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Seismological Aspects of Korean and other Nuclear Explosions

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ABSTRACT

The largest nuclear explosion by North Korea on 3 September 2017 after the Comprehensive Test Ban Treaty attracted world wide attention raising questions about its magnitude, yield and its claim as a hydrogen bomb. In this article, an overview of the seismological aspects of the nuclear explosions has been presented. Comparison of the largest North Korean nuclear explosion with that detonated by the other countries has been made. Its source parameters and yield are compared with similar nuclear explosions in the past.

Keywords: *Korean nuclear explosion, Yield and Applications in seismology.*

1. Introduction

North Korea conducted its largest nuclear explosion on 3 September 2017 about 22 km ENE of Sungjibaegam at 03h 30m 01.94s UTC in a mountainous area (Fig.1a). It attracted worldwide attention due to its size and the claim of using nuclear fusion technology deployed in the most devastating hydrogen bomb. However, the largest

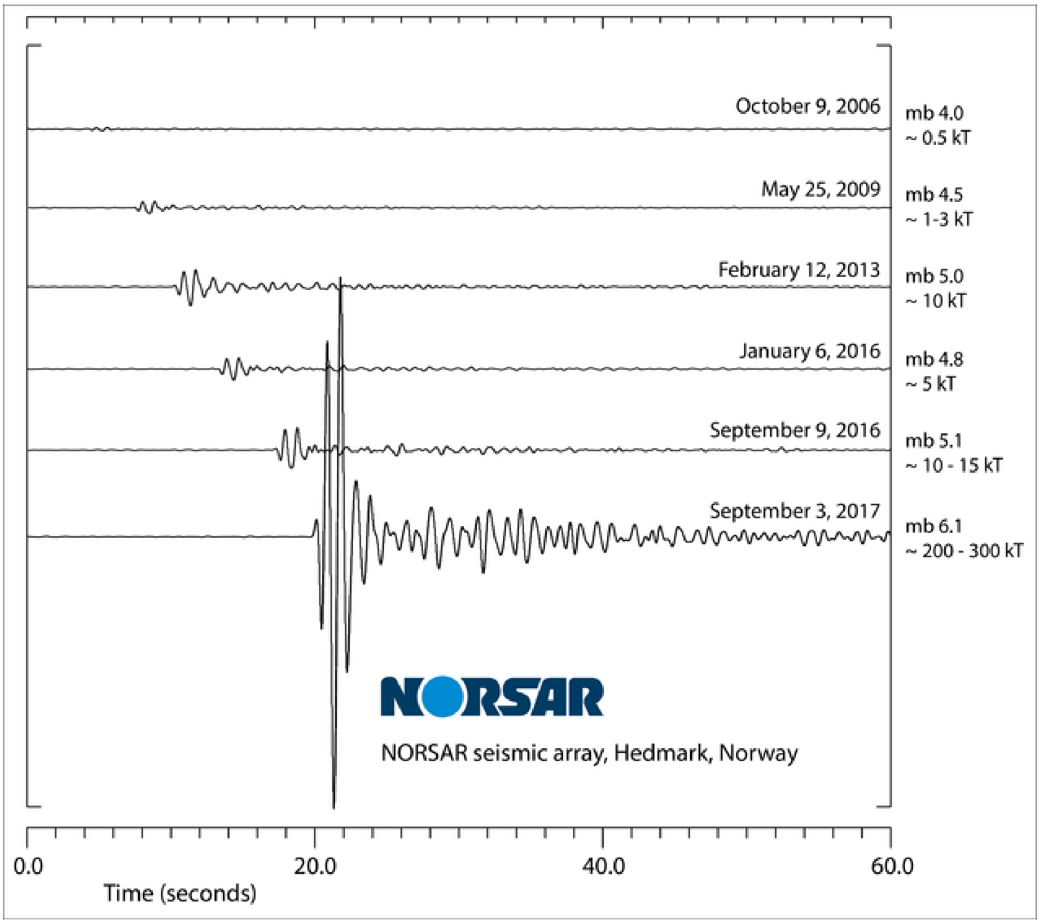

Figure 1a: Signals from the six North Korean nuclear tests to the common scale. (from the NORSAR seismic array station in Hedmark, Norway)

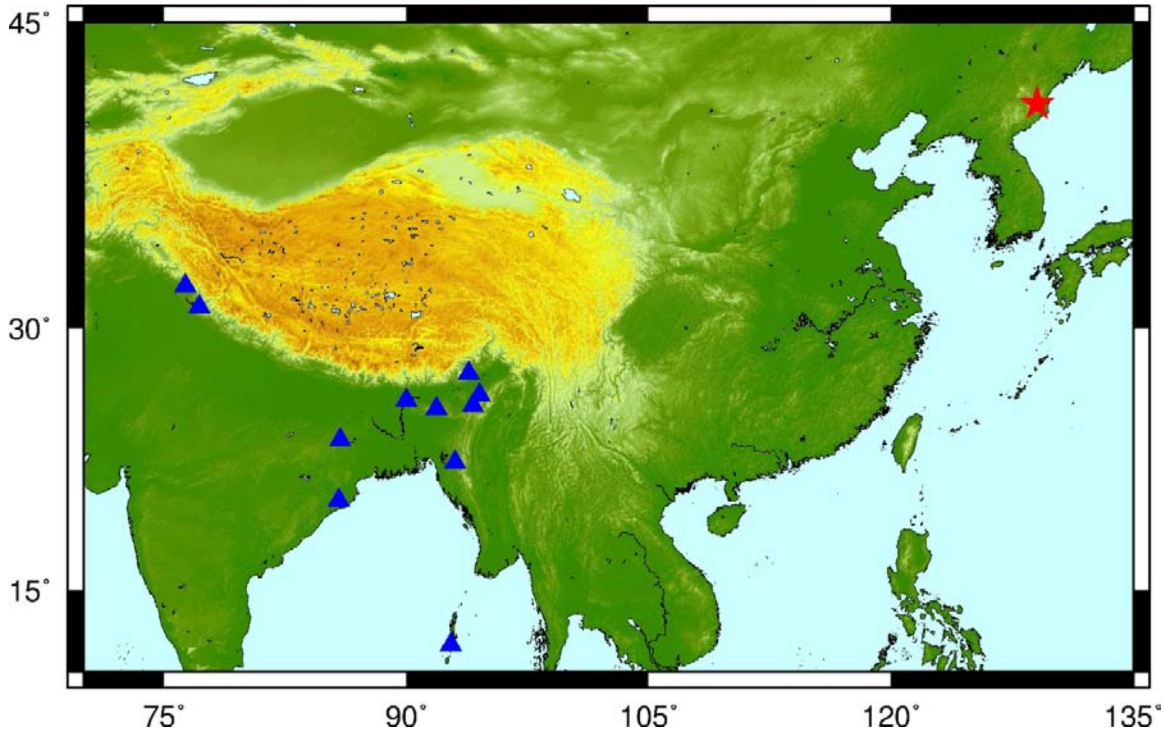

Figure 1b: Map showing location of nuclear blast (Sept. 2017: red star) by North Korea. Blue triangle shows location Indian stations used for ground motion analysis of this nuclear blast.

underground nuclear explosion (M6.8) called Cannikin was detonated by the U.S.A on 06 November 1971 in Amchitka islands, Alaska. It is estimated that there are about 15900 nuclear weapons in the world held by Russia (~7000), USA (~6800), France (~300), China (~260), UK (~218) Pakistan (~130), India, Israel, and Korea. Experiments on the nuclear explosions have been undertaken in the atmosphere as well as underground with special devices to control their radioactivity emitted into the atmosphere. As soon as any nuclear explosion takes place, seismologists are asked to clarify whether it was a nuclear explosion and if so its yield. Of late, seismologists have developed methods to discriminate them from natural earthquakes and utilized them for several problems in seismology like earth’s crust and mantle structure and explored their use even for earthquake precursory studies.

The objective of this paper is to compare the nuclear explosions in North Korea with those detonated by other countries. Seismological methods to discriminate them from the earthquakes have been reviewed in the light of the refinements after the Comprehensive Test Ban Treaty (CTBT). Their seismological applications have also been briefly discussed.

2. Effects of Nuclear Explosions

Energy from a nuclear device is initially released in several forms of radiation. When an underground nuclear explosion is detonated, for example in alluvium or desert, the energy of the explosion is released in fractions of a second or microsecond. This causes the temperature to rise several million degrees Kelvin and pressure to many kilobars. The alluvium is vaporized and melted and the initial cavity around the device expands spherically to a radius depending upon its yield, water content etc. Kinetic energy created by this expansion contributes to the formation of a shock wave in all directions and generates seismic waves called P, S and surface waves. The thermal radiations generally cause irreversible damage to human beings while the blast winds may damage buildings and other structures.

3. Comprehensive Test Ban Treaty (CTBT)

The comprehensive test ban treaty was signed by more than 180 countries which have banned nuclear weapons testing. The United Nations Security Council in September 2016 urged the United States, North Korea, Pakistan, India, China, Iran, Israel and Egypt to ratify the treaty banning nuclear explosions. This treaty has a unique and comprehensive verification regime to make sure that no nuclear explosion goes undetected.

The following geophysical and other technologies are used to monitor the compliance of the Treaty:

i. Seismological stations pick up the waves emitted from the source of nuclear explosions just like earthquakes. This method is the fastest and very reliable method to confirm an underground nuclear explosion. (170 stations worldwide).
ii. Hydro acoustic stations detect sound waves from underwater explosions.(11 Stations)
iii. Infrasound stations record low-frequency sound waves passing through the atmosphere (60 stations)
iv. Radionuclide stations monitor the radioactive by-products of an atmospheric test.(80 stations)

Statistical theories and methods are an integral part of CTBT monitoring providing confidence in verification analysis. Once the Treaty enters into force, an on-site inspection will be provided at the places where questions are raised about its compliance.

The Preparatory Commission for the CTBT Organization (CTBTO) is an international organization with its headquarters in Vienna, Austria. It was created to build the verification regime, including establishment and provisional operation of the network of monitoring stations, the creation of an international data center, and development of the on-site inspection capability. The monitoring stations register data that is transmitted to the International Data Center in Vienna for processing and analysis. The data are sent to the countries who have signed the Treaty. Models of nuclear explosions based on the source physics experiments are being developed for the discriminatory purpose (Ford and Walter, 2013).

4. Seismological Network in India

Keeping in view the utility of seismological stations for the detection of nuclear explosions, the United States of America established the first worldwide standardized seismological network consisting of about 120 stations throughout the world excluding Russia and China during 1962 to 1965. Of these, four stations were set up in India, at New Delhi, Shillong, Pune and, Kodaikanal. While these stations were helpful for several major regional and global researchers in seismology, they also detected nuclear explosions. A more sophisticated chain of seismographs in the form of the L-shaped array was set up at Gauribidnaur, Bangalore under the Atomic Energy Commission during 1965. India also set up an observatory at National Geophysical Research Institute (NGRI), Hyderabad with similar instrumentation as the worldwide standardized network of seismological stations. The seismological observatory at Shillong was upgraded in 1972 to Seismic Research Observatory consisting of three borehole short period and intermediate period seismographs at a depth of about 100 meters. The data of all of these seismographs was digital and multiplexed for recording on magnetic tapes. Although it was designed to detect small yield nuclear explosions, its utility was found to be limited after the broadband digital seismographs were developed with online data transmission facility through satellites. Since 1998, ten observatories in peninsular India were upgraded to broadband digital stations under this program. Since then the network of seismological stations in India is constantly being expanded not only in the India Meteorological Department (IMD) but by the other geophysical and even geological departments. The new programs in the institutions other than IMD were initially funded by the Department of Science & Technology and later transferred to the Ministry of Earth Sciences. Scientists of the Seismology Division of IMD (now National Centre for Seismology) got accustomed to recognizing the nuclear explosions by Russia and China from single station seismograms due to their detonation almost at the same locations in Semipalatinsk and Lop Nor producing similar wave motions at specific sites.

5. Discriminatory Characteristics of Earthquakes and Nuclear Explosions

Study of the seismograms of earthquakes and nuclear explosions recorded at different distances from the source brings out the following differences:

i. Keeping in view the explosive nature of nuclear events, the seismic waves generated, push the earth away producing compressions on the seismogram in all directions. This is generally difficult to infer in seismograms of stations located in thick alluvium or at noisy sites. The use of proper filters may, however, in some cases, enable a seismologist to infer the sense of first motion of the seismic waves from a broadband digital station. If the source mechanism of earthquakes in the region is known, it is possible to define a critical area for that region where one would expect a dilatation. If compression is observed in that region for a suspected nuclear explosion, it would support the event to be an explosion.

ii. In general P-wave amplitudes are larger than the S-waves in the case of explosions provided the epicentral distance of the recording station is more than 1000 to 1500 km. For lesser epicentral distances, it is sometimes difficult to distinguish it from an earthquake since most of the near-source phases are developed as seen from the seismograms of New Delhi due to the Indian nuclear explosions of 1974 and 1998 in Pokhran, Rajasthan. Because of higher frequency content, however, the seismic waves are rapidly attenuated with the distance as compared to earthquakes.

iii. A more reliable method for their discrimination is based on the ratio of body wave magnitude with the surface wave magnitude (Marshal and Basham, 1972). Lesser amplitude surface waves are produced from the nuclear explosions as compared to that from earthquakes. Thus the Mb versus Ms plot of the events for a region clearly provides the distinction between them.

The body wave magnitude Mb is defined as

$$Mb = \log (A/T) + Q$$

Where, A is one half of the trough to peak amplitude, reduced to ground motion in microns of the wave on the short period vertical component seismogram measured within 5 seconds of the onset; Q (quality factor) is available in tabular form.

The surface wave magnitude is given by

$$Ms = \log (Au/T) + 1.66 \log \Delta + 3.3$$

Where Au is the maximum peak to trough amplitude in microns of Rayleigh waves of 18-22 seconds period (T). Here Δ is the epicentral distance. Earlier long period seismographs were used but nowadays, the broadband seismographs are easier to extract desired signals by using proper filters.

iv. The amplitude spectra of surface waves have also been used for the discrimination purpose. The spectral content from the Rayleigh waves from the nuclear explosions differs markedly from the earthquakes.

v. Lg waves are quite often distinctly recorded from the nuclear explosions. These waves are observed at larger regional distances and caused by superposition of multiple S-wave reverberations and SV to P and/or P to SV conversion inside the whole crust. The maximum energy travels with a group velocity of approximately 3.5 km/s (ISC, IASPEI) for Lg waves.

6. The Yield of Nuclear Explosions

The yield of nuclear explosions indicates its destructive power. It, therefore, gives an idea about the amount of energy released when that nuclear device is detonated. It is usually expressed as a TNT implying the equivalent mass of tri nitro toluene would produce the same energy if exploded. It is expressed in thousands of tons of TNT(kt) or millions of tons of TNT (Mt). In simple terms, one kiloton of TNT is taken as 10^{12} calories or 4.2×10^{19} ergs. Less than 1% of the energy of the underground nuclear explosions is converted into seismic energy. The yield is generally computed from the body wave magnitude Mb by the relation

$$Mb = A + B \log Y$$

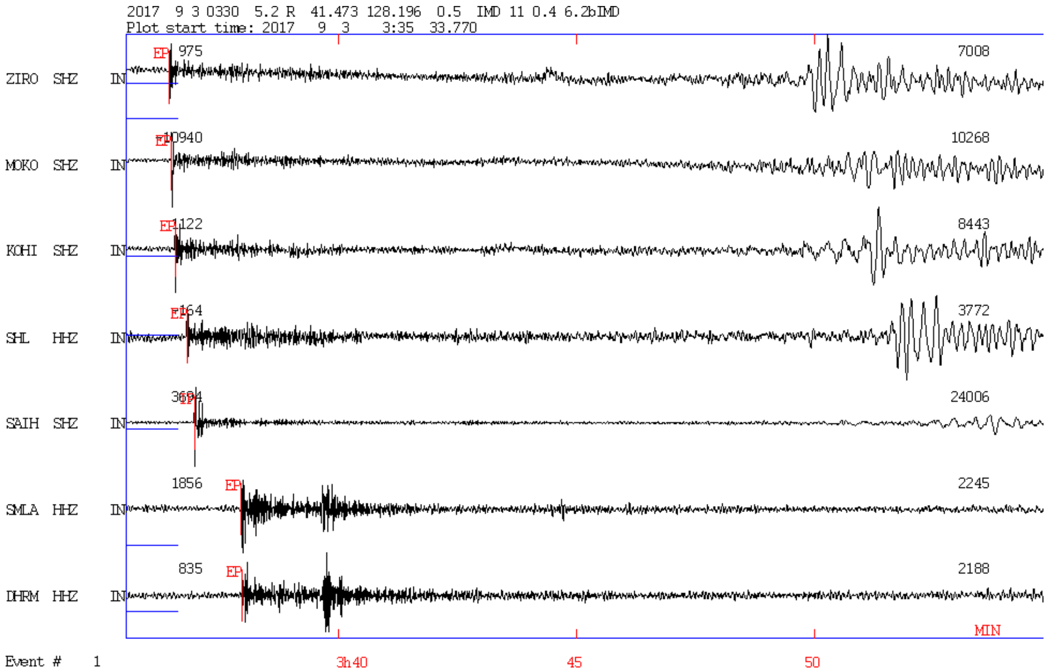

Figure 2: Ground motion record of North Korea blast recorded at Indian seismological stations

Here Y is the yield ranging from 4 to 1300 kt of TNT, A and B are constants which depend upon the geological conditions and extent of coupling or decoupling of blast energy into seismic waves. Several statistical relations between the magnitude and the yield have been given but they give only a rough measure of its yield which is always debated (US Congress, 1988).

As mentioned above, the extent of conversion of yield into seismic energy is dependent upon the site condition and the depth of the bore hole. It is found that the explosions in the granite, dolomite or wet turf typically of rocks produce about 2% of the explosively released energy. A similar explosion in porous rocks, dry turf or alluvium produces seismic sources one order of magnitude weaker than those in rocks. The North Korean nuclear explosions are carried out at a site in mountainous terrain but its details are not fully known.

So far North Korea has carried out 6 nuclear tests which have been recorded by the seismological stations. The figure-1a shows the signals from the six North Korean nuclear tests to the common scale from the NORSAR seismic array station in Hedmark, Norway. The trace at the bottom shows the signal from the very large, 3 September 2017 event, whereas the five upper traces display the signals from the five preceding tests, conducted by North Korea in 2006, 2009, 2013, and 2016 (two explosions).

All the six North Korean tests were picked up by the International Monitoring System set up by the Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission. Figure-2 shows the seismogram of the largest North Korean nuclear explosion recorded at six Indian seismological stations. The difference in the seismic waveforms at different epicentral distances is well marked. IRIS has given seismograms of 140 stations worldwide for this event.

7. North Korean Nuclear Explosion Parameters

The epicentral parameters of the six North Korean nuclear explosion events as determined by the US Geological survey are given in Table 1. Gibbons et al.(2017) gave relative location estimates for the 5 nuclear tests conducted by North Korea up to 2016 using empirical slowness corrections.

The largest North Korean explosion is claimed by them as the test of a hydrogen bomb which may be confirmed from the leaked radionuclides if any in the near future. As

Table 1. The Epicentral parameters of the six North Korean nuclear blast events as determined by the US Geological Survey

Date yyyy-mm-dd	Time(UTC) hh:mm:ss	Lat. 0N	Long. 0E	Mag. (mb)	Depth (km)
2006-10-09	01:35:28	41.294	129.094	4.3	0
2009-05-25	00:54:43	41.294	129.094	4.7	0
2013-02-12	02:57:51	41.299	129.004	5.1	0
2016-01-06	01:30:01	41.300	129.047	5.1	0
2016-09-09	00:30:01	41.287	129.047	5.3	0
2017-09-03	03:30:01	41.343	129.036	6.3	0

mentioned earlier, the correspondence between the seismic magnitude and explosive yield of an underground nuclear test is associated with a very large uncertainty. Since no reported and reliable reference yields are available for the North Korean test site, the northern Novaya Zemlya test site data was taken which gave yield estimate of 250 kilotons for the magnitude 6.1 event on 3 September 2017. NORSAR, however, estimated the explosive yield at 120 kilotons TNT corresponding to a magnitude of 5.8 but revised later. In comparison, the explosive yield of the nuclear bomb dropped on Hiroshima on 6 August 1945 was estimated at approximately 15 kilotons TNT, while the bomb dropped on Nagasaki three days later was estimated at approximately 20 kilotons TNT. The highest yielding test series by the USA and USSR gave a yield of 50 megatons. The largest underground nuclear explosion of magnitude 6.8 by the USA called Cannikin gave a yield of 5 megatons. On the other hand, the yield estimate of 58 ±10 kilotons was estimated for the Indian nuclear explosions in 1998 while the first event in 1974 gave a yield of 12 to 13 kt only. However, Douglas et al(2001) consider the yield of Indian nuclear explosions much less.

7.1 Analysis of North Korean explosion from Indian seismological stations

The data of the Indian stations where the North Korean nuclear explosion (2017) were well recorded are shown in Figure 1b. The record of the surface waves at some stations is also quite clear (Figure 2). It may be noted that our Indian network of stations are about 3500 to 4500 km away from the Korean blast where higher frequencies are greatly attenuated. The data were, however, used to determine the epicentral parameters of this event as follows:

Date 3.9.2017, Origin time, 03:30:5.2 GMT

Epicenter 41.473^0 N, 128.196^0 E

Magnitude Mb 6.2, Ms 5.2,

Depth 0.1 km fixed

The USGS epicenter for the largest north Korean nuclear explosion is 41.343^0N, 129.036^0E. This magnitude of this explosion is comparable to that from the Indian data (Mb 6.2). The difference in the epicenter is attributed to the limited azimuthal control from Indian stations as compared to that by USGS. The lower surface wave magnitude from the Indian data as compared to Mb supports it as a nuclear explosion. Semin et al (2013) presented an analysis of DPRK nuclear test of February 12, 2013 by Belbasi nuclear tests monitoring centre (KOERI) and used the following relation for the yield (Murphy, 1996)

$$Mb = 4.45 + 0.75 \log Y$$

Where Y is the yield in kilotons. They found the yield of September, 2013 nuclear explosion as 7.4 kiloton corresponding the body wave magnitude of 5.1 for the North Korean explosion. Using this equation, the yield of the largest North Korean nuclear explosion comes out as 215 kt corresponding to Mb of 6.2 from the Indian stations. This compares well with the yields of similar large nuclear explosions (Mb 6.2 or slightly more) in Semipalatinsk and Nevada. If the yield of 2013 event is compared with that of the Indian nuclear explosions of 1974 and 1998, the yield of Korean explosion is much less. Douglas et al (2001) however surmise much smaller yield of Indian nuclear explosions.

Two minor tremors of magnitude 2.9 and 2.4 were detected on 9 December 2017 from North Korea which were probably aftershocks of the nuclear explosion in September 2017. According to US Geological Survey and CTBT, they were tectonic in origin but in the vicinity of the nuclear test site.

8. Applications of Nuclear Explosions in Seismology

i. For known origin times and locations of the nuclear explosions, the time of arrival of P and S-waves at a station(s) and their inversion provides more accurate crust and mantle structure of the region. This is because the earthquake origin time and epicenter are approximately determined. The velocity model from the explosions can be used to improve the location of the earthquakes occurring in the region. The method can be considered supplementary to that based on the chemical explosions which have been very useful. (Srivastava et al, 1974)

ii. Since the nuclear explosion source is symmetrical, the surface waves emitted from the source are relatively free from other disturbances. They are not only useful to determine the surface wave magnitude to discriminate them from the earthquakes but also determine velocity models of the regions. Thus the methodology provides additional details for the models as compared to that from the P and S-waves.

Surface waves can also be used to study the phenomenon of absorption, scattering, and diffraction which can be validated from those deduced from the earthquakes

iii. If there are some regions where earthquakes do not generally occur, the data from the nuclear explosions can be specifically used for the regional crust and upper mantle studies.

The considerable impetus to research in seismology was given after the U.S. Atomic Energy Commission agreed to release the exact time and place of the three series of explosions conducted by them during 1954, 1956 (Enewetak Atoll) and 1957 (Nevada). Compared to the earthquakes whose epicentral parameters are computed from the travel times of seismic waves resulting in errors in the location and larger errors in the focal depth, nuclear explosions overcome this problem and give higher accuracy in the seismological applications. However, since many other countries like the Russia and China do not release this information, the seismological results obtained from them are generally not so accurate. These are however still better because the focal depth of the explosions being nearer the ground surface offers a better alternative as compared to the earthquakes which have large errors in the focal depths.

9. Some Results from the Nuclear Explosions

a. Atmospheric nuclear explosions

i. Tandon (1959) found that out of ten tests conducted by the U.S.A in Nevada during the period, nine were well recorded by one or more Indian seismological stations.

ii. Tandon (1961) studied the atmospheric nuclear explosions (hydrogen bombs) by Russia during 23 October and 30 October 1961 at a height of 50 to 60 km near Novaya Zemlya. Due to air coupling, both these explosions were recorded throughout the world including Indian stations.

iii. Tandon and Chaudhury (1962) examined the long period Press Ewing and vertical component Benioff seismograms which recorded the Russian nuclear explosion of 5 August 1962. From the P and S-phases, the epicentral distance was found as 47 degrees which correspond to the distance of Novaya Zemlya. Comparison with the Russian explosions in the year 1961, it was found that its yield was somewhat less than 50 megatons. The pressure waves were also recorded on the seismograms which were corroborated by the microbarograph observations.

iv. The high yield atmospheric nuclear explosions by USSR in 1962 generated well-marked Love and Rayleigh waves. Also, another phase called the Caloi phase was well recorded on the seismograms. The dispersion of surface waves was studied in detail by Tandon and Chaudhury (1963). It was found for the first time that the thickness of the crust in the Himalayan region was 50 to 60 km.

a. Underground nuclear explosions

i. Srivastava and Chaudhury (1973) studied the P-wave anomalies at the Indian stations recorded from the largest nuclear explosion by the U.S.A called Cannikin in Amchitka Island on November 6, 1971. The residuals showed better agreement with the Herrin's travel time tables. These residuals were larger near the stations in the Himalayan foothills as compared to that in peninsular India. This was possibly due to the under thrust Indian plate or to a thinning of the low-velocity layer from the shield region of the peninsula toward the orogenic Himalayan belt.

ii. The seismogram at a close station like Delhi from Pokhran from the first Indian underground nuclear explosion looked remarkably similar to an earthquake (Srivastava 1974). On the other hand, the underground nuclear explosions by the USSR and China with their locations in Semipalatinsk and Lop Nor respectively produced typical seismograms which could be easily identified even from a single station like New Delhi due to attenuation of higher frequency seismic waves. This difference could be attributed to the rapid attenuation of high-frequency seismic waves with distance which make the record simpler if the epicentral distance increases.

iii. Kazakh nuclear explosions by the U.S.S.R were detonated almost every month till CTBT was signed in 1998. Although the exact location of these explosions was not given but considering their focal depth close to zero, they offer a better method as compared to the earthquakes to study changes in the travel times of seismic waves prior to earthquakes in the light of dilatancy diffusion model. While the Herrin's travel times gave lesser errors as compared to Jeffreys-Bullen tables, no significant anomalies could be detected which could be considered as precursory in nature (Srivastava, 1979). The results could perhaps improve if the exact origin times were known instead of deducing them from the travel times.

iv. Detailed analysis was done for the second Indian nuclear explosion in Pokhran on 11 May 1998 (Gupta et al, 1999 and Roy et al, 1999). On comparison with the Chaghai explosion of 28 May 1998 in Pakistan, it was found that the energy from the Pokhran event peaked in the frequency of 3.5 to 6 Hz as compared to a range of 1 to 3 Hz for the Pakistan explosion at similar distance which was attributed to the difference in the soil conditions at the two test sites. Comparison of the amplitude ratio of Lg waves recorded from the Pokhran nuclear explosions of 1998 and 1974 gave yield ratio of 4.83 between the two events.

10. Forensic Seismology

The nomenclature of Forensic seismology was evolved after the need was felt to apply seismological techniques to detect nuclear explosions. The distance up to which seismic waves are recorded depends upon the magnitude or its yield. Larger is the yield, larger is the distance up to which seismic waves can be detected. Therefore, attempts are being made to develop small nuclear explosions below the detection threshold. However, in order to comply with the test ban treaty (CTBT), organizations like Los Alamos National Laboratory (USA), Lawrence Livermore National Laboratory (USA), and a few others have developed special techniques to monitor them through data of seismological stations and other monitoring systems. Special algorithms are used to remove noise from the seismic signals to improve the signal to noise ratio. This is because the yield from the smaller explosion may be difficult to detect due to similar seismograms produced by the earthquakes or other natural events. Another method to conceal nuclear explosions is called mine masking but the method is questionable. A detailed overview of forensic seismology may be had from Douglas (2013).

11. Earthquake Triggering due to Nuclear Explosions

Analysis of the seismic waves generated by the nuclear test sites in Nevada (USA) showed that the source can be characterized as 70-80 % dilational (explosive like) and 20-30% as deviatoric (earthquake like). Almost similar type of source mechanism is found for the largest North Korean nuclear explosion in 2017 by IRIS (Figure 3). The rock in the vicinity of the thermonuclear device is shattered by the shock waves released by the explosive source. Thus, the elastic strain energy stored in the rock is released which gives rise to earthquake like component to the seismic waves. Detailed investigations of the thermonuclear explosions in Nevada, the USA with the seismic activity did not show any peak in seismicity at the times of nuclear explosions. This is attributed to small transient strain from the nuclear explosions which is not sufficiently large to trigger fault ruptures at distances beyond a few tens of kilometers from the shot point. The largest nuclear explosion Cannikin (M 6.9) did not trigger any earthquakes in the seismically active Amchitka Islands (USGS) . Thus there is no direct evidence that nuclear explosions can trigger earthquakes.

12. Conclusions

The above study has shown that the largest North Korean explosion of 3 September 2017 had similar source characteristics as in other regions such as Semipalatink and Nevada. Its yield was also in conformity with similar magnitude nuclear explosions in other areas. Further studies are needed to determine whether it was a controlled hydrogen bomb.

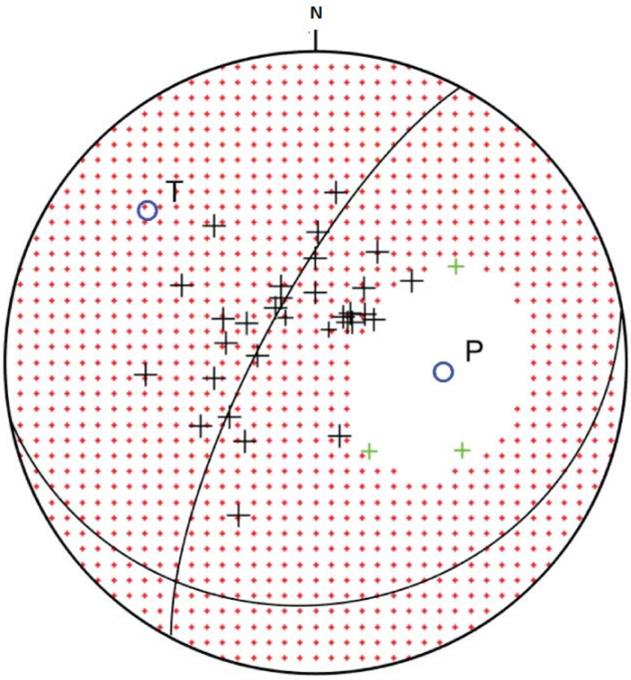

Figure 3: Comparison of observed compressional (black plusses) and dilational (green plusses) first motion polarities and the source-type moment tensor inversion solution. [Explosive moment is 3.36e+23 dyne-cm (Mw 4.95); DC % = 34; CLVD % = 24]
***Source*: Douglas Dreger, UK Berkeley.**

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