations on August 2016 and 2017.

There are several factors, such as ambient temperature, rainfall, humidity, ventilation, etc., that may have effects on the indoor radon concentration. With the use of weather data from the Korea Meteorological Administration [9], we compared those factors in 2016 summer and 2017 summer to check if there was any factor, except tectonic activity, causing the striking increase in the indoor radon concentrations in 2016 summer. The comparison, shown in Table 3 and Figs. 5 and 6, shows no salient difference in those factors between 2016 and in 2017.

Because August is the summer vacation period, there was no class and only a few students were coming into and going out of the building in both years. We also found that there was no air-conditioning in the corridor where measurements were made and no special internal events such as repair work in August in 2016 and 2017 that could influence the indoor radon concentration. Hence, the indoor radon measurement conditions in August in 2016 and 2017 were almost the same; the only difference between them was tectonic activity.

Under the given situation, the difference between those years' indoor radon concentrations was remarkable: the indoor radon concentration in August 2016 was much higher than that in August 2017. In Fig. 7, it can be seen that the highest peak in 2016 was 117.6 Bq/m^3; that in 2017 was 33.9 Bq/m^3. The difference between the two peak values was 83.7 Bq/m^3. The monthly average on August 2017 was 9.1 ± 8.7 Bq/m^3, while the monthly average in 2016 was 26.6 ± 24.6 Bq/m^3. The difference between the two measurements was 17.5 Bq/m^3. Given those measurements, we could not help considering tectonic activity as a crucial factor causing the striking increase in indoor radon concentrations.

Next, to check if radon anomalies due to aftershocks occurred, we reviewed the indoor radon concentrations over the period from October 2016 to January 2017. For this, as described before, we



** Seasonal average + 2σ

Fig. 8. Daily radon concentrations and magnitudes of the earthquakes from October 2016 to January 2017.

Table 4
Details of earthquakes and the indoor radon concentration measurements to be investigated.

Radon measurement date	Earthquake magnitude	Measurements			
		m+2σ[a]	Daily average	Daily peak[b]	Difference[c]
2016.10.19		35.0	9.7	37.1	2.1
2016.10.20	2.4		11.2	30.9	−4.1
2016.10.21	2.6		10.6	30.9	−4.1
2016.10.22			7.9	37.1	2.1
2016.10.23	2.7		5.7	18.5	−16.5
2016.10.24			8.5	30.9	−4.1
2016.10.25	2.4, 2.0		12.8	37.1	2.1
2016.10.26			13.8	43.3	8.3
2016.11.01			6.8	18.5	−16.5
2016.11.02			7.6	24.7	−10.3
2016.11.03	2.3, 2.3, 2.1		12.8	37.1	2.1
2016.11.04			17.6	43.3	8.3
2016.11.05			16.2	43.3	8.3
2016.11.06			13.9	43.3	8.3
2016.11.07			13.3	30.9	−4.1
2016.11.08			11.2	37.1	2.1
2016.11.09			13.9	49.5	14.5
2016.11.10			17.3	37.1	2.1
2016.11.11			15.6	43.3	8.3
2016.11.12			20.5	37.1	2.1
2016.11.13			21.6	61.8	26.8
2016.11.14			17.9	43.3	8.3
2016.11.15	2.0		11.1	30.9	−4.1
2016.11.16			13.6	43.3	8.3
2016.11.17			16.0	33.9	−1.1
2016.11.18			19.3	50.9	15.9
2016.11.19	2.1		12.8	28.3	−6.7
2016.11.20			12.4	33.9	−1.1
2016.11.21			14.6	67.8	32.8
2016.11.22			13.8	45.2	10.2
2016.11.23			12.1	33.9	−1.1
2016.11.24			12.2	33.9	−1.1
2016.11.25	2.3		9.8	28.3	−6.7
2016.11.26			17.3	50.9	15.9
2016.11.27			15.5	45.2	10.2
2016.11.28	2.4		12.8	33.9	−1.1
2016.11.29			11.7	45.2	10.2
2016.11.30			15.7	39.6	4.6
2016.12.01		39.6	10.0	28.3	−11.3
2016.12.29			23.8	50.8	11.2
2016.12.30			16.2	39.5	−0.1
2016.12.31			14.8	50.8	11.2
2017.01.01			15.7	39.6	0.0
2017.01.02			22.0	96.0	56.4
2017.01.03			18.2	73.5	33.9
2017.01.04			20.1	56.6	17.0
2017.01.05			18.1	45.2	5.6
2017.01.06	3.3, 2.2		7.4	28.2	−11.4
2017.01.07			19.1	45.2	5.6
2017.01.08			10.4	33.9	−5.7
2017.01.09			7.8	28.2	−11.4
2017.01.10			12.2	39.5	−0.1
2017.01.11			11.5	39.5	−0.1
2017.01.12			12.8	56.5	16.9
2017.01.13			13.8	39.6	0.0
2017.01.14			10.9	28.2	−11.4
2017.01.15			13.4	33.9	−5.7
2017.01.16			18.6	39.5	−0.1
2017.01.17			24.9	45.2	5.6
2017.01.18			21.2	50.9	11.3
2017.01.19			22.4	45.2	5.6
2017.01.20			21.8	67.8	28.2
2017.01.21	2.6		14.1	33.9	−5.7
2017.01.22			18.1	45.2	5.6
2017.01.23			12.8	33.9	−5.7

[a] m+2σ is seasonal average plus seasonal standard deviation.
[b] Daily peak is the peak indoor radon concentration measured on the corresponding date.
[c] Difference is the value that subtracts (m+2σ) value from the daily peak.

finally chose for scrutiny the 14 earthquakes of magnitude 2.0 or greater whose occurrence times fell into the span of the indoor radon measurements. Then, we examined the indoor radon concentration distributions measured 1–7 days earlier than the timings of the 15 earthquakes and checked if the peak indoor radon concentrations exceeded the seasonal average plus 2σ, 35.0 Bq/m^3 for the autumn season (October and November 2016), and 39.6 Bq/m^3 for the winter season (December 2016 and January 2017).

Fig. 8 shows the measurements over the period between October 2016 and January 2017. Except for a few cases, we observed a similar spike-like pattern between earthquakes and the indoor radon concentration distributions: a sudden increase in the peak indoor radon concentration 1–4 days before an earthquake, a gradual decrease before the earthquake, and sudden dropping on the day of the earthquake if the interval between successive earthquakes was moderately longer, for example, 3 days in this article. However, we did not see the spike-like pattern if the interval between earthquakes was short. The examples were earthquakes on October 21 and 25, 2016. For the three earthquakes on November 3, 2016, we could not make any definite conclusion on the relationship between the indoor radon concentrations and earthquakes because we did not have indoor radon measurements over the span between 27 and 30 October, 2016. The details of the indoor radon concentration measurements and earthquakes were described in Table 4.

4. Discussion

In this article, to check if there were indicative changes in the indoor radon concentrations prior to earthquakes, we measured and analyzed the indoor radon concentrations at one university building in Gyeongju, where there have been hundreds of aftershocks since 12 September 2016.

Though the analysis cases were not sufficient, we observed the following noteworthy relationships between earthquakes and the indoor radon concentrations, which could be regarded as a precursor of an earthquake:

- For earthquakes with magnitudes of 5.0 or greater, radon anomalies, that is, the indoor radon concentration exceeding 2σ above the seasonal average, were observed even month earlier than the earthquakes; and
- For earthquakes with magnitudes of 2.0–4.0, similar spike-like patterns between the indoor radon concentration distributions and earthquakes were observed: there is a sudden increase in the peak indoor radon concentration 1–4 days before an earthquake, a gradual decrease before the earthquake, and sudden dropping on the day of the earthquake if the interval between successive earthquakes was moderately longer, for example, 3 days in this article.

Because the number of cases to be investigated is limited, we cannot definitely assert that there is a clear trend between earthquakes and indoor radon concentrations. We can tell that, for some cases, there were definite patterns between earthquakes and indoor radon concentrations, which seem to be due to tectonic activities of the Earth's crust prior to the earthquake. We hope that our study will be helpful in identifying a clearer relationship between earthquakes and indoor radon concentrations.

Conflicts of interest

The authors declare no conflicts of interest.

References

[1] M.K. Timothy, Geological Hazards: A Sourcebook, Greenwood Press, 2003.
[2] J. Dacey, A Radon Detector for Earthquake Prediction, Physicworld.com, 2010. http://physicsworld.com/cws/article/news/2010/mar/18/a-radon-detector-for-earthquake-prediction. 19 December 2017.
[3] M.M. Sac, C. Harmansh, B. Camgoz, H. Sozbilir, Radon Monitoring as the Earthquake Precursor in Fault Line in Western Turkey, Ekoloji 20 (79) (2011) 93–98.
[4] H. Wakita, Y. Nakamura, H. Notsu, M. Noguchi, T. Asada, Radon Anomaly: A Possible Precursor of the 1978 Izu-Oshima-Kinkai Earthquake, Science 207 (4433) (1980) 882–888.
[5] Y. Omori, Y. Yasuoka, H. Nagahama, et al., Anomalous radon emanation linked to preseismic electromagnetic phenomena, Nat. Hazards. Earth. Syst. Sci. 7 (2007) 629–635.
[6] Y.S. Kim, C.M. Lee, S.L. Lee, T. Lida, K. Yoshioka, A study of the prediction of earthquake occurrence by detecting radon radioactivity, J. Environ. Sci 12 (6) (2003) 677–688.
[7] Durridge Company Inc, RAD7, Electronic Radon Detector User Manual, 2009.
[8] U.S. Environmental Protection Agency (U.S. EPA), Indoor Radon and Radon Decay Product Measurement Device Protocols, Office of Air and Radiation, U.S. EPA Publication, 1992, 402-R-92-004.
[9] Korea Meteorological Administration, https://data.kma.go.kr/data/grnd/selectAsosRltmList.do?pgmNo=36. 19 December 2017.
[10] E. Hauksson, J.G. Goddard, Radon earthquake precursor studies in Iceland, J. Geophys. Res. 86 (B8) (1981) 7037–7054.
[11] A. Gregorič, B. Zmažek, S. Dzeroski, D. Torkar, J. Vaupotič, 9. Radon as an Earthquake Precursor – Methods for Detecting Anomalies, Earthquake Research and Analysis – Statistical Studies, Observations and Planning, 2012.