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TEMPORAL CHANGES IN THE INDOOR RADON CONCENTRATION AS AN EARTHQUAKE PRECURSOR

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ABSTRACT: This paper reviews the changes in indoor radon concentrations, measured in a university building in Gyeongju, Rep. of Korea, to find the relationship, it exists, between the indoor radon concentrations and the seismic activities in the area neighboring Gyeongju. The measurement period was from June 1, 2017, to May 31, 2019. During this period, numerous seismic activities occurred in the southeastern region of the Korean peninsula. Considering the magnitude and distances from our measurement place to epicenters, 11 earthquakes for analysis were chosen. Among these, nine earthquakes were found to have radon anomalies before their occurrences. Three earthquakes with a magnitude greater than 4.0 were scrutinized for the correlation between radon anomalies. Effects of the environmental variables such as relative humidity, barometric pressure, rainfall, and inlet temperature were also examined. Similar to those found in our previous study, spike-like patterns were also found in the indoor radon concentration distributions before the earthquakes.

Keywords: Indoor radon concentration, Gyeongju, Seismic activities, Pohang, Radon anomaly

1. INTRODUCTION

Radon is an inert radioactive gas generated by a series of the decay of uranium and released to the air from the soil, groundwater, and cracks in buildings [1]. Due to cracks in the crust before seismic activity, radon gas emits more highly than usual [2]. Using this phenomenon, lots of research has studied radon concentrations as an earthquake precursor. Yasuoka et al. observed that in the earthquake in Kobe, Japan, a rise in the atmospheric radon concentration was evident before the earthquake [3]. Sunarno et al. found that radon concentration increased 3 days before the earthquake in Situbondo, Indonesia [4].

In general, radon concentrations in the atmosphere are affected by meteorological variables. Planinic et al. presented radon concentrations over four years along with the barometric pressure, rainfall, and air temperature, and investigated whether the weather variables affected changes in the environmental radiation [5]. Virk et al. measured the release of radon gas in the wake of an earthquake in the Himalayas' main boundary fault and explained that the soil, air temperature, rainfall, pressure, humidity, and wind speed were related to radon gas abnormalities [6].

Those studies focused on the outdoor radon concentrations in the air, soil, or groundwater. However, unlike these previous studies, our previous studies investigated the relationship between the indoor radon concentration and earthquakes that occurred in Gyeongju and Pohang, Republic of Korea. In the case of the Gyeongju earthquake, we observed similar spike-like patterns between them: 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 long, for example, 3 days [7]. In the case of the Pohang earthquake, on the other hand, we observed no noticeable patterns between the earthquake and indoor radon concentration due to the long distance between the epicenter and the measurement spot [8].

This study is an enlarged version of our previous studies. Our previous studies investigated the relationship between radon concentration and earthquake during the specific periods in which the mainshock and its aftershocks occurred. However, this study investigated the changes in the indoor radon concentrations before and after earthquakes for two years from June 1, 2017, to May 31, 2019, to see if a similar pattern of indoor radon concentration is recurred before the earthquake, as in our previous study. We also scrutinized three earthquakes with magnitude 4 or greater and radon anomalies before each one.

2. RESEARCH SIGNIFICANCE

This study scrutinized the changes in the indoor radon concentrations to see whether radon anomalies occurred before the earthquake or not. We analyzed the 11 earthquakes and identified that, in nine cases of them, they have radon anomalies. For three of the nine earthquakes with a magnitude greater than 4.0, we checked what environmental variables mainly caused the fluctuation in the indoor radon concentration. From this, we could not find any environmental variable that seemed to have a large influence on the indoor radon concentration. We hope that our study could help identify a clearer relationship between radon concentration and quakes.

3. MATERIALS AND METHODS

3.1 Measurement Device and Procedure

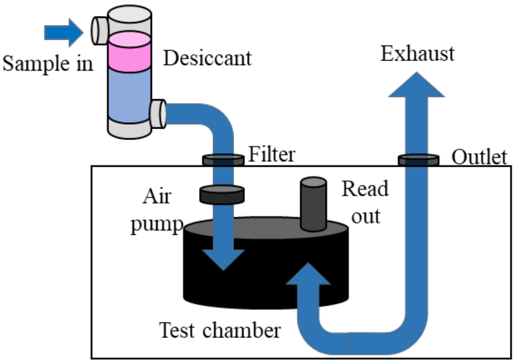

Fig. 1 Structure of a RAD7 detector

As shown in figure 1, we used a RAD7 detector to measure the indoor radon concentration continuously. The RAD7 can measure radon concentration in the range 0.1–20,000 pCi/L, with approximately 5% uncertainty [9]. The protocol of the U.S. Environmental Protection Agency was applied to measure indoor radon concentration [10]. The measurement place was the first floor of the Engineering Hall at Dongguk University-Gyeongju, Rep. of Korea. Because the RAD7 was equipped next to the central entrance of the Hall, where hundreds of people come in and out of the building a day, we assumed that there was no influence on ventilation. Measurements were made every 30 minutes, and the measurement data were collected and analyzed using the computer program for RAD7.

3.2 Data Analysis Method

Gyeongju is located 360 km southeast of Seoul in the Korean Peninsula, and Pohang is located 20 km north of Gyeongju. After a 5.8-magnitude quake (Gyeongju, September 12, 2016) and a 5.4-magnitude quake (Pohang, November 15, 2017) occurred, their aftershocks have still occurred in Gyeongju and Pohang. To identify the relationship between indoor radon concentrations and seismic activities, we investigated daily radon concentrations with seasonal average radon concentrations for two years from June 1, 2017, to May 31, 2019.

Earthquakes for analysis were screened by applying the following formula proposed by Hauksson and Goddard [11]:

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

$$D_{MAX} = 10^{(M+0.43)/2.4} \qquad (2)$$

Where
M = magnitude of the earthquake (Richter scale)
D_{max} = maximum measurable distance from the epicenter (km)

Table 1 Information of the selected earthquakes using eq. (2)

Number	Date	Magnitude	Distance[b] [km]	D_{max} [km]	Distance Differences [km]
1	17.06.11	2.5	13.5	16.6	3.2
2	17.10.16	2.5	11.8	16.6	4.8
3[a]	17.11.15	5.4	29.0	268.6	239.6
	17.11.15	3.6	28.0	47.8	19.8
	17.11.15	3.5	26.9	43.4	16.5
	17.11.15	4.3	30.1	93.5	63.4
4	17.11.16	3.6	30.1	47.8	17.7
5	17.11.19	3.5	30.1	43.4	13.3
6	17.11.20	3.6	32.2	47.8	15.6
7	17.12.25	3.5	29.0	43.4	14.4
8	18.02.11	4.6	25.9	124.7	98.8
9	18.04.09	2.4	14.3	15.1	0.8
10	19.01.10	2.5	8.1	16.6	8.5
11	19.02.10	4.1	71.5	77.2	5.7

[a] Regards that 5.4 magnitude earthquake occurred only on that day.
[b] Distance means the straight distance between the measurement point and the epicenter
[c] Distance difference = D_{max} – Distance

D_{max} in equation (2) means the maximum distance from the epicenter, which radon anomaly could be measured. It means that, if the M-magnitude quakes occurred and the measurement place is located within D_{max}, radon anomalies could be observed.

For analysis, we employed the value of 'seasonal average radon concentration + 2 × standard deviation (σ)' as a criterion to assume radon anomaly. That is, if radon concentration exceeded this value, we could consider it as the effect of earthquakes, not environmental impacts [12].

4. RESULTS AND DISCUSSIONS

4.1 Reviewing the Measurement Data and Earthquakes

Table 1 shows the information of the earthquakes selected by using eq. (2). If the distance were equal to or less than D_{max}, that is, if the distance difference were 0 or higher, the radon anomalies could be found at the measurement place as a precursor of the earthquake. The magnitude of those earthquakes ranged from 2.5 to 5.4. There were 14 earthquakes from June 1, 2017, to May 31, 2019. In the case of two or more earthquakes that occurred on the same day, however, we regarded that only the largest magnitude earthquake occurred on that day. Finally, the 11 earthquakes were analyzed to identify the relationship between earthquake and radon concentrations.

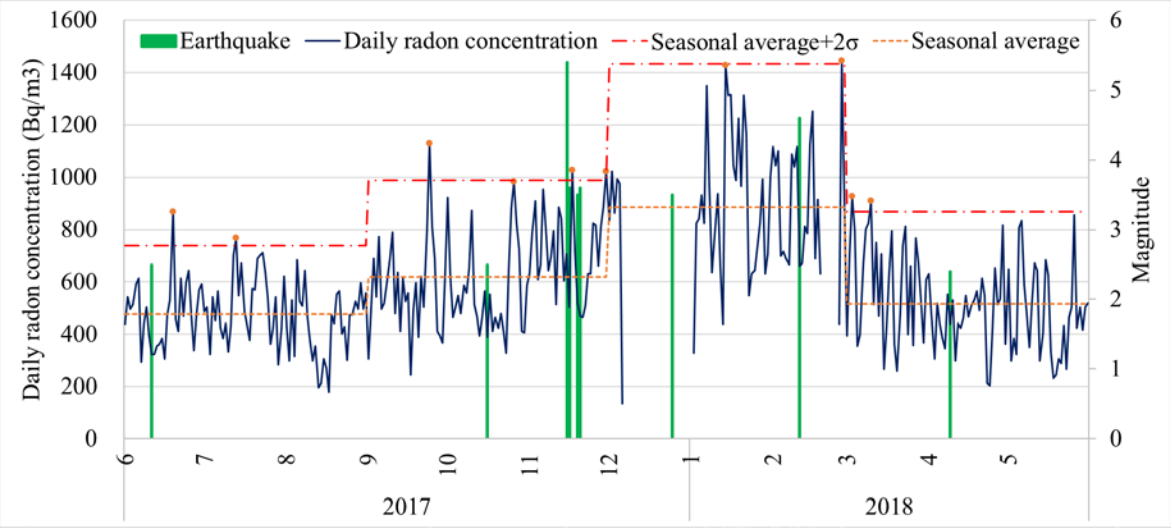

Fig. 2 Daily radon concentrations and earthquakes from June 1, 2017, to May 31, 2018

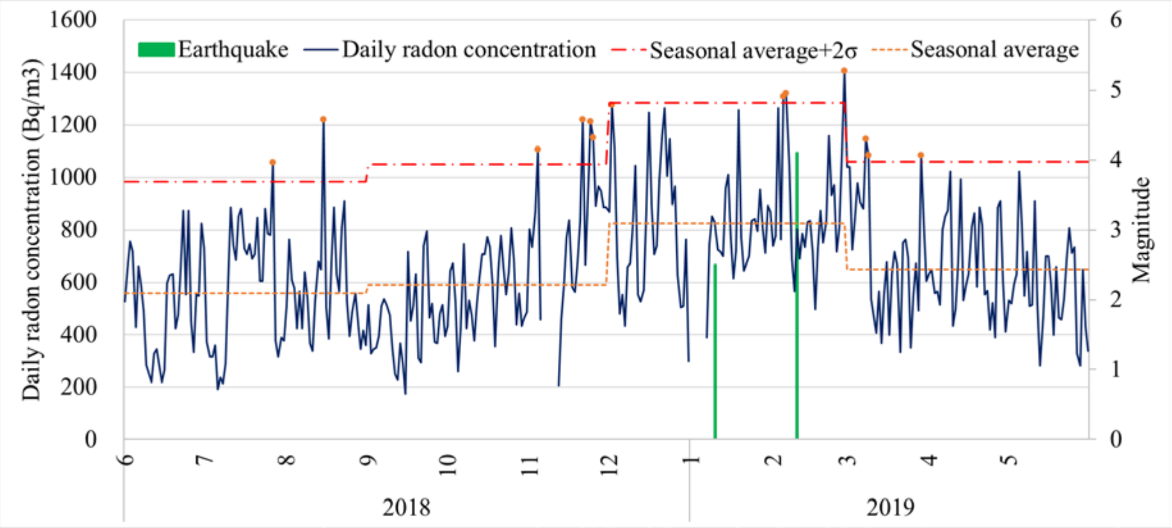

Fig. 3 Daily radon concentrations and earthquakes from June 1, 2018, to May 31, 2019

Because we are not able to show the measurements all together in one figure, we presented the measurements in the two figures: Fig. 2 and 3. In figure 2, we observed ten radon anomalies that reached or exceeded the ‘seasonal average + 2σ’ and nine earthquakes. In figure 3, we found thirteen radon anomalies and two earthquakes. We observed 23 radon anomalies marked in the small orange circle for our measurement period in total, and the details of the anomalies were summarized in Table 2. In Table 2, the difference means how much the radon concentration exceeds the seasonal average + 2σ. Next, we checked if any anomalies occurred before seismic activities, and found that radon anomalies occurred before the nine among the eleven earthquakes as shown in Table 3. The earthquakes on November 19 and 20, 2017 were assumed to have the same radon anomaly because they happened over two consecutive days. It was interesting that no radon anomaly which exceeds the value of ‘seasonal average radon concentration + 2σ’ was observed through the 5.4-magnitude earthquake that occurred on November 15, 2017, and the distance between the epicenter and the measurement place was relatively short. We think that this was because radon was released already due to a 2.5-magnitude quake on October 16, 2017, a month before the 5.4-magnitude quake.

Table 2 Radon anomalies which exceed or reached seasonal average radon concentrations + 2σ

Date	Radon anomaly concentration [Bq/m^3]	Seasonal average + 2**σ** [Bq/m^3]	Difference [Bq/m^3]
17.06.19	869.7	739.4	130.2
17.07.13	768.7		29.2
17.09.24	1129.2	989.5	139.8
17.10.26	982.47		-7.0
17.11.17	1027.7		38.2
17.11.30	1022.0		32.6
18.01.14	1428.81	1433.5	-4.7
18.02.27	1445.9		12.4
18.03.03	926.2	870.7	55.6
18.03.10	909.2		38.5
18.07.27	1057.3	983.7	73.6
18.08.15	1221.1		237.4
18.11.04	1106.8	1049.6	57.2
18.11.21	1219.7		170.0
18.11.24	1214.2		164.6
18.11.25	1151.9		102.3
18.12.02	1276.2	1285.3	-9.0
19.02.05	1310.2		24.9
19.02.06	1321.6		36.3
19.02.28	1406.6		121.3
19.03.08	1146.3	1060.8	85.5
19.03.09	1084.5		23.7
19.03.29	1084.4		23.6

[a] Difference = Radon anomaly – (seasonal average + 2**σ**)

Table 3 Earthquakes that are accompanied by radon anomalies

Number	Earthquake occurrence date	Magnitude	Radon anomaly occurrence date	Radon anomaly concentration [Bq/m^3]	Time interval [Day]
1	17.10.16	2.5	17.09.24	1129.2	22
2	17.11.15	5.4	17.10.26	982.47	20
3	17.11.19	3.5	17.11.17	1027.7	2
4	17.11.20	3.6			3
5	17.12.25	3.5	17.11.30	1022.0	25
6	18.02.11	4.6	18.01.14	1428.81	28
7	18.04.09	2.4	18.03.10	909.2	30
8	19.01.10	2.5	18.12.02	1276.2	39
9	19.02.10	4.1	19.02.05	1310.2	5
			19.02.06	1321.6	4

[a] Time interval between the occurrence date of the earthquake and that of radon anomaly

Table 4 Indoor radon concentrations and environmental variables over 39 days for earthquakes of magnitude ≥4.0

Earthquake occurrence date	Analysis period	Average radon concentration [Bq/m³]	Maximum/minimum					
			Daily radon concentration [Bq/m³]	Air inlet temperature [℃]	Relative humidity [%]	Rainfall [mm]	Barometric pressure [mmHg]
17.11.15	17.10.12-17.11.19	631.7 ± 191.0	1027.7 / 327.5	21.3 / 11.4	4.0 / 2.0	24.0 / 0.0	1023.2 / 1006.4
18.02.11	18.01.08-18.02.15	903.1 ± 249.0	1428.8 / 440.5	12.8 / 7.5	2.6 / 1.0	9.5 / 0.0	1026.9 / 1005.2
19.02.10	18.01.07-18.01.14	823.1 ± 198.6	1321.6 / 389.6	14.8 / 10.6	3.9 / 1.4	6.5 / 0.0	1026.9 / 1010.2

4.2 Scrutiny of Change in Indoor Radon Concentration

For three of the nine earthquakes with a magnitude greater than 4.0, we scrutinized the indoor radon concentrations over 39 days including the day of the earthquake from 34 days before the earthquake to 4 days after it. Table 4 shows the indoor radon concentrations and environmental variables including relative humidity (RH), barometric pressure, rainfall, and inlet temperature. Analysis periods were October 12–November 19, 2017, January 8–February 15, 2018, January 7–February 14, 2019, respectively.

Figures 4, 5, 6 show the daily indoor radon concentration and measurements of the environment variables such as barometric pressure, air temperature at the inlet of the RAD7, rainfall, and relative humidity (RH) inside the building. We checked if the fluctuation in the indoor radon concentration could have mainly resulted from variation of any environmental variables except seismic activity. Though the rainfall could potentially influence the indoor radon concentration, we measured the radon concentration inside the building using absorbents to avoid the effects of moisture and the rainfall had no significant impact.

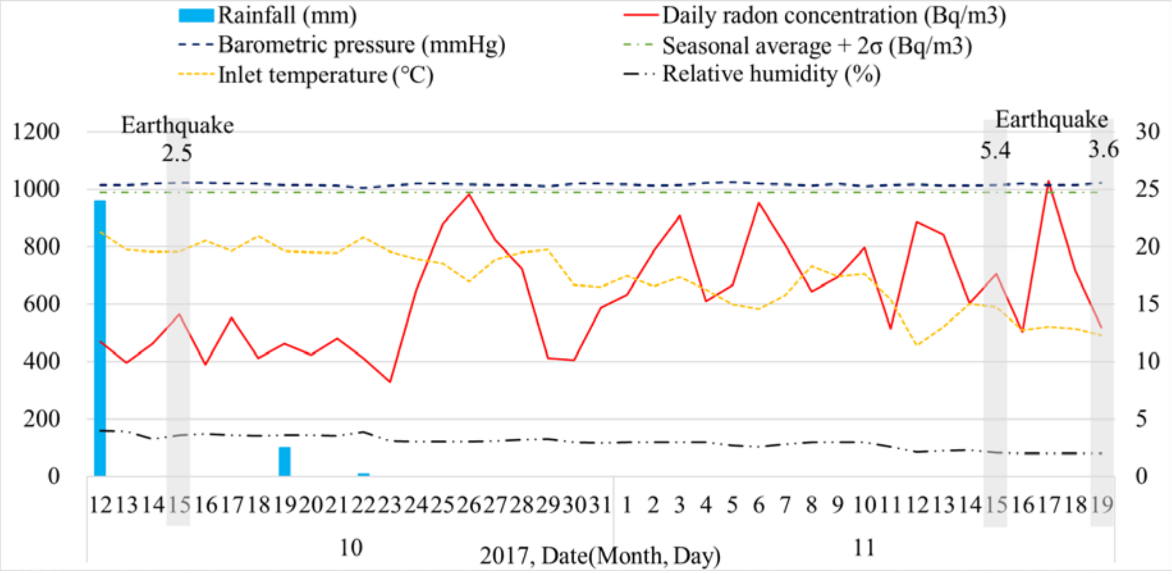

Fig. 4 Daily indoor radon concentration over 39 days October 12-November 19, 2017

As shown in figure 4, there were limited changes in the measurements of the environmental variables over the same period, from October 12 to November 19, 2017. The indoor radon concentrations for October 12–23, 2017 changed with a small deviation, but it fluctuated after October 24 with a spike-like pattern that was also identified in our previous study [7].

The temperatures at the inlet of the RAD7 gradually decreased overall throughout the same period since the measurement time was during a change of season from autumn to winter. In addition, radon concentrations were measured inside the building and the range of temperature fluctuations was limited. The temperature change trend did not synchronize with the indoor radon concentration change.

The RH was only 4%, even on the day when the rainfall was highest at 24 mm for the measurement period, which indicated that the rainfall did not impact the indoor radon concentration.

The barometric pressure was also relatively constant. Even though was observed an abnormal pattern in the indoor radon concentration patterns starting on October 24, it had changed little. Therefore, the abnormal pattern of the indoor radon concentration could not have resulted from a change in the barometric pressure.

As shown in figure 5, on January 14, 2018, the peak of the indoor radon concentration reached 1428.8 Bq/m^3, just 4.7 Bq/m^3 lower than 'seasonal average + 2σ'. After that day, the indoor radon concentrations had kept low with a little deviation.

RH and barometric pressure were almost constant for this period. For the four days of this period, it rained, but it did not influence the radon concentrations and radon fluctuation. In contrast, the inlet temperature seemed to synchronize with the daily radon concentration. However, that could not account for the peak and high radon concentrations during January 14-22, 2018.

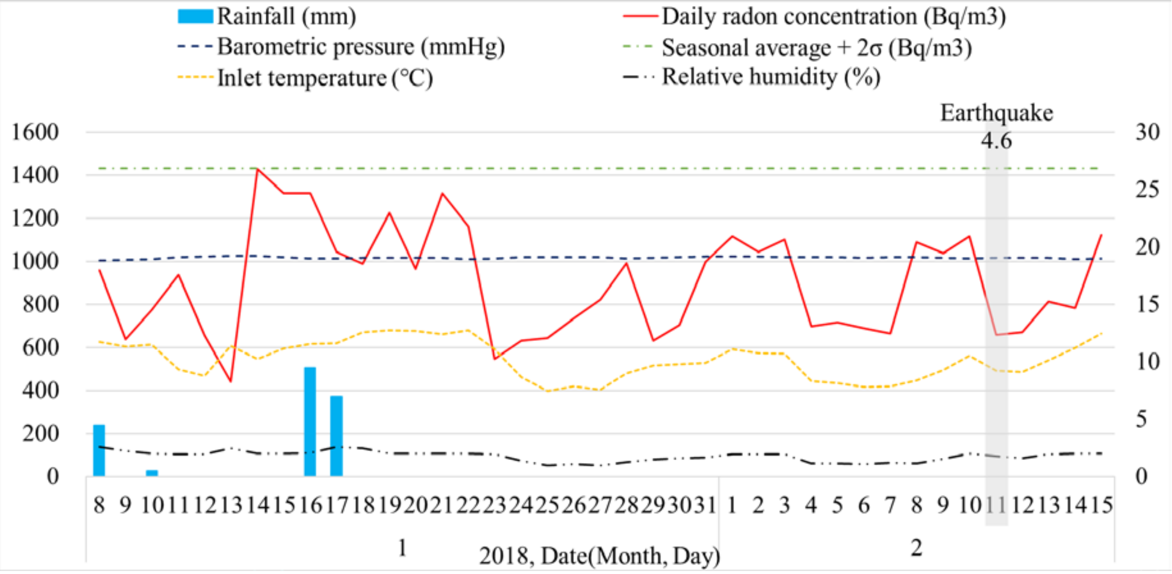

Fig. 5 Daily indoor radon concentration over 39 days January 8-February 15, 2018

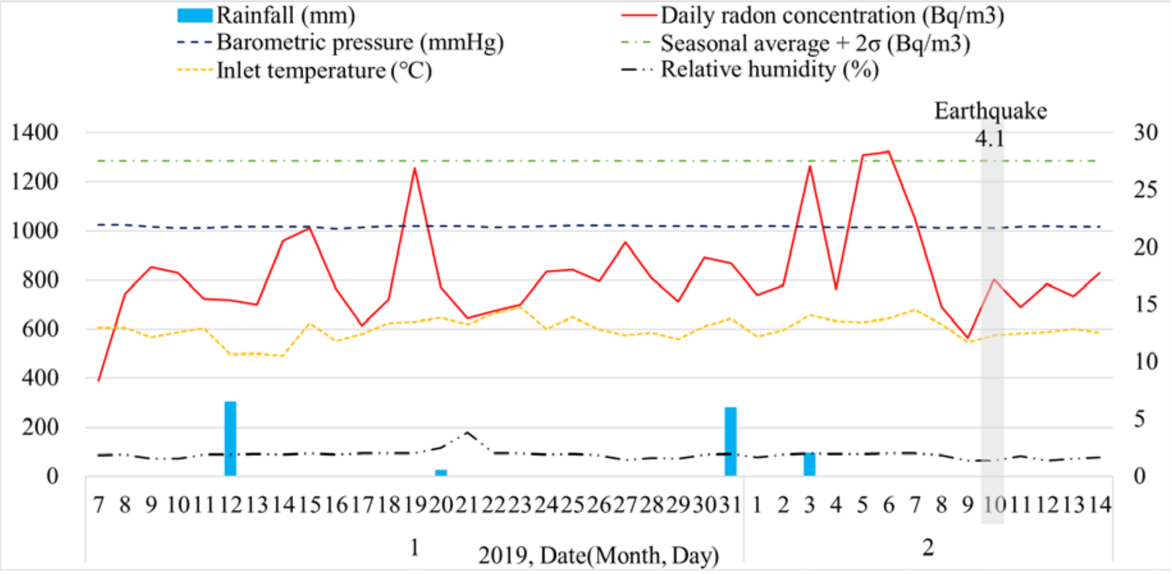

Fig. 6 Daily indoor radon concentration over 39 days January 7-February 14, 2019

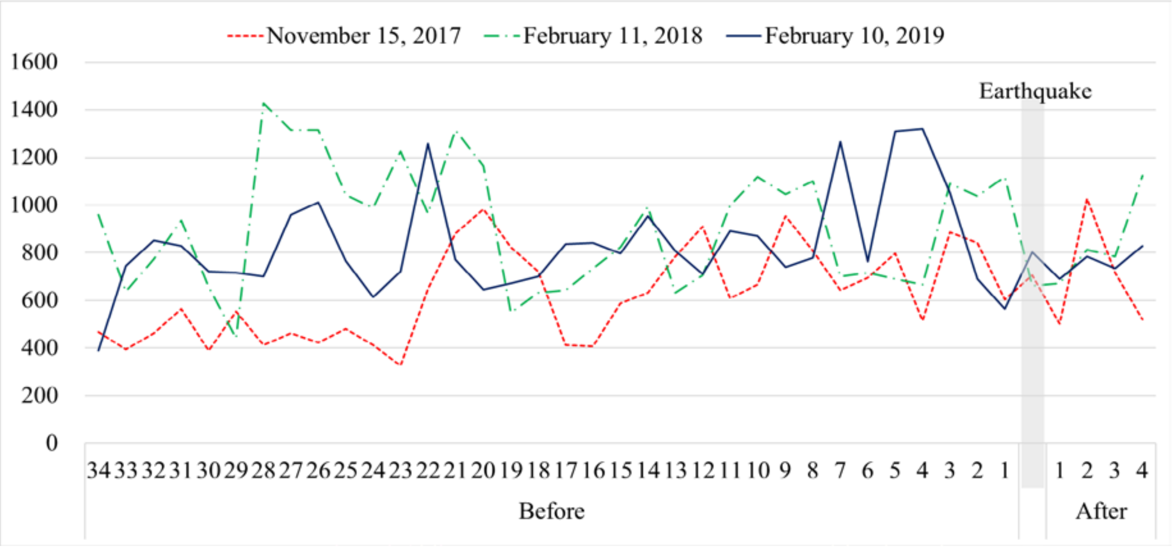

Fig. 7 Comparison of the daily indoor radon concentration over 39 days for the earthquakes of magnitude ≥4.0

As shown in figure 6, three spike-like patterns were observed in this period, for January 7–February 14, 2019. On January 19, which was 21 days before the earthquake, the daily radon concentration remarkably increased and reached near the 'seasonal average radon concentration + 2σ'. Next, On February 3, the indoor radon concentration rose sharply to 1264.9 Bq/m^3 and it decreased to 762.2 Bq/m^3 on February 4. The next day, it increased again to 1310.2 Bq/m^3 and then gradually decreased to 564.6 Bq/m^3 on February 9, which was one day before the earthquake. The temperature change trend did not synchronize with that of the indoor radon concentration change overall. The barometric pressure and RH changes were somewhat irrelevant to the indoor radon concentration.

The only notable difference between figs. 4, 5, and 6 was the occurrence time of the radon anomalies before the earthquake. The daily indoor radon concentrations over 39 days for three earthquakes were compared in fig. 7. For the earthquake on November 15, 2017, the spike-like patterns were observed on October 26, 2017, 20 days before the earthquake. The peak radon concentration was measured on January 14, 2018, 28 days before the earthquake on February 11, 2018. Finally, there were the four peaks measured before the earthquake on February 10, 2019. The first occurred 22 days before the earthquake, and others occurred seven, five, four days before the earthquake. For comparison, our previous study found that radon anomalies occurred a month before the 5.8 magnitude earthquake on September 12, 2016, in Gyeongju, and a few days before its aftershocks [7].

5. CONCLUSIONS

This study scrutinized the changes in the indoor radon concentrations that were continuously measured in a university building in Gyeongju, Rep. of Korea to see whether a similar pattern recurred in the indoor radon concentration before the earthquake or not, which was found in our previous study [7]. We analyzed the 11 earthquakes and identified that, in nine cases of them, they have radon anomalies before they occurred. For three of the nine earthquakes with a magnitude greater than 4.0, we checked what environmental variables mainly caused the fluctuation in the indoor radon concentration. From this, we could not find any environmental variable that seemed to have a large influence on the indoor radon concentration. As in our previous study [7], we also identified similar spike patterns before earthquakes.

The recurring identifications imply that the indoor radon concentrations inside a building dozens of kilometers from the epicenter might have changed due to seismic activities before the earthquake, which could be a precursor and provide indications of an upcoming earthquake. We hope that our study could help identify a clearer relationship between them.

6. ACKNOWLEDGMENTS

This work is an enlarged version of our previous study [7], [8].

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7. REFERENCES

[1] Timothy M.K., Geological Hazards: A Sourcebook, Greenwood Press, 2003.

[2] Sac M.M., Harmansh C., Camgoz B., and Sozbilir H., Radon Monitoring as the Earthquake precursor in a fault line in western turkey, Ekoloji, Vol. 20, No. 79, 2011, pp.93–98.

[3] Yasuoka Y., Igarashi G., and Ishikawa T., Evidence of precursor phenomena in the Kobe earthquake obtained from atmospheric radon concentration, Applied Geochemistry, Vol. 21, No.6, 2016, pp.1064–1072.

[4] Sunarno, Firdaus H.L., Luckyarno Y.F., Waruwu M.M., and Wijaya R., Detection system for deterministic earthquake prediction based on radon concentration changes in Indonesia, Journal of Engineering science and technology, Vol. 15, No. 3, 2020, pp.1787-1798.

[5] Planinić J., Radolić V., and Vuković B., Radon as an earthquake precursor, Nuclear Instruments and Methods in Physics Research, Vol. 530, No.3, 2004, pp.568–574.

[6] Virk H.S., and Singh B., Radon anomalies in soil-gas and groundwater as earthquake precursor phenomena, Tectonophysics, Vol. 227, No. (1-4), 1993, pp.215–224.

[7] Kim J.W., Joo H.Y., Kim R., and Moon J.H., Investigation of the relationship between earthquakes and indoor radon concentrations at a building in Gyeongju, Korea, Nuclear Engineering and Technology, Vol. 50, No. 3, 2018, pp.512–518.

[8] Joo H.Y., Kim, J.W., and Moon J.H., Investigation of changes in indoor radon concentrations before and after seismic activities in Gyeongju and Pohang, Korea, International Journal of GEOMATE, Vol. 16, No. 56, 2019, pp.98–103.

[9] Durridge Company Inc., RAD7, Electronic Radon Detector User Manual, 2009.

[10] 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, 402-R-92-004. 1992.

[11] Hauksson E. and Goddard J.G., Radon precursor studies in Iceland, Journal of Geophysical Research, Vol. 86, No. B8, 1981, pp.7037–7054.

[12] Gregorič A., Zmazek B., Deroski S., Torkar D., and Vaupotič J., Radon as an Earthquake Precursor – Methods for Detecting Anomalies, InTech, Rijeka, Croatia, 2012.