

Monitoring North Korea Nuclear Tests: Comparison of 1st and 2nd Tests

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북한 핵실험 모니터링 : 1, 2차 비교

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Abstract: Two suspicious events, which were claimed as underground nuclear tests by North Korea, were detected in the northern Korean Peninsula on October 9, 2006 and May 25, 2009. The KIGAM and Korea-China Joint seismic stations are distributed uniformly along the boundaries between North Korea and adjacent countries. In this study, the data from broadband stations with the distance of 200 to 550 km from the test site are used to analyze and compare two nuclear tests of North Korea. By comparing the time differences of the Pn-wave arrival times of 1st and 2nd tests at multiple stations, the relative locations of two test sites could be calculated precisely. From the geometrical calculation with the velocity of Pn wave $V_{Pn} = 8$ km/s, the 2nd test site is estimated to move in the WNW direction from 1st one with the distance of 2 km. Body wave magnitude, m_b of the 2nd test, which was announced officially as the network average of 4.5, varies widely with the directional location of stations from 4.1 to 5.2. The magnitude obtained from Lg wave, $m_b(Lg)$, shows less variation between 4.3 to 4.7 with the average of 4.6. The moving-window spectra of time traces of 1st and 2nd tests show very similar pattern with different scale level. In addition, the corner frequencies of P wave of 1st and 2nd tests at each station show no or negligible difference. This indicates the burial depths of two tests might be very similar. The relative yield amount of the 2nd test is estimated 8 times larger than that of the 1st from the weighted average of ground-velocity amplitude ratios.

Keywords: nuclear explosion, test site, magnitude, corner frequency, yield estimation

요 약: 북한지역에서 핵실험으로 추정되는 두 번의 발파가 관측되었다. 한국지질자원연구원 관측소와 한중 공동관측소는 북한과 주변국간의 경계에 고르게 분포하고 있다. 본 연구에서는 북한 핵실험 장소로부터 200 km에서 550 km 거리에 있는 광대역 지진 관측소의 자료를 사용하여 북한의 2차례 핵실험을 비교 분석하였다. 관측소별 1차 실험과 2차 실험의 초동 Pn 도착 시간차를 비교함으로써 상대적인 위치이동을 계산할 수 있다. Pn 속도를 8 km/s로 가정하고, 실험 장소와 관측소간의 기하학적인 관계를 이용하여 계산한 결과, 2차 장소는 1차 장소로부터 서북서 방향으로 2 km 거리에 위치하는 것으로 추정된다. P 파로부터 계산된 2차 실험의 실체파 규모는 평균적으로 4.5이나, 관측소별로는 최대 5.2에서 최소 4.1로 아주 큰 차이를 보인다. 이에 비해 Lg 파로부터 계산한 2차 실험의 규모는 평균적으로 4.6이며, 관측소별로 최대 4.7에서 최소 4.3사이로 P 파에 의한 규모에 비해 관측소간의 차이가 작다. 1, 2차 실험의 이동 윈도우 주파수 스펙트럼은 매우 비슷한 패턴을 보여 주며 두 실험의 초동 P 파의 모서리 주파수는 거의 차이가 없다. 따라서 2차 실험의 깊이가 1차 때와 비슷한 것으로 추정된다. 2차 실험의 폭발력은 관측소별 1차와 2차의 지반속도비로부터 계산한 결과 1차에 비하여 8배 큰 것으로 추정된다.

주요어: 핵폭발, 실험장소, 규모, 모서리주파수, 폭발량 추정

2010년 8월 2일 접수; 2010년 8월 18일 수정; 2010년 8월 20일 채택

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Introduction

Under the signature on Comprehensive Nuclear-Test-Ban Treaty (CTBT), all States Parties should nominate their own National Data Centers (NDCs) to achieve the object and to ensure the implementation of provisions of Treaty. Korea nominated Korea Institute of Geoscience and Mineral Resources (KIGAM) as Korea NDC through the Ministry of Foreign Affairs and Trade (MOFAT) with the strong support of both the Ministry of National Defence (MND) and the Ministry of Education, Science and Technology (MEST) to United Nations (UN) Conference on Disarmament (CD) in Geneva, Switzerland. Since Korea signed CTBT in 1996 that was established at 50th UN General Assembly in New York, KIGAM has conducted the obligation of Korea NDC. The first mission of NDC is to operate and maintain International Monitoring System (IMS) stations inside its territory, and to transmit IMS data in real time to International Data Center(IDC) in Vienna and to interface with other countries' NDCs. The second is to discriminate artificial explosions from natural earthquakes, and if a suspicious event is detected, NDC should report the seismic characteristics such as epicentral location and yield estimation not only to the National Authorities but also to the CTBT Organization.

The first suspicious seismic event, which was declared as the underground nuclear test by North Korea, occurred in the northern Korean Peninsula on October 9, 2006 (NK1ST). Using KIGAM own stations as well as Korea-China joint stations, the calculated body wave magnitude of NK1ST is 3.9. Even though KIGAM estimated officially its yield as 0.4 kt with the variation between 0.2 and 0.8 kt, the inherent uncertainty is inevitable due to the lack of critical information: 1) test environmental constraints such as tunnel dimension and burial depth, and 2) the geological features such as porosity and saturation ratio. North Korea conducted the second test at the adjacent location on May 25, 2009 (NK2ND) and even the possibility of the third test was recently brought up by some press and newscast.

In this study, we show how to calculate the relative epicentral shift of NK2ND from NK1ST by using the change of arrival-time difference between stations. In order to show the effect of attenuation factor, we compared the conventional body wave magnitude of P wave with that of Lg wave. We also estimate the yield of NK2ND by the comparison of seismic wave amplitude ratio of two tests. The corner frequency in the explosive source type is shown to be more

sensitive to burial depth than explosion energy amount.

Arrival time difference vs. Relative location of test sites

Fig. 1 shows the locations of seismic stations used in this study with the basic station information in Table 1. Under the assumption of the spherically layered Earth model, the epicenter is conventionally calculated from the observed arrival times of many phases such as Pg, Pn, Sg, Sn and Lg at multiple stations with the corresponding two dimensional travel time-distance curves. In Fig. 2, KIGAM NK1ST is the KIGAM's best epicentral determination of 1st test site calculated with KIGAM travel time-distance curves (velocity model), even though the reported 1st site was just above the suspected tunnel in some press. The inherent location error should be inevitable because the local topographic effect and wide-range variation of crust thickness could not be considered without full three dimensional velocity model.

Due to possible damage and radioactive contamination of the 1st test, the 2nd site should be prepared somewhat far away from the 1st site. Therefore the relative location can be estimated more precisely just by comparing two data sets. In Fig. 1, the first arrival is the Pn phase. If the distance

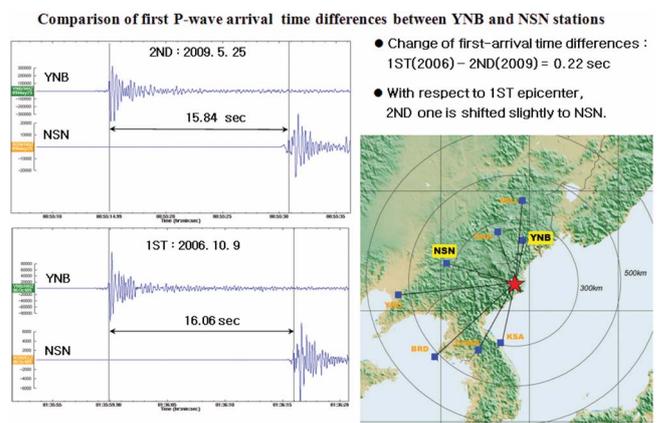


Fig. 1. Comparison of P-wave arrival time difference between YNB and NSN stations for 1st and 2nd tests.

Table 1. Description of KIGAM and Korea-China Joint Stations

Code	Latitude (°N)	Longitude (°E)	Elevation (m)	Sensor
BRD	37.9771	124.7142	78	STS-2
CHNB	38.2685	127.1185	176	STS-2
KSA	38.5926	128.3538	103	STS-2
DNH	43.3446	128.1982	560	STS-2
NSN	42.0183	125.3180	520	STS-2
YNB	43.0029	129.4987	300	STS-2
YNG	40.6836	122.6031	103	STS-2

between the 1st test site and YNB station is denoted by $r_{1st}(YNB)$, the first-arrival time difference between YNB and NSN stations of two tests and their change are given by

$$\frac{r_{1st}(NSN) - r_{1st}(YNB)}{V_{Pn}} - \frac{r_{2nd}(NSN) - r_{2nd}(YNB)}{V_{Pn}} = 16.06 - 15.84 = 0.22 \quad (1)$$

where $V_{Pn} = 8$ km/s is assumed and only the coordinates of 2nd site is unknown. Since only YNB station is located at the east side from test site, YNB is used as reference station for comparing two stations, and Table 2 shows the corresponding difference changes. In Fig. 2, KIGAM NK2ND is the relative location estimated from difference changes with minimum weighted error but the inherent location error in KIGAM NK1ST still exist in KIGAM NK2ND. The relative location of the 2nd test site was estimated to move in the WNW direction roughly by 2 km.

Magnitude m_b vs. $m_b(Lg)$

The concept of magnitude was introduced by Richter in

NK2ND location

1. Date : 2009. 5. 25. 09:54:42 (Korea local time)
2. Location : 41.279N, 129.065E

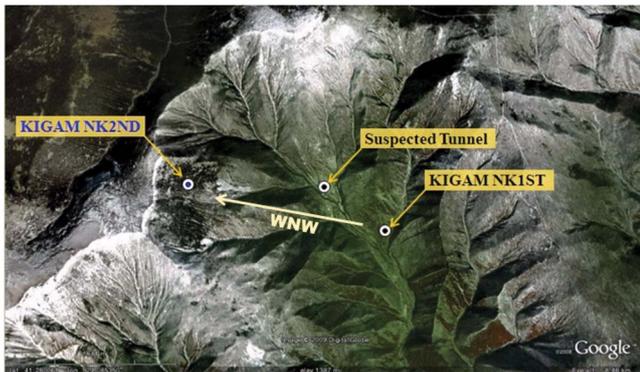


Fig. 2. Relative location of 2nd test. 2nd site was estimated to move in the WNW direction roughly by 2 km.

Table 2. Difference of first P-wave arrival-times observed at Reference and Pair stations. Change of 1st difference into 2nd difference due to epicentral movement in the WNW direction

Ref. Sta.	Pair Sta.	1st ('06)	2nd ('09)	Change (sec.)
	DNH	4.97	4.85	0.12
	NSN	16.06	15.84	0.22
YNB	BRD	41.05	40.96	0.09
	CHNB	22.30	22.29	0.01
	KSA	12.32	12.45	-0.13

1930's in order to scale the earthquake sizes in Southern California and this scale method has been modified for different observational environments and different target phases. Body wave magnitude m_b , which is used recently for explosion yield estimation, was originally invented to measure the size of teleseismic deep earthquakes and is given by

$$m_b = \log(A/T) + C(h, \Delta) \quad (2)$$

where A is the maximum trace displacement amplitude in the few cycles of the P-wave arrival and T is the corresponding period in seconds (Lay *et al.*, 1995). $C(h, \Delta)$ is calibrating function of epicentral distance Δ and the depth h is set to zero for the evaluation of explosion source.

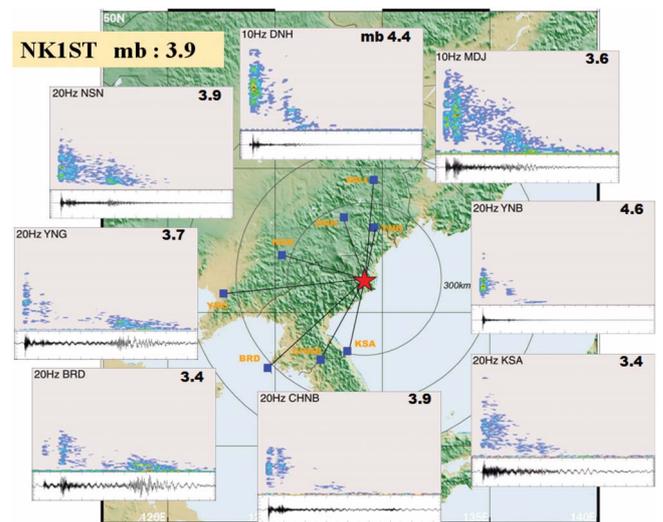


Fig. 3. Estimated body wave magnitude m_b of the 1st test with the weighted average of 3.9.

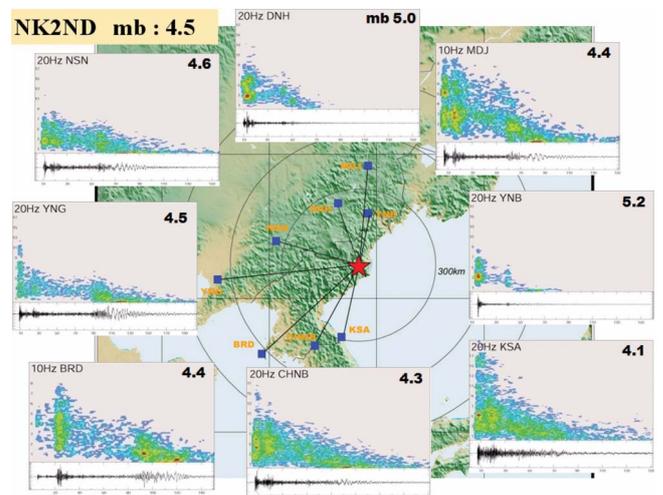


Fig. 4. Estimated body wave magnitude m_b of the 2nd test with the weighted average of 4.5.

For NK1ST, the estimated m_b is shown in Fig. 3 with the network average of 3.9. The directional variation is very large from 4.6 at the YNB station to 3.4 at the KSA station. This big difference is also easily identified at the estimated m_b of NK2ND shown in Fig. 4 with the largest 5.2 at the YNB station and the lowest 4.1 at the KSA station. The body wave magnitudes at the northern stations are clearly recognized larger than those at the southern stations. This systematic contrast is related to the different attenuation characteristics in the northern and southern directions from test site because the dominant period T of P-wave magnitude is strongly dependant on the attenuation through propagation path.

If Lg-wave attenuation along a particular path is estimated correctly, $m_b(Lg)$ is known to be very stable and accurate (Shin *et al.*, 2010). From the calibration Lg-wave amplitude $C(10)$ of m_b 5.0 at a distance of 10 km, $m_b(Lg)$ is defined as

$$m_b(Lg) = 5.0 + \log[A(10: \Delta, \pi f/UQ)/C(10)] \quad (3)$$

where $A(10: \Delta)$ is the extrapolated amplitude at 10 km from observed epicentral distance Δ after the geometric spreading and attenuation with frequency f , Lg group velocity U and dimensionless quality factor Q . Two attenuation models were proposed: Zhao *et al.* (2008) applied 420 and Hong *et al.* (2008) used two different Q as 1025 for the pure continental path group and 366 for the continental margin path group to estimate $m_b(Lg)$ of NK1ST. These two different models were applied to NK2ND and $m_b(Lg)$ was plotted with corresponding m_b in Fig. 5. As expected, the variation of $m_b(Lg)$ is

reduced in Hong's model compared with Zhao's. But it was remarkable that $m_b(Lg)$ in Hong's model shows very linear relationship with m_b . Theoretically if the attenuation factor as well as geometric spreading is completely compensated, both m_b and $m_b(Lg)$ should be shrunk into one point like as open star in Fig. 5. Consequently, it clearly shows that the directional variation of attenuation factor should be considered even into m_b estimation.

Spectrum and Energy

Most of explosion energy is consumed in cracking and melting of the surrounding rocks, but only a portion is converted into seismic waves. The conversion ratio is strongly dependant on geological features: the ratio is known to change up to four times with the saturation ratio. The test-site configuration such as tunnel dimension and burial depth is also crucial factor. Most of these informations are intentionally prohibited to access except for seismic waveform data observed at the limited available stations.

The observed time trace $O(t)$ and its spectrum $O(f)$ are usually expressed by the convolution form in time domain and by the multiplication form in frequency domain as follows:

$$O(t) = S(t)*P(t)*R(t) \Leftrightarrow O(f) = S(f) \cdot P(f) \cdot R(f) \quad (4)$$

where $S(t)$ is a source function, $P(t)$ is a ray path function and $R(t)$ is a receiver function. $S(f)$, $P(f)$ and $R(f)$ are corresponding spectra. Since the 2nd test site moved in the western direction by roughly 2 km as shown in Fig. 2, the relative arrival times of most phases should change slightly with their raypath changes. Geometrical spreading and attenuation characteristics are also affected but their contributions are very little and disregarded for simplicity. The conditions at stations have not been varied with the same sensor and data logger. Then the spectra ratio of observed events can be directly related to the ratio of source spectra and it is given by

$$\frac{O(f)_{2nd}}{O(f)_{1st}} = \frac{S(f)_{2nd}}{S(f)_{1st}} \quad (5)$$

Fig. 6 shows the moving-window spectra of vertical-component ground velocity recordings at the YNB station for two tests. It is noticeable that the pattern shape of two spectra are very closely identical even though the absolute scale of NK2ND is much larger than NK1ST. This similarity could be easily identified at other stations. This high resemblance

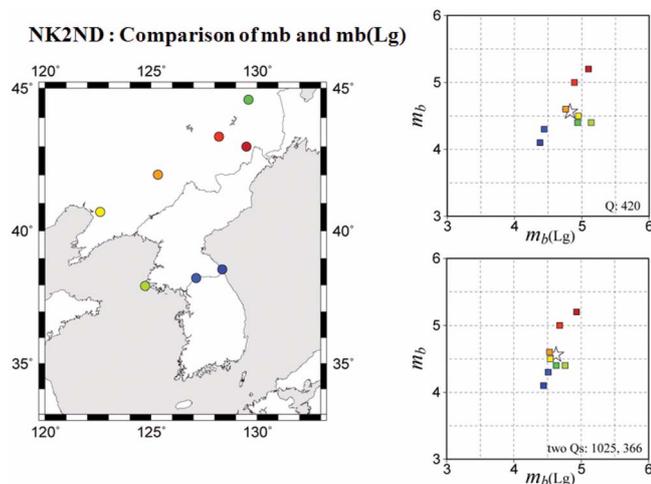


Fig. 5. Comparison of m_b and $m_b(Lg)$ of the 2nd test for two different attenuation models: one quality factor of $Q=420$, and two quality factors of $Q=1025$ in the northern direction and $Q=366$ in the southern direction.

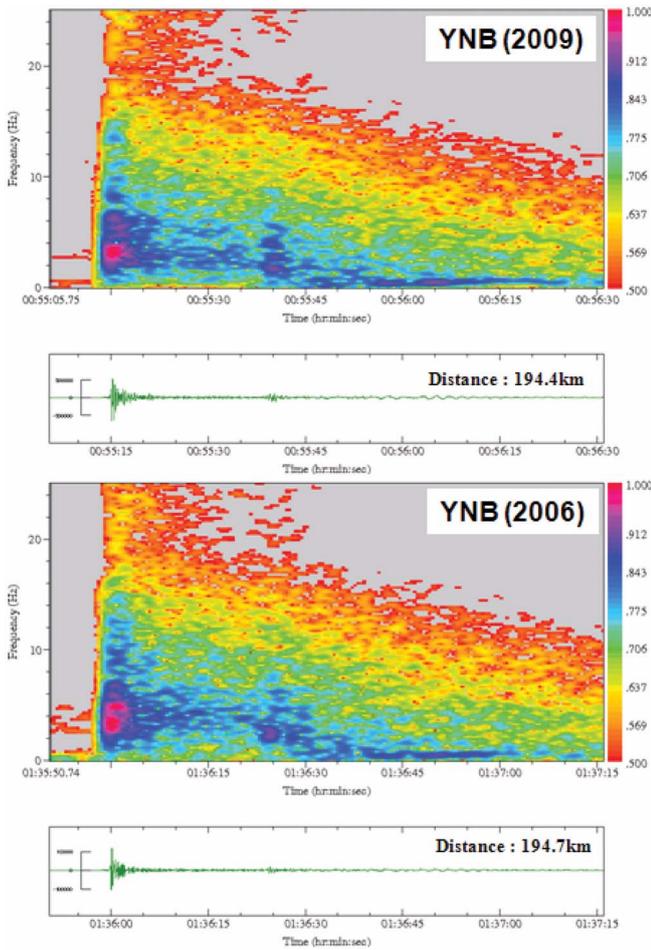


Fig. 6. The moving-window Fourier spectra and time traces of 1st and 2nd tests observed at the YNB stations.

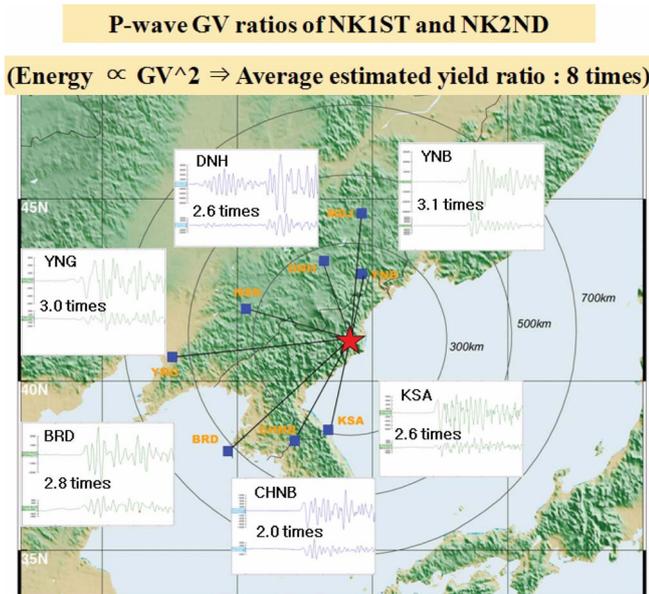


Fig. 7. The ratio of P-wave vertical ground-velocity (GV) amplitude and their weighted average yield ratio.

might indicate that geological features and configurations of two test sites were almost invariant and the ratio of two explosion yield amount is nearly equal to the ratio of observed seismic energy without the complicated consideration of frequency dependant conversion variation.

The seismic energy is proportional to the square of amplitude in the ground-velocity recordings. Fig. 7 showed the P-wave ground-velocity (GV) ratio of two tests. The energy ratio was estimated from the multiple stations in order to reduce the amplitude biases caused by radiation pattern, directivity, attenuation factor, and anomalous raypath distortion. The conclusion is that the yield of NK2ND was 8 times larger than NK1ST, even though the ratio varies slightly with selected phases and/or frequency band.

Corner frequency and Burial depth

If the accumulated strain in the vicinity of fault plane reaches the threshold imposed by fault-material properties, abrupt frictional sliding occurs and the strain energy is exhausted into fracturing of rocks. The shaking wave, earthquake is generated during rupturing along the fault surface. The whole fault plane is not ruptured simultaneously at once. From the initiated break called as hypocenter, the fault plane is progressively fractured outward. This outward speed is called as rupture velocity and it is about 70% of S-wave velocity. The duration of source waveform is determined by the rupture velocity and the distance from hypocenter to the margin of fault plane. Correspondingly the dominant frequency content related to the corner frequency is dependant on rupture velocity and fault dimension: the corner frequency generally decreases with the magnitude of earthquake. In nuclear explosion test, the ignition is just instantaneous irrespective of test size and it is too short to be compared with the speed of fault rupture, which is similar with sequential delay blasting. Hence the corner frequency in nuclear test is not directly proportional to the yield of test.

In the underground nuclear test, the destructive effect radius is dependant on the size of test. In order to prevent surface damage, the burial depth increases with the test size. Even though empirically the corner frequency decreases with test size, the corner frequency is more sensitive to the burial depth (Taylor, 1991). Fig. 8 shows the Fourier spectra of P wave for the two groups, southern and northern stations. The corner frequency of southern stations is clearly higher than that of northern stations. But it is remarkable that the corner

Cut-off frequency vs. Azimuthal direction

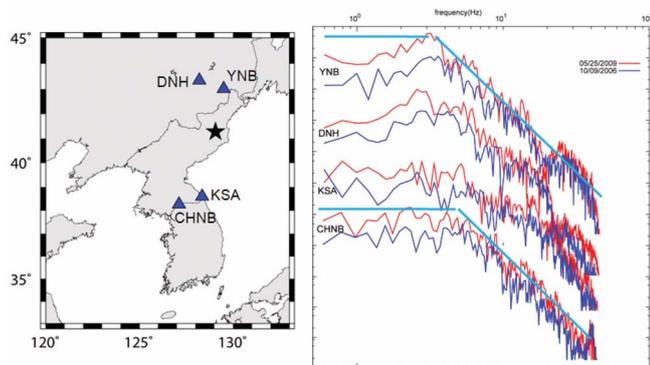


Fig. 8. Comparison of 1st and 2nd displacement spectra of first P wave of two groups: YNB and DNH stations at the northern part and KSA and CHNB stations at southern part.

frequency of NK2ND is slightly larger but almost similar with the frequency of NK1ST, even though the yield estimation of NK2ND is much larger (roughly 8 times) than NK1ST. The observed seismic wave of NK1ST was strangely weak in sense of successful nuclear test, but presumably two test sites were prepared in advance with the similar test configuration and burial depth.

Discussion and Conclusion

We investigated the inherent uncertainty as well as the clear relative estimations of North Korea nuclear tests using seismic data at the KIGAM and Korea-China Joint stations. Due to the lack of full three dimensional velocity model, it is inherently impossible to estimate the exact location from seismic data even if the wide directional range of stations are available. But the relative site location can be estimated accurately just by comparing the relative arrival time differences of two tests. The 2nd site was estimated to move in the WNW direction with the distance of 2 km.

Since the body wave magnitude m_b is estimated without any correction of attenuation on the ray path, m_b might be affected by significant change of attenuation factor Q . This influence was well recognized in the estimated m_b of two tests: it varies from the largest 5.2 to the smallest 4.1 with the average of 4.5. But the magnitude from surface wave, $m_b(Lg)$ is estimated with the compensation of attenuation factor, so it showed less variation just by using only two different attenuation factors. This indicated the potential benefit

of $m_b(Lg)$ to reduce the uncertainty of m_b estimation.

The observed dominant-period T was shown very clearly to change with stations and it is very natural corresponding to the different attenuation factors. But at the same station, the moving-window Fourier spectra including T of two tests showed very similar patterns. Only the scale levels were different due to the different yield amounts. Usually the burial depth increases with the yield amount in order to prevent possible damage on the surface. It is remarkable that the burial depth of 2nd test is very similar to 1st test even though 2nd test is much larger than 1st. Presumably this indicates that 1st test might be not successful as designed.

If the frequency content is not changed, the energy is theoretically proportional to the square of velocity amplitude. The spectrum of 2nd test is nearly identical to that of 1st test, so the energy ratio of two tests could be estimated directly from the ratio of square of ground-velocity amplitude. The yield amount of 2nd test was estimated to be 8 times larger than 1st test from the directional average amplitude ratio.

Acknowledgements

This research was supported by National Nuclear R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2009-0066491).

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