Tukey Control Chart for Radon Monitoring in Relation to the Seismic Activity.

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Abstract

Earthquakes are among the most destructive natural disasters, which cause damage on a huge scale not only to life but to property also. Radon is one of the precursory phenomena that exist in connection to the occurrence of earthquakes and may have potential in forecasting these hazards. The data set in this study contains the observations of radon from August 01, 2014, to January 31, 2015 collected in Sobra city, northern Pakistan. Weibull, Gamma, Log-Normal, Log-Logistic, and Pareto probability distribution were fitted over the radon on its original scale and a log scale. Log-logistic best fits the radon on both scales. Log-logistic based Tukey control charts suggest a central limit of 2465.459 Bq/m³ and upper control limit of 12704.080 Bq/m³ on the original radon data, while they suggest a central limit of 7.759, upper control limit of 11.080 and lower control limit of 4.524 on the log scale. The Tukey control charts reveal several anomalies that were compared with earthquake occurrence. There are five earthquakes that occurred during the same period as the radon monitoring program, having magnitude ranges between 4.9 – 5.5, with the ratio between strain radius and distance to the epicenter greater than or equal to 1. Among several radon anomalies exceeding the upper control limit, the five are identified as earthquake precursors. The results of this study demonstrate that for earthquakes, seismic events show a correlation with increasing concentrations of radon gas before their occurrence.

Keywords: Earthquakes; Tukey control chart; Probability distribution; Radon; Northern Pakistan.

1. Introduction

Earthquakes are natural disasters that strike so suddenly and cause damage on a larger scale. Forecasting these events has tremendous promise in terms of protecting human life and wealth. A variety of recent studies have found that certain preliminary signs, both geophysical and seismological, can be detected before the earthquakes. [1, 2, 3, 4].

Radon gas emitted from the earth is being used as an earthquake precursor; many recent studies have shown that changes in radon concentration prior to major earthquakes may occur [5, 6, 7, 8]. Radon is produced by decay product of uranium that is present in rock and soil minerals and some amount of radon may accumulate in the cracks present in the earths crust.

It is found that there are certain shifts in the surface that may trigger the release of radon gas before the incidence of the earthquake. This increased emission of radon which is considered as a precursor for the earthquake. Vaupotic et al. [9] have studied the radon concentration in soil and rate of exhalation of radon at the Ravne Fault in NW Slovenia by calculating the concentration of radon in soil gas, rate of radon emission from the ground, permeability of soil and gamma dose rate in the above-said region. The acquisition was done with the help of an Alpha Guard radon monitor and Gamma Tracer for radon in soil gas and gamma dose. The study concluded that the values of radon concentration and radon exhalation were lower as compared to other areas of Slovenia and there was not an increasing trend in the data because the investigation sites were a little bit far from the fault and were perpendicular in direction. Sac et al. [10] has monitored the radon concentration for earthquake precursory in
Tuzla fault line in western Turkey. Active as well as passive techniques were used for measuring the concentration of radon in soil gas and thermal waters. Solid-state nuclear track detectors (LR-115) were used to measure the radon concentration in soil and thermal water fields.

Recent work for radon as an earthquake precursor [11] carried out the analysis of radon and its daughter products in relation to the great Japan earthquake that occurred in March 2011 (Richer magnitude 9.0). Two geochemical precursors were studied i.e. radon gas (Rn-222) and thoron gas (Rn-220) in the underground controlled environment. Based on annual data, a rise in thoron concentration was observed February 2011 only, whereas rise in radon concentration were detected twice in a year. Researchers found that for earthquake forecasting purposes both radon and thoron were reliable geochemical precursors and the magnitude 9.0 Japan earthquake (March 2011) was successfully correlated with anomalous trends. Similar examples where radon and its daughter product were studied for short term earthquake forecasting include [5, 6, 7, 8]

For continuous monitoring of radon gas, the study used an online radon measurement system named Alpha-Meter 611 [10], where a few positive anomalies were detected. Later a prominent increase in radon concentration was detected in the period March - June 2007, which was correlated with seismic activities in the area. The variation in radon concentration reached its highest values 10 days before the Seferihisar earthquake of magnitude 3.0 occurred on June 4, 2007, while the epicenter was 35 km away from the radon detector. Another earthquake of magnitude 3.1 occurred on March 28, 2007, in the same region. After this event, abrupt decreases in radon values were observed in LR-115 data. Two other earthquakes of magnitude 3.0 and 3.5 occurred 35 km away from the Cumali radon monitoring station, and again the sharp decrease in radon concentration was observed after each event, moreover, the concentration maintained its low level afterwards. This research concluded that continuous monitoring of radon concentration in soil and thermal waters required understanding the relation of variations in radon gas emission with the occurrence of seismic events.

Navman and Negarestani [12] measured soluble radon in the above-said study area and compared it with the earthquake forecasting process. They monitored the concentration of radon gas in groundwater over the period December 2011 to March 2012 with the help of RAD7. Continuous monitoring with a cycle of 10 minutes was selected and compared with the earthquake catalogues of the Iranian Seismological Center (IRSC) and International Institute of Earthquake Engineering and Seismology (IIEES). Pulinets et al. (2004) [1] worked on the emanation of radon and metallic aerosols before some strong earthquakes and compared their effects with changes occurring in the atmosphere and ionosphere. The study concludes the electric field values present in the atmosphere and ionosphere are not affected by radon emission but can be used for earthquake prediction studies. In Taiwan, along the two most famous geological faults Hsincheng and Hsinhua, radon gas variations in a soil were monitored using RTM 2100 where soil gas survey was performed followed by continuous monitoring of radon on few sensitive locations [13].

Das et al. (2006) [5] has worked on continuous monitoring of radon and its progeny at a remote station for seismic hazard surveillance in thermal springs at Bakreswar, West Bengal India. German-made electronic radon monitor SARAD DOSEM was used to determine the concentration of radon and its progeny from Dec 2004 to Feb 2005, where exceeding radon values exceeding $2\sigma$ were considered as an anomaly. Anomalous values of radon and its daughter products correlated with seismic events that occurred around Indonesia, Nicobar, and the Andaman Islands. The use of a $2\sigma$ limit for radon anomaly comes from statistical process control, which found extensive application for monitoring changes in environmental and geological properties e.g. temperature, humidity, air pressure, clouds movement and rainfall [14, 8]. Instrumental errors may occur in the radon measurement system [15] which may misguide the radon anomalies. Traditional parametric $2\sigma$ limits may become unreliable if the data are not independent and are deviated from the normal distribution, which is the case for radon data [5]. The Tukey Control Chart (TCC) has been used
as a nonparametric alternative to the 2σ control limit and is one of the potential candidate in determining radon anomalies [16, 17, 18]. The TCC is tested in the current study for monitoring the radon from August 01, 2014, to January 31, 2015, at the measuring station located at Sobra city in northern Pakistan, which is the area affected by earthquakes.

2. Material and Methods

2.1. Data Description

The radon (0 – 10 mega Bq/m³) data set in this study was obtained from the earthquake station located in Sobra city, Pakistan, using Sarad RTM 2200 analyser [8]. The time span covers the six months i.e. from 1st August 2014 to 31st January 2015. Continuous monitoring [19] method with one sample every 15 minutes was used. This data set is held by the Centre for Earthquake Studies, National Centre for Physics (NCP), Islamabad.

2.2. Instrumental Error

The data contains the sudden presence of extremely high value that occurred for a very short time. For example, high radon emissions were recorded just one or two times then values drop back to the average trend. According to theory and previous trends, extreme radon emission peaks cannot appear and disappear suddenly [5, 14, 20]. Hence, such extreme peaks are considered as instrumental error. The instrumental error was replaced with missing values for the purposes of data processing. Moreover, whilst the instrument RTM 2200 fulfills all the technical requirements, some missing values are observed. The methods we have chosen to monitor the radon data, can work with a missing observations so missing observations were not inputed to keep the best originality of the data.

2.3. Monitoring Radon Concentration

For monitoring the radon concentration appropriate limits can be determined by first fitting a probability distribution over the radon data. Let X represent the radon data whose probability distribution can be presented by \( P(X) \) where \( X > 0 \) and radon distribution is positively skewed [5]. Hence, the potential candidates for fitting the radon data include Weibull, Gamma, Log-Normal, Log-Logistic, and Pareto probability distribution. The goodness of fit of probability distribution includes both graphical techniques and hypothesis testing. The graphical hypothesis testing includes the empirical and theoretical densities plot, Q-Q plot, empirical and theoretical CDFs plot, and P-P Plot, while the hypothesis testing includes the Kolmogorov Smirnov test, Anderson Darling test and Cramer-von Mises test for goodness of fit. Assuming the radon data are not normally distributed, the Tukey control chart is one of the potential candidates [16, 17, 18] to assess the radon data. A Tukey control chart is based on following steps.

- Find the quartiles i.e. Q1, Q2 (Median) & Q3 and Inter Quartile Range (IQR) from the best fitted probability distribution.
- Setup the control limits of the Tukey chart as

\[
\text{CentralLimit} : CL = Q2 \\
\text{Uppercontrollimit} : UCL = Q3 + 1.5 \times IQR \\
\text{Lowercontrollimit} : LCL = Q1 - 1.5 \times IQR
\]

Since, radon concentration is expected to follow a skewed distribution with some really large measurements, radon concentration is assessed on the original scale and on the log scale as well.

2.4. Earthquake Preparation Zone

The earthquake is supposed to accure within the earthquake preparation zone(EPZ), called D. The schematic diagram for measuring the earthquake activity is presented in the upper panel of Figure 1, and the lower panel describes the schematic diagram for D and observed distance. The radius R is computed by following empirical distance formula [12].

\[
R = \begin{cases} 
10^{0.140M}, & \text{if } M \geq 3.0 \\
10^{0.133M}, & \text{otherwise} 
\end{cases}
\]

An event with D/R ratio greater than or equal to 1 indicates the occurrence of earthquake in that particular radios.
2.5. Computations

For computations and statistical radon assessments R computing environment www.r-project.org/ software is used. For fitting the probability distribution and computing the Tukey limits R-package ‘fitdistplus’ [21] and ‘actuar’ [22] are used. For plotting results R-package ‘ggplot2’ [23] and ‘gridExtra’ [24] are used.

3. Results and Discussions

The studied data set contains 4026 radon valid observations having minimum concentration 370 Bq/m3, maximum concentration 249702 Bq/m3, Q1 concentration 938 Bq/m3, median i.e. Q2 concentration 2419 Bq/m3 and Q3 concentration 5529 Bq/m3. The radon data contains 361 (8.23 %) missing values of total observation. Among 4026 observation 23 were marked as instrumental error, so the missing values increases to 8.76 %. Since the proposed method did not require to input the missing observations, radon data having missing observations were used to construct the probability distribution based Tukey control chart. The graphical comparison of the fitted and theoretical probability distribution over the original and log scale data are presented in Figure 2. Radon is a positively skewed distribution. All four probability distributions being considered fit the radon data with some minor difference. With log transformation, radon tends to normal but remains positively skewed. Log-logistic and Log-normal both fit the log radon data. To determine the one best-fitted probability distribution, we have used several goodnesses of fit measures. The comparison of fitted probability distribution through Kolmogorov Smirnov (KS) test, Cramer Von Misses (CM) test, and Anderson Darling (AD) test together with Akaike’s information criterion (AIC) and Bayesian information criterion (BIC) is presented in Table 1. Log-logistic has the least AIC (68822.020) and BIC (68834.371) on the original scale and also has the least AIC (12109.650) and BIC (12122.001) on a log scale. A p-value of (leq0.001) is used to test the KS, AD and CM statistics. Log-logistic best fits radon on the original and on a log scale; hence, is used to construct the Tukey chart. The estimated Log-logistic parameters (shape and scale) and Tukey chart parameters estimated form radon data are presented in Table 2.

Radon is present everywhere in the environment. It tends to move upwards the atmosphere from rocks and soil and using different pathways e.g.: faults, rocks, caves) and carriers such as air and water. This means radon is non negative real quantity, that is, its concentration is always positive rarely zero, but never negative. Hence, on the original scale Tukey chart the UCL and CL are considered while on the log scale, the UCL, CL and LCL are shown in Figure 3. Log-logistic based Tukey control chart results in a central limit of 2465.459 Bq/m3 and upper control limit of 12704.080 Bq/m3 on the original radon data, while it results in a central limit of 7.759 (2343 Bq/m3), upper control limit of 11.080 (64861 Bq/m3) and Lower control limit of 4.524 (92 Bq/m3) on log scale. On both scales the data show the variations and indicate the anomalies if the measurement falls out of the limit. For example, multiple collections of increased or decreased values reported by the measurement device were collected during August 2014. Another significant trend occurred between 10-26 September 2014 and a couple
of peaks occurred near 10 October 2014. It is obvious that, during September, the upper control limit is very successful in classifying the continuous increase in results. In comparison, further increases in a brief period can be readily detected from November to December 2014, even though the dataset has the lowest radon concentration at that time. The majority level of elevated radon levels are found after 15 January 2015 in Figure 3, and the maximum value is readily detectable on the Tukey chart. In short, based on the Tukey chart of the radon database we detect three general anomalies. The first and last anomalies have persisted for two to three weeks between September 2014 and January 2015. Based on this analysis, it is concluded that the Tukey chart performs well for data with outliers or extreme values by detecting both gradual increases in radon concentration and sharp increase in concentration. Since both original and log-transformed results identify significant radon anomalies based on the upper limit only.

It is obvious from Figure 3 that the log-transformed radon data allows to better define a general radon background. This background varies along time, with lower values in the summer (in August it goes up to ca 7.7, that is, 2208 Bq/m²), increasing through time, and reaching a maximum background value in winter (in January it goes up to ca 10.25, that is, 28283 Bq/m²), thus ca 10 times higher than in August. On the other hand, UCL from original data 'cuts' through the winter radon background, and, thus, is not the best option for a recommendation. Hence the manuscript finally recommends the use of the log-transformed radon for monitoring radon.

| Table 1: The comparison of fitted probability distribution on radon data through Kolmogorov Smirnov (KS), Cramer Von Misses (CM), and Anderson Darling (AD) test statistics (p-value) together with Akaike’s information criterion (AIC) and Bayesian information criterion (BIC). |
| KS | AD | CM | AIC | BIC |
| Log-logistic | 0.077 | 1.598 | 25.682 | 68822.020 | 68834.371 |
| Pareto | 0.120 | 5.698 | 53.683 | 69096.200 | 69108.560 |
| Weibull | 0.172 | 27.218 | 175.568 | 70439.490 | 70451.851 |
| Log-normal | 0.074 | 5.388 | 44.859 | 68935.581 | 68947.940 |
| Log-logistic | 0.055 | 1.279 | 14.707 | 12109.650 | 12122.001 |
| Pareto | 0.526 | 245.354 | 1145.90 | 21875.120 | 21887.480 |
| Weibull | 0.125 | 13.269 | 96.031 | 13058.680 | 13071.041 |
| Log-normal | 0.048 | 1.611 | 17.255 | 12145.190 | 12126.012 |
mountainous area of the Hindu Kush with a magnitude of 5.4 on the Richter scale. On 20 October 2014, an earthquake of magnitude 5.5 occurred in the Hindu Kush region, also falling within the EPZ with a ratio of D/R 1.1. The fourth earthquake occurred on 14 November 2014 (M = 5.5) in the Hindu Kush region, also falling within the EPZ with a ratio of D/R 1.1. The last occurrence happened on 15 January 2015, with a magnitude of 49 and a ratio (D / R) closes to 1 (0.9). All of these earthquakes are associated with rise in radon concentration.

4. Conclusion

A data set of radon gas measurement was assessed for possible use as precursory indicator of earthquakes occurred that in the vicinity of Sobra city, northern Pakistan from Aug 01, 2014, to Jan 31, 2015. The log-logistic probability distribution fitted the radon data on the original scale and log scale. A Tukey control chart was applied to the database with the goal of statistical process control monitoring. From the earthquakes catalogue, five earthquakes fulfill the condition of a D/R ratio criteria selected to include in the analysis to determine the temporal relationships between radon concentrations and earthquake occurrence. Tukey control charts of the radon highlighted different anomalies from the whole radon dataset. Among several anomalies five are associated with earthquakes, indicating they may be used as earthquake precursors. For earthquakes, seismic events show a correlation with increasing concentration of radon gas before their occurrence. Moreover, the use of the log-transformed radon for monitoring radon is recommended.

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Figure 2: The graphical compression of a fitted and theoretical probability distribution over the original and log scale.
Figure 3: Tukey Control Chart with CL and UCL at proceeded radon data set.
Figure 4: Earthquake magnitude distribution over time is presented.