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The application of multi-criteria synthetic method in classification of DPRK events

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1. Introduction

In annex 2 to the protocol of the Comprehensive Nuclear-Test-Ban Treaty, there is a list of the characterization parameters for International Data Centre (IDC) standard event screening. For events detected by the International Monitoring System (IMS) seismic component, the following parameters, inter alia, may be used: location of the event, depth of the event, ratio of the magnitude of surface waves to body waves, signal frequency content, spectral ratios of phases, spectral scalloping, first motion of the P-wave, focal mechanism, relative excitation of seismic phases, comparative measures to other events and groups of events and regional discriminants where applicable.

The standard event screening criteria used in IDC system are depth of the event, ratio of the magnitude of surface waves to body waves, regional amplitude ratio of P-wave to S-wave in high frequency and hydroacoustic screening. The statistic results of REB and SSEB events of IDC in 2018 indicate that only 11561 of 37387 (~30%) REB events were screened out as natural earthquakes by criteria in IDC system (**Figure 1**). The rest of the events in SSEB are focus events to States Parties, such as the six nuclear test happened in Punggye-ri nuclear test site of North Korea.

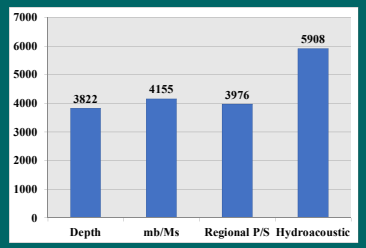

Fig.1 Events screened out by IDC standard event screening criteria in 2018

2. Classification Criteria to Explosions

The source rupture process of natural earthquakes is considered to consist of multiple ruptures, whose source-time function is a linear combination of several time delayed functions, while the source-time function of underground explosions is approximately a single pulse, so the frequency spectrum of natural earthquakes is different from underground nuclear tests. Based on this assumption, complexity of waveform, spectral ratio and synthetic ratio are selected as classification criteria for explosions.

● Complexity of Waveform

Short-period P-wave from source radiation of explosions is simpler than natural earthquakes. Especially, as scattered waveform from each substation of seismic array is beamed and fully compressed, the complexity of waveform from natural earthquakes will be more obvious than explosions.

Setting X(t) is the time series of recorded seismic waveform, the value of waveform complexity is:

$$C = \int_{t=0}^{t=L} X^2(t)dt \Big/ \int_{t=L}^{t=H} X^2(t)dt$$

where L is the length of short time window, H is the end of long time window.

The energy of explosion is focused on the front of time period, and the coda is suppressed. So the molecular of the formula is much larger than the denominator. On the contrary, waveform of natural earthquakes is more complex than explosions because of various seismic phases are widely distributed throughout the seismic waveform.

Complexity of Waveform was considered to be effective criteria earlier, it began to be questioned since more complex explosion seismic waveforms appeared later. However, as a characteristic to describe seismic waveform, it can still be used as auxiliary criteria.

● Spectral Ratio

In general, the propagation attenuation of natural earthquakes is more slowly than explosions, and there are differences in the frequencies of seismic waveforms excited by natural earthquakes and explosions.

Setting X(f) is the amplitude spectrum of recorded seismic waveform, the value of spectral ratio is:

$$SR = \int_{f=L_1}^{f=H_1} |X(f)|df \Big/ \int_{f=L_2}^{f=H_2} |X(f)|df$$

where L1 and H1 are the starting and ending frequencies of low-frequency band, and L2 and H2 are the starting and ending frequencies of high-frequency band. The underground nuclear explosion and natural earthquake have different frequency components. It is generally accepted that nuclear explosion seismic signal has more high frequency components than natural earthquake. The SR value can be used to identify natural earthquake and underground nuclear explosion.

● Synthetic Ratio

The synthetic ratio takes into account both the time domain and the frequency domain of the signal. It is defined as follows:

$$SRC = SR / C$$

where SR and C are the values mentioned above.

3. Multi-criteria Synthetic Method Based on the D-S Evidence Theory

The Artificial Neural Network (ANN) with 35 hidden layers is used to train and classify the past natural earthquakes and artificial explosions. The input of ANN is single value mentioned above: Complexity of Waveform, Spectral Ratio, and Synthetic Ratio, and outputs are probability values of natural earthquake, artificial explosion and uncertainty. For a change of other model that either natural seismic or artificial explosion event, the ANN result has an additional option of uncertainty. The three categories of probability are applicable to the D-S Evidence Theory (Figure2), and the rule of combination by D-S Evidence Theory is:

$$m(C) = K \sum_{A \cap B = C} m_1(A)m_2(B) \qquad K = (1 - \sum_{A \cap B = \Phi} m_1(A)m_2(B))^{-1}$$

Where m(C) is the probability value of category C .

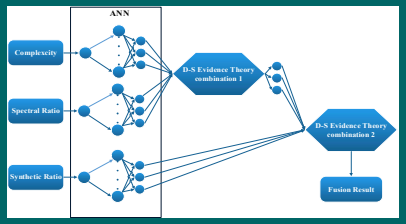

Fig.2 ANN and D-S Evidence theory . The first combination of D-S Evidence Theory is Complexity of Waveform and Spectral Ratio, and the second combination of D-S Evidence Theory is the result of the first combination and Synthetic Ratio. Finally, the fusion result of event classification is provided by the second combination.

4. Classification of nuclear explosions and natural earthquakes in North Korea

The station of KSRS, which is located in the South Korea and the primary seismic array in IMS, lies to 350 km south of Punggye-ri nuclear test site of North Korea. It is selected to classify nuclear explosions and natural earthquakes in Punggye-ri nuclear test site of North Korea and verify the effectiveness of multi-criteria synthetic method.

Table.1 Classification to nuclear explosions in North Korea

Event Date	Screening Criteria	Prob of earthquake	Prob of explosion	Prob of uncertainty	Conclusion
20061009	Complexity	0.15	0.49	0.36	*uncertainty*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.01	0.82	0.17	Explosion
	Fusion Result	**0.01**	**0.98**	**0.01**	**Explosion**
20090525	Complexity	0.41	0.19	0.40	*uncertainty*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.01	0.82	0.17	Explosion
	Fusion Result	**0.03**	**0.95**	**0.02**	**Explosion**
20130212	Complexity	0.53	0.13	0.34	*Earthquake*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.02	0.80	0.18	Explosion
	Fusion Result	**0.05**	**0.93**	**0.02**	**Explosion**
20160106	Complexity	0.51	0.14	0.35	*Earthquake*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.01	0.82	0.17	Explosion
	Fusion Result	**0.05**	**0.93**	**0.02**	**Explosion**
20160909	Complexity	0.53	0.13	0.34	*Earthquake*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.02	0.81	0.17	Explosion
	Fusion Result	**0.05**	**0.93**	**0.02**	**Explosion**
20170903	Complexity	0.52	0.13	0.35	*Earthquake*
	Spectral Ratio	0.03	0.80	0.17	Explosion
	Synthetic Ratio	0.03	0.77	0.20	Explosion
	Fusion Result	**0.06**	**0.92**	**0.02**	**Explosion**

● Table 1 shows the result of single criterion and fusion result of multi-criteria synthetic method to nuclear explosions in North Korea. The fusion result can make correct conclusion, but the result of waveform complexity contains faulty conclusions of natural earthquake and uncertainty. In the case of all three probabilities of single criterion are less than 0.5, the conclusion of uncertainty is given by the criterion.

Table.2 Classification to natural earthquakes in North Korea

Event Date	Screening Criteria	Prob of earthquake	Prob of explosion	Prob of uncertainty	Conclusion
20160330	Complexity	0.75	0.07	0.18	Earthquake
	Spectral Ratio	0.19	0.55	0.26	*Explosion*
	Synthetic Ratio	0.58	0.06	0.36	Earthquake
	Fusion Result	**0.82**	**0.15**	**0.03**	**Earthquake**
20170903	Complexity	0.73	0.08	0.19	Earthquake
	Spectral Ratio	0.00	0.55	0.45	*Explosion*
	Synthetic Ratio	0.77	0.01	0.22	Earthquake
	Fusion Result	**0.86**	**0.10**	**0.04**	**Earthquake**
20170923a	Complexity	0.75	0.07	0.18	Earthquake
	Spectral Ratio	0.19	0.55	0.26	*Explosion*
	Synthetic Ratio	0.61	0.04	0.35	Earthquake
	Fusion Result	**0.82**	**0.14**	**0.04**	**Earthquake**
20170923b	Complexity	0.79	0.06	0.15	Earthquake
	Spectral Ratio	0.03	0.80	0.17	*Explosion*
	Synthetic Ratio	0.60	0.05	0.35	Earthquake
	Fusion Result	**0.67**	**0.29**	**0.04**	**Earthquake**
20171012	Complexity	0.78	0.07	0.15	Earthquake
	Spectral Ratio	0.19	0.55	0.26	*Explosion*
	Synthetic Ratio	0.64	0.06	0.30	Earthquake
	Fusion Result	**0.86**	**0.11**	**0.03**	**Earthquake**

● Table 2 shows the result of single criterion and fusion result of multi-criteria synthetic method to natural earthquakes in North Korea. The fusion result can make correct conclusion, but the criterion of spectral ratio makes faulty conclusion of explosion.

5. Discussion and Conclusion

From the result of classification application to nuclear explosions and natural earthquakes in North Korea, the conclusion was obtained as follows.

- The method of multi-criteria synthetic can be used to solve the situation that different criterion gives different conclusions.
- The results of application indicated that multi-criteria synthetic method came to an accurate conclusion for these nuclear explosions and natural earthquakes, even if one of the criteria provided a wrong decision, which verified the effectiveness of multi-criteria synthetic method.

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