VARIATIONS IN AIR RADON CONCENTRATIONS IN TUNNELS FOR OBSERVATION
OF CRUSTAL MOVEMENT IN THE TOKAI REGION OF JAPAN

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Abstract. Concentrations of air radon in the tunnels for observation of crustal movement have been monitored since 1977 in the Tokai region of Japan using a flow-type ionization-chamber in order to study the radon use in earthquake prediction. Radon concentrations exhibit seasonal variations such that their values is high in summer and low in winter. Concentrations are also influenced by meteorological variations of the pressure and rainfall, and they correspond well with ground strain changes. Since noticeable increases can be seen in the data after heavy rainfalls at the Toyohashi site, variations of radon concentration were estimated from the local strain changes due to the rainfall. The observed and calculated values showed a relatively good correlation. Spiky increases in radon concentrations were occasionally observed before the occurrence of nearby earthquakes at the Kikugawa site, and the use of radon concentration in the earthquake prediction is suggested.

1. Introduction

Observations connected with the earthquake prediction research began in 1973 in Japan. Radon concentrations in soil gas or in groundwater were currently monitored using various methods at more than 40 observation sites, but only some of them provided useful information for earthquake prediction research. Wakita et al. (1980) reported on precursory changes in radon concentrations in groundwater prior to the Izu-Oshima-Kinkai earthquake in 1978, and their continuous monitoring systems for observing radon concentrations in groundwater were described by Noguchi and Wakita (1977).

In this report, we discuss the cause of fluctuations of radon concentration in the air on the basis of the data obtained from the Toyohashi observation tunnel, and its possible use in earthquake prediction.

2. Methods for monitoring radon concentrations used in earthquake prediction research

The methods employed to monitor radon concentrations (Table 1) are all highly stable so that valuable information related to earthquake occurrence can be accumulated every day. An outline of the applied observation methods and precursory changes associated with earthquake occurrences was reported in the proceedings of '91 Radon Symposium held in Kumatori, on August 8-10, 1991 (Yamauchi, 1992).

The Research Center for Seismology and Volcanology at Nagoya University has been monitoring radon concentrations in the air (aRn) in crustal movement observation tunnels. The observation

sites are shown in Fig. 1. Three additional instruments are used for observation in these tunnels: silicatus extensometers, watertube tiltmeters, and an atmospheric pressure gauge. The data are monitored using an on-line telemetry system set at a 5-minute sampling rate. Several overlapping aluminum sashes are installed near the entrance of each tunnel to seal off the area from air circulation, creating a near-perfect state of radioactive equilibrium. An ionized current induced by α -ray from an ionization-chamber was measured after removing moisture from the air by silica gel. This instrument has shown great endurance throughout this study, so that we can presume that no data errors occurred due to possible malfunctions of any of the instruments.

Table 1 Methods for measuring radon concentrations for earthquake prediction research in Japan.

Method	Reference
Radon in groundwater	
Toluene extraction-liquied scintillation counting	(Wakita et al., 1976)
ZnS(Ag) scintillation detection system	(Noguchi and Wakita, 1977)
Ionization chamber(vibrating read electrometer)	(Nishimura, 1985)
PIN photodiode method	(Sasaki et al., 1989)
Radon in soil gas	
Track density(cellulose nitrate film)	(Katou et al., 1980)
Ionization chamber(vibrating read electrometer)	(Yamauchi and Shimo, 1982)
PIN photodiode method	(Sasaki et al., 1989)
Scintillation cell	(Hikawa et al., 1990)
Intensity of γ -ray	
γ -ray scintillation survey meter(Nal)	(Nakao et al., 1987)
GM counting survey meter	(Shimo and Yamauchi, 1989)

3. Observed results of aRn

Fig. 2 shows the variations of ground strain (NS40), aRn, γ -ray intensity by GM-survey meter (GM05, GM06), and radon concentration in groundwater (wRn) at the Toyohashi site in the period from May to August 1991. The downward histogram at the top shows the amount of precipitation. Observed data of aRn correspond well to the strain data obtained by the detector NS40. Ground contractions as well as the increases in aRn, γ -ray intensity, and wRn are observed after a heavy rainfall; however, no such variations can be found after light rainfalls. Changes in aRn are found to be rapid in compression with ground strain, while wRn changes are slow. Incremental changes in the former are also larger than the latter. Variations in the γ -ray intensity, GM05 and GM06 are likely to differ slightly from each other, and this may be because the two observation sites are about 40 m apart in

Fig. 1 Location of the observation sites. AS is the observation site of Asahi, TY, Toyohashi, TN, Toyone, IB, Inabu, and KI, Kikugawa.

Fig. 2 An examples of the daily variation of the measurements of strain (NS40), radon concentration in the air (aRn), radon concentration in groundwater (wRn), γ -ray intensities (GM05, GM06), and amount of precipitation (downward histogram at the top).

the tunnel. Variations in GM06 are rapid with incremental changes and they are larger than those recorded for GM05. GM06 is positioned beside the observation site of aRn so that variations based on γ -ray intensity closely coincide with variations in aRn.

Fig. 3 illustrates the monthly relationship of the variation in aRn with those of the strains observed by the detectors NS30 and NE30 for a particular year of 1991. It is found that the variations in aRn also corresponds rather well to that of the strain, NS30 at the Toyone site in a similar way to the data obtained at the Toyohashi site. It is seen in Fig. 3 that some short term variations are super-imposed in the variation of NE30, but we can readily notice the general tendency in variation being synchronous with NS30. Variation in aRn at the Asahi site also showed a good coincidence with the ground strains(although not shown). As the general tendency it is found that the values for aRn are high in summer and low in winter. The reason will be discussed in the next chapter.

4. Simulation of aRn at Toyohashi

Yamauchi and Shimo (1982), and Yamauchi et al. (1988) proposed a radon-rich fault model to estimate aRn as shown in Fig. 4. It is assumed in this model that the source of radon in the tunnel is not from dissolved radon in groundwater but rather from the radon-rich soil gas in the basement rock. Assuming furthermore that the soil gas in the basement rock is very rich in radon concentration, aRn is then calculated using the following formulas (1)-(3).

Fig. 3 The annual variation for a particular year of 1991 of the strain changes of the detectors NS30 and NE30, and variations of radon concentration at the Toyone site.

The amount of radon Q_{n+1} at a specified time (t_{n+1}) is expressed as

$$Q_{n+1} = Q_n (1 - \exp(-\lambda (t_{n+1} - t_n))) + C_s + C_r \quad (1)$$

where Q_n is proportional to aR_n at a specified time (t_n) and λ is the decay constant of radon. Both C_s and C_r represent the amount of radon supplied to the tunnel during the time from (t_n) to (t_{n+1}) . C_s indicates the supply of radon constant over long-term, while C_r corresponds to the radon resulting from the short-term effect such as rainfall. C_r is proportional to the rate of compression of the basement rock caused by the rainfall and is expressed as follows,

$$C_r = a (dX/dt), \quad dX/dt > 0 \quad (2)$$

where X is the compression of a rock and dX/dt corresponds to the volume of the radon-rich sol gas escaped from the basement rock. We then assume that C_r becomes zero when the basement rock is altered in a state of expansion as expressed by Eq. (3):

$$C_r = 0, \quad dX/dt < 0 \quad (3)$$

C_s and other parameters were calculated by trial and error to obtain the best fit to the observed data. In the present calculations, however, we incorporated the value of C_s into the new model to simulate aR_n . The value C_s incorporated into the model was estimated using the annual variations of aR_n , and it was assumed to be four times greater in summer than in winter. The righthand side of Eq. (2) was also transformed into Eq. (4):

$$C_r = b C_s (dX/dt), \quad dX/dt > 0 \quad (4)$$

Fig. 5 is the results of the simulation as calculated by this formula and are indicated as Cal. in the figure. It is found that the calculated results are significantly consistent with the observed aR_n . The same calculations were also performed during other periods (although not shown), and we had a good coincidence between the calculated and observed variations as in Fig 5. It may hence be concluded that aR_n can be calculated easily based on this model.

Fig. 4 A radon-rich fault model used to calculate the radon variations in the tunnel (See the text for explanation of C_s and C_r).

The amount of groundwater discharge in the tunnel is also shown at the bottom of Fig. 5 and it is found that there seems to be a large time lag between the strain and discharge variations. This may imply that rain water needs some time to drain out of the tunnel after replacing by the radon-rich soil gas. The amount of discharge also corresponds well to the assumed value of Cs over long-term. It seems that the radon concentration in the radon-rich soil gas changes its value according to a gap of the basement rock. The value is high in the wet season and low in the dry season. Therefore the values for aRn are high in summer and low in winter as discussed in the previous chapter.

5. Discussion

Variations in aRn at Toyohashi, Toyone, and Asahi are found to exhibit a good correspondence with the strain variations and this phenomenon may be explained in terms of following possible mechanism:

- 1) Tectonic forces applied to the basement rock near the tunnel;
- 2) Cracks running along a particular direction in the basement rock open up and spread;
- 3) The flux rate of the radon rich soil gas into the tunnel changes.

It is well known that the tectonic force in and around a focal region, is expected to change when an earthquake occurs. If the opening and closing of a crack occurs at the same time as the generating force of an earthquake, conditions for the flux rate of the radon-rich air, are also expected to alter. If these conditions have a strong effect on aRn and wRn, it may be

Fig. 5 Variation in aRn; calculated (Cal.) and observed radon concentrations, observed strains (upper curve), and discharge of groundwater in 1991.

possible to obtain useful information on such tectonic forces because they relate to the earthquake occurrence. The aRn and/or wRn is seen to exhibit complex variations as presented in this paper; however, if the reason for this variation could be explained, it would probably be possible for us to make good judgments on whether the data would be normal or abnormal.

Observations of aRn at the Kikugawa site started in June 1980, and Fig. 6 illustrates an example of abnormal variations in aRn observed there before an earthquake occurred near the site in 1982. A spiky variation in aRn was observed several days before the event. The corresponding variations of the atmospheric pressure and precipitation are also shown in Fig. 6. This event is the largest earthquake which took place near the site since the commencement of the observation. If the change in atmospheric pressure could affect aRn, such spiky variations should have been observed on January 5 and/or January 20 as well. If the rainfall could affect aRn, such spiky variations should have also been observed on March 4. However, the variations in aRn on these particular days were minimal, and it may suggest that the spiky variations shown in Fig. 6 have actually been abnormal changes. Similar spiky variations in aRn were observed as well prior to other earthquakes which occurred near the site (increments were about 5-10% each time). The flux rate in the radon-rich soil gas may indicate occasional changes

Fig. 6 An example of abnormal variation in aRn before and after an earthquake (February 26, 1982; $M=4.7$, $\Delta=40 \text{ Km}$) near the Kikugawa site. Changes of atmospheric pressure and precipitation are also shown.

before an earthquake at the Kikugawa site. If such a change occurs near the site with an especially large fault, then radon-rich soil gas will escape through the surface, causing the radon concentration in the air to greatly increase, including a number of atmospheric electrical phenomena.

6. Conclusions

This paper has dealt with the observation of radon concentrations in the air in crustal movement observation tunnels in the Tokai region of Japan, and the following results have found from the present study:

1) Radon concentration at each site is found to vary from season to season with high levels seen in summer and low levels in winter. Concentrations are also influenced by the meteorological changes in pressure and rainfall.

2) Comparisons with the observed radon concentrations and ground strain variations indicate that the two are closely correlated with each other at each observation site. The flux rate of radon-rich soil gas into the tunnel may show a change depending on the forces applied to the basement rock around the tunnel.

3) Variations in radon concentrations at the Toyohashi site exhibit impulsive changes after a heavy rainfall. In order to clarify these changes, radon concentrations were estimated based on the premise that radon-rich soil gas is supplied from the basement rock. Relatively good correlations were obtained between observed and calculated values.

4) Abnormal and spiky variations in the radon concentrations were sometimes observed at the Kikugawa site. A large quantity of radon may be released from the tunnel before an earthquake occurs. This site may provide good conditions for monitoring such abnormal variations which precede the earthquake occurrences.

The data obtained on radon concentrations are systematically accumulated every day at our observing stations, and we hope that we could clarify these variations in radon concentrations in the air in these tunnels in greater detail.

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