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Probability Calculation of Seismic Events on Deep Geological Repository

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1. Introduction

For the safety assessment of deep geological repository, safety assessment should be done by simulating radionuclide release scenarios. Following Nuclear Safety and Security Commission Notice No. 2021-21, scenario can be classified into two categories: normal and abnormal, and the radioactivity from these scenarios should not exceed regulatory limits. For the precise result of scenario simulations, drawing out the probability of scenario is an essential process of safety assessment.

This paper describes a method for calculating probability of earthquake occurrence, which can affect radionuclide release from repository. Earthquake occurrence characteristics of Korea is analyzed by statistical and probabilistic approach on historical data, and the probability for future seismic events is derived by the statistical model. This study is expected to contribute to improving the reliability of safety assessment of deep geological repository and the further research on the impact of abnormal scenarios.

2. Methods and Results

2.1 Methods

There are several methods being used to calculate the probability of earthquakes. Korea Atomic Energy Research Institute(KAERI) have evaluated earthquake scenarios by assuming the magnitude of the earthquake and the distance between the repository and the epicenter to have statistical behaviors of the log uniform distribution and the triangular distribution respectively [1].

POSIVA(Finland) and SKB(Sweden) both used Gutenberg-Richter equation to get the relationship between magnitude and occurrence of earthquake [2][3]. This study used this method of utilizing Gutenberg-Richter Equation and showed further study of calculating the probability of a valid earthquake and probability of multiple earthquakes during the repository evaluation period.

2.2 Historical data

Earthquake records of Korea can be classified into two types as of 1905. Korea Meteorological Administration analyzed earthquakes recorded in various historical documents, and organized the date, location, intensity for each seismic event from 2 to 1904. Instrumental earthquake observation began from 1905, when a mechanical seismometer was installed in Incheon, but only the records since 1978 are provided from Korea Meteorological Administration since the records before 1978 were lost from several wars [4].

The data used for this paper, shown on Table 1, is the most recent one (1978~2023) with 445 data, provided by the Meteorological Agency [5]. Location and intensity of each earthquake was used to analyze Korea's seismic event occurrence.

Table 1. Data for past seismic events.

Occur time	Magnitude	Latitude	Longitude
1978/08/30	4.5	39.1	124.2
1978/09/16	5.2	36.6	127.9
1978/10/07	5	36.6	126.7
1978/11/23	4.6	38.4	125.6
1978/12/12	3.3	35.9	126.3
1979/01/24	3	35.7	126
1979/01/29	3.3	38.3	126
⋮	⋮	⋮	⋮

2.3 Results

To derive the probabilities of future earthquakes, relationship between the magnitude of earthquakes and the number of occurrences through past earthquakes were used [2][3]. Gutenberg-Richter equation, showing the distribution of cumulative occurrences according to the magnitude of the earthquake was used as follows:

$$log_{10}N(M) = a - bM \quad (1)$$

M represents magnitude of the earthquake, $N(M)$ stands for number of earthquakes per unit time (i.e., frequency) have a magnitude greater than M, and a, b are constants.

As the constant a increases, the number of earthquakes increases overall and as constant b increases, proportion of small earthquake increases.

Using the data of Korea, the values of constants a, b have been calculated by method of least squares, a method finding the equation f(x) which makes the value of $(f(x_i) - y_i)^2$ when there are several measurements y_i according to x_i. The value of constants a and b are 5.3372 ± 0.1354 and 0.8911 ± 0.0313, respectively. The relationship of magnitude and the occurrence of the earthquake driven by Gutenberg-Richter equation is expressed in Fig. 1.

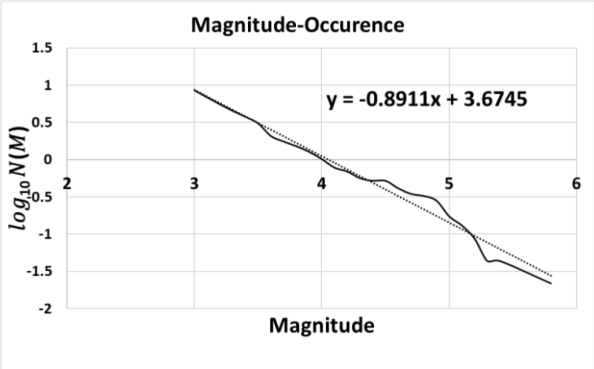

Fig.1. Frequency-magnitude relationships.

The occurrence of large earthquakes is difficult to obtain since the record period is short. Regression line from the relationship of magnitude-occurrence can serve as an indicator for calculating the unknown frequency of large earthquakes. The occurrence for earthquakes of magnitude 3~8 predicted from Fig. 1 is shown in Table 1.

Table 2. Expected occurrence rate of earthquakes for different magnitudes.

Magnitude (M_L)	Expected occurrence rate($year^{-1}$)
3	10.02
4	1.29
5	1.7e-1
6	2.1e-2
7	2.7e-3
8	3.5e-4

The earthquake phenomena is usually assumed to follow a Poisson process, so its occurrence timing can be modeled by an exponential distribution. This research used equation (2), a modified cumulative density function of Poisson distribution which represents the probability that an earthquake of magnitude M or larger will occur within evaluation period *t*.

$$P(T \leq t) = 1 - \exp(-\lambda t) \quad (2)$$

$P(T \leq t)$ is the probability of earthquake occurring within time *t*, and λ represents the average frequency of earthquake occurrence per unit time.

Probabilities of earthquakes according to evaluation period *t* and magnitude M is shown in Table 2.

Table 3. Probability of earthquakes within time t in Korea.

M_L	t=10 y	t=50 y	t=100 y	t=1000 y	t=10000 y
3	1	1	1	1	1
4	9.9e-1	1	1	1	1
5	8.1e-1	9.9e-1	9.9e-1	1	1
6	1.9e-1	6.5e-1	8.8e-1	9.9e-1	1
7	2.7e-2	1.3e-1	2.3e-1	9.4e-1	1
8	3.5e-3	1.7e-2	3.5e-2	3.0e-1	9.7e-1

The driven values are the probability for all earthquakes occurring in Korea. However, not all earthquakes give an effective damage to a repository, the further the epicenter of the earthquake is, the lower damage to the repository. To draw out the probability of effective earthquakes, we set a hypothetical disposal site and calculated the distance from the repository to the epicenter of the earthquake. Referring to the study of KAERI, which determines that the value of Magnitude/Distance(M/D) would be 0.6 or higher to be a valid earthquake, we analyzed only the data with M/D values larger than 0.6 km^{-1}[6]. In other words, the data below 0.6 km^{-1} are screened out. The expected occurrence rate for each magnitude and calculated probability for screened earthquakes of a hypothetical repository is adjusted in Table 4 and Table 5.

Table 4. Expected occurrence rate of screened earthquakes for different magnitudes.

Magnitude (M_L)	Expected occurrence rate($year^{-1}$)
3	1.1e-1
4	3.3e-3
5	1.0e-4
6	3.3e-06
7	1.0e-07
8	3.2e-09

Table 5. Probability of screened earthquakes of a hypothetical earthquake.

M_L	t=10 y	t=50 y	t=100 y	t=1000 y	t=10000 y
3	6.5e-1	9.9e-1	9.9e-1	1	1
4	3.2e-2	1.5e-1	2.8e-1	9.6e-1	1
5	10.e-3	5.2e-3	1.0e-2	9.9e-2	6.5e-1
6	3.3e-5	1.6e-4	3.3e-4	3.2e-3	3.2e-2
7	1.0e-6	5.1e-6	1.0e-5	1.0e-4	1.0e-3
8	3.2e-8	1.6e-7	3.2e-7	3.2e-6	3.2e-5

Using Table 4, probability of multiple earthquakes was calculated using gamma distribution. Equation for gamma distribution is as below:

$$F(x) = \frac{\lambda(\lambda x)^{k-1} e^{-\lambda x}}{\Gamma(k)} \quad (3)$$

λ stands for occurrence rate of earthquake, k for number of occurrences, and x for time. F(x) represents the probability for a kth earthquake occurred at time x. The values of Table 4 were used for λ and the probability over time was calculated for the number of occurrences from one to five times. The results for gamma distribution of seismic event of magnitude greater than 4 is shown on Fig. 2.

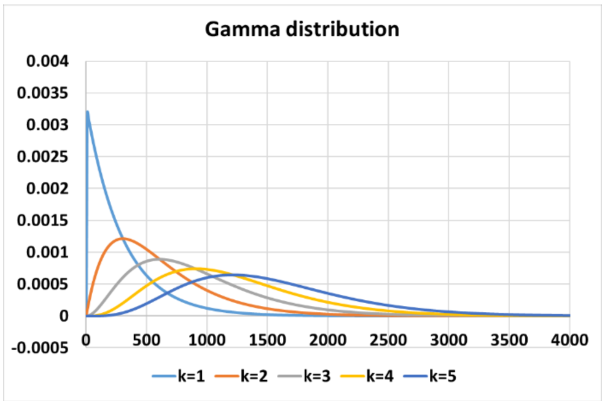

Fig.2. Gamma distribution for earthquakes of magnitude greater than 4.0

3. Conclusions

This study demonstrated a method for predicting the occurrence of events in the earthquake scenario evaluation, which is part of the safety evaluation of deep geological repository. Statistical analysis and event prediction methods for past data in Korea is presented, and the probability of multiple earthquakes is also shown. The detailed results can make deviation depending on the data source and some screening assumptions.

Considering that disposal sites go through more than hundreds of thousands of years of evaluation, earthquake record data history is relatively short. This lack of data and unexpected crust movements in the future increases uncertainty in statistical analysis, so the results of this study should be limitedly accepted. However, it will be meaningful to present this data as the base for scenario evaluation.

Earthquake scenarios can't be fully evaluated only with the probabilities of the earthquakes, other issues such as the impact the event will bring out, should be also considered. There are needs for additional quantitative studies (e.g., Sensitivity analysis of the impact that depth and magnitude of the earthquake gives on the repository or the uncertainty analysis of statistical model) of how much the earthquake will affect the repository and nuclear migration, to perform an effective safety assessment for the repository.

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