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Discrimination of Explosions and Earthquakes: An Example Based on Spectra and Source Parameters of the 11th May 1998 Pokhran Explosion and the 9th April 2009 Earthquake

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Abstract: We compare the P-, S- and Lg- spectra of the 11th May, 1998 Pokhran underground nuclear explosion (NE) with those of an earthquake (EQ) of comparable magnitude that occurred in its vicinity (~100 km west) on 9th April, 2009, utilizing the waveforms recorded by a Global Seismograph Network station at Nilore (NIL), Pakistan. The contiguous occurrence of these events and the similarity of the travel paths provided a good opportunity to discriminate the nature of the sources. Our results suggest that the Pn/Lg and Pn/Sn amplitude ratios of the explosion and earthquake waveforms exhibit distinct differences in the higher frequency window. Further, since the P-phases have high signal to noise ratio compared to their S counterparts, we utilize their spectra to derive the source parameters of the NE and EQ sources. Our results show that the seismic moment, corner frequency and source dimension of the explosion are ~1.58×10^{17} Nm, 1.18 Hz and ~0.793 km respectively. The moment magnitude (M_W) and surface wave magnitude (M_S) for the nuclear explosion are estimated to be ~5.4 and ~3.57 respectively. The values of M_W (5.3) and M_S (4.3) obtained by us for the earthquake are consistent with the estimates in the Harvard catalog and earlier published results. The estimate of M_W for the nuclear explosion was hitherto not available. Lastly, we estimate the yield of the NE to be ~50 kt from the surface wave magnitude and discuss the various limitations related to its estimation.

Keywords: Spectral analysis, Nuclear explosion, Seismic moment, Corner frequency, Source dimension.

INTRODUCTION

Discriminating nuclear explosions from earthquakes remains a challenge, especially in regions experiencing low to moderate levels of seismicity. Such a discrimination has implications for deciphering the active tectonics in stable continental regions and more importantly for verifying the compliance with CTBT. A variety of discriminants have been proposed to differentiate the natural and nuclear explosion sources. Lavshin and Ritzwoller (1995) studied the differences in spectral amplitudes between earthquakes and explosions using frequency-time diagrams. Allmann and Shearer (2008) also observed discrepancies in the spectra of explosions and earthquakes. Also, regional phases like Pn, Pg and Lg are used to establish empirical far-field nuclear explosion model based source spectrum. Zhao et al (2014) noticed abrupt P, weak Lg and strong Rayleigh waves for the 12 February 2013 North Korean nuclear test. They relocated the event and estimated the yield using Lg wave magnitude m_b(Lg).

World-wide, numerous studies have been carried out to compare the source parameters of various nuclear explosions and earthquakes. For example, Toköz et al., (1964) employed amplitude equalization method to estimate the source parameters of explosions and earthquakes using amplitude spectra of surface waves. Seismic-spectrum scaling model have been proposed for the nuclear seismic source function based on the underground explosion (Mueller and Murphy, 1971). Tsai and Aki (1971), analyzed 13 underground nuclear explosions from the Nevada Test Site and 12 earthquakes, using amplitude spectra of Rayleigh waves at high frequencies and suggested that both types of sources can distinguishable. Nuttli (1986), presented a new methodology to estimate the yield of underground nuclear explosions using Lg phases. Gupta et al (1992), successfully explained the mechanisms behind the generation of short and long period Lg phases, after analyzing the spectral characteristics of Pn and Lg phases from East Kazakh (USSR) and Nevada test site underground nuclear explosion data. Pomeroy (1963) studied the generation of long period body and surface waves due to

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series of explosions of 1958 of the US and USSR.

Prior to this study, quite a few attempts have been made to determine the source character and yield estimation for the 11th May 1998 Indian nuclear explosion performed at an underground test site in Pokhran, Rajasthan. The seismic waves were recorded by the seismographs deployed world-wide. Soon after the explosion, the seismological waveforms at local to intermediate distance ranges were investigated to estimate the nature of source and path characteristics using Lg (Roy et al. 1999) and Rayleigh wave data (Sikka et al. 1998). Further, based on the regional data set they estimated the yield to be in the range of 54 to 63 kt. Gupta et al. (1999), compared the spectral characteristics of the Pokhran and the Chaghai (28th May, 1998, Pakistan) explosion data recorded at the Indian stations including the GEOSCOPE station at Hyderabad and found noticeable variations in energy content in different frequency ranges for both the explosions. They further noticed that Pokhran explosion has more energy confined in the higher frequency range (3.5 to 6 Hz), whereas in case of Chaghai explosion the more energy is towards the lower frequency range of 1 to 3 Hz. Sikka et al. (2000), reviewed the regional and tele-seismic data and analyzed the Lg and surface waves. Their estimate of yield using close-in seismic network to be ~58 kt, which was further substantiated by the fusion component corroborated with the simulation result.

The present study is primarily aimed at understanding the explosion source and its various parameters using a grid search method applied to the spectra of waveforms recorded by a seismic station NIL in Pakistan. Also, the record of an earthquake that occurred in its close proximity on 9th April 2009 at the same station provided an excellent opportunity to discriminate the two types of sources (Fig.1). The advantage of this scenario is that the path, site and attenuation effects being common to both the explosion and the earthquake enable a meaningful comparison of their sources. Previously, Doglus et al. (2001) compared the P-wave amplitudes at various stations and estimated the yield of the Pokhran explosion to be substantially lower than those reported by others. Barker et al. (1998) also discussed the strength of the Indian explosions and reported the yield to be 12kt for 11th May 1998 source. Based on the presence of strong Love and reversed Rayleigh waves observed at regional distance recorded by station NIL, Rodgers et al., (2002) opined that the nuclear explosion could be associated with a strong tectonic stress release.

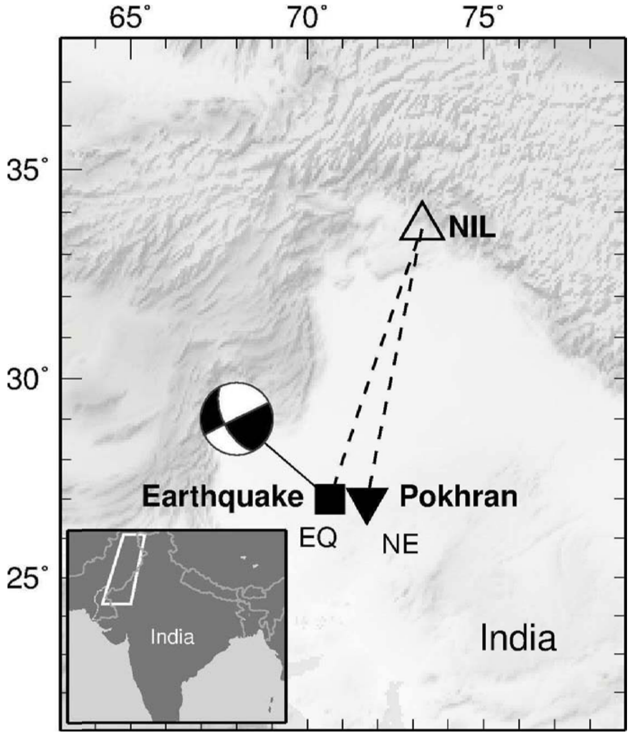

Fig.1 Location map of 11th May 1998 Pokhran nuclear explosion site (inverted black triangle, NE) and a nearby earthquake (solid square, EQ) occurred on 9th April, 2009. Both are having comparable body wave magnitudes of 5.2 (EQ) and 5.2 (NE) as reported by USGS. In the present study, the seismological waveforms are from GSN broadband station NIL (open triangle), where both the sources are recorded simultaneously. The focal mechanism of the earthquake is also shown (Fault Plane 1: Strike=153, Dip=60, slip=179; Fault Plane 2: Strike=243, Dip=89, slip=30).

DATA AND METHOD

The Pokhran nuclear explosion of 11th May 1998 (Mb 5.2, USGS), and the earthquake of 9th April 2009 (Mb=5.2, CMT, 5.1, USGS)) are recorded by one of the GSN stations NIL (see Fig.1). The seismological waveform data are publicly available on the Incorporated Research Institutions for Seismology (IRIS), Data Management Center (DMC). Firstly, the instrument response was removed from the waveforms to obtain the true ground motion, by designing appropriate filters with the knowledge of their poles and zeros. Subsequently, integrated the data to obtain displacement waveforms. The waveforms are then de-meaned and de-trended for further processing. Also, these

Table 1. Data used in this study with the event and station information

Event	Origin Time	Lat (^{0}N)	Long. (^{0}E)	Depth (km)	Mb	Dist (deg)
Nuclear Explosion (NE) USGS	1998-05-11 10:13:41.47 _	26.95	71.70	0	5.2	6.83
Earthquake (EQ) CMT	2009-04-09 01:47:02.30	26.99	70.64	38.8	5.2	7.03

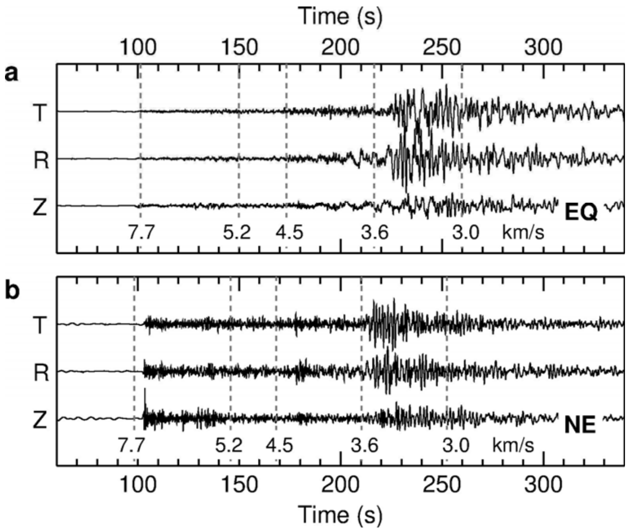

Fig.2. Three-component instrument corrected displacement seismograms for earthquake and nuclear explosion (as shown in Figure 1). The three components are rotated to vertical (Z), radial (R) and transverse (T) using back-azimuth information. Amplitude of the explosion seismograms are multiplied by a factor 5 for better visibility. The vertical dashed lines are apparent group velocity indicted by respective numbers in km/s. Explosion waveform shows an impulsive P-wave onset compare to the earthquake data.

3-component displacement seismograms are rotated into the vertical (Z), radial (R) and transverse (T) coordinate system using back azimuth information (Fig.2). The waveforms corresponding to both the sources are marked by the apparent velocities of the phases of interest, computed using the source-receiver coordinates. While the vertical components are used for the direct P and Lg waves, the transverse components are used for analyzing S-waves. Spectra of the P, S and Lg phases have been computed by applying the fast Fourier transform to data within a time window encompassing the phase i.e., a few seconds before and after the phase. The displacement spectra are then corrected for geometrical spreading, site effects, radiation pattern and frequency dependent attenuation due to the travel path. The frequency dependent attenuation is corrected based on a power law, $Q = Q_0 f^\eta$, where Q_0 is Q at 1 Hz and η is the term denoting frequency dependence. Q_0 is related to the extent of heterogeneity in the medium, whereas η represents tectonic activity. In this study, attenuation values of P, S and coda waves in north-western Himalaya given by Kumar et al., (2005), Parvez et al., (2012) are adopted for P, S and Lg phases respectively. Here, we derived the seismic source parameters utilizing a grid search method. The amplitude spectra of body waves are used to obtain source parameters such as seismic moment and source dimensions (Hanks and Wyss, 1972). When presented on a logarithm scale, the displacement spectra reveal two characteristics; a flat portion at lower frequencies that can be fit by a straight line parallel to frequency axis and inverse decay with square of frequency, at higher frequencies. The amplitude of the flat portion of the spectrum yields seismic moment and the intersection of higher and lower frequency trend gives the corner frequency. Further, the crack radius and stress drop are calculated from estimated moment and corner frequency. The far field displacement spectra for one corner frequency model is given by (Abrecrombie, 1995)

$$D(f) = \frac{D_o\, e^{-(\pi f t/Q)}}{[1 + (f/f_c)^{\gamma n}]^{1/\gamma}} \qquad (1)$$

D_o= mean spectral amplitude for low frequencies, f_C=corner frequency, t=travel time, γ=high frequency decay rate, n=constant. Since both the sources are of moderate size, we can safely approximate them to represent the Brune's model (Brune, 1970) that assumes n=2 and γ=1. For the Lg phase, the displacement equation (1) is modified by replacing the travel time t by the term D/V_{Lg}, where D, is the epicentral distance and V_{Lg} is the group velocity of Lg wave (~3.5 km/s in the present case). For body waves, the static stress drop $\Delta\sigma s$ is calculated using the circular crack model (Eshelby, 1957) using the relation $\Delta\sigma s = (7/16)M_0/r^3$; where, crack radius, r = mVs/ fc. Here, m is considered to be equal to 0.21 for S waves and 0.24 for P-waves (Madariaga, 1976). The moment magnitude is calculated from seismic moment using the relation M_W= 2/3M_0 – 6.06 (Hanks and Kanamori, 1979), where, M_0 in Nm.

DISCRIMINATION BETWEEN EARTHQUAKE AND EXPLOSION

The discrimination between an earthquake and a nuclear explosion is an important problem faced by seismologists. Although quite a large number of discrimination methods are in vogue, they are not effective at all distance ranges. It is well recognized that (i) earthquakes are mostly of tectonic origin, due to relative motion between two blocks, whereas a nuclear explosion leads to a sudden release of energy, mainly in the form of heat (ii) though seismic waves are generated by both these sources, the nature of the observed seismograms are quite different, (iii) usually, an earthquake gives rise to strong S-waves but such phases are not clear for underground explosions (Fig.2), (iv) in the case of nuclear explosions the surface waves are weaker compared to those due to an earthquake, (v) the impulsive nature of the P phase is dominant in the seismograms of explosions (Fig.2). The discrimination is simpler in the case of a high-energy explosion, where the ratio of body (m_b) and surface wave (M_S) magnitudes can be effective (Douglas et al., 1974; Stevens and Day, 1985). However, for events of intermediate and low magnitude, techniques employing P/S amplitude ratios are known to effective for regional distances (i.e. Pn/Lg, Pn/Sn, Pg/Lg, Pg/Sn) in different environments (Bennett et al., 1989; Richards and Kim, 1997; Kim et al., 1993, Kim, 1987; Walter et al., 1995; Taylor, 1996; Taylor and Hartse, 1997; Hartse et al., 1997; Bottone et al., 2002; Fisk, 2006). Spectral P-wave amplitude method (Ericsson, 1970; Basham and Whitham, 1971; Dahi and Hassib, 2009) and coda studies (Su et al., 1991; Hartse et al., 1995) are also used as discriminants.

In nuclear explosion monitoring, the spectral ratio of P and S waves (P/S) is an effective discriminant at high-frequencies, but not so at low frequencies. However, use of regional phases makes it more reliable and accurate. Using the data from station NIL, Pasyanos et al (2001) used the m_b:M_S technique to separate a nuclear explosion from 28 earthquakes located near the explosion station NIL. Using short period data from the same station NIL, Rodger and Walter (2002) tried to discriminate a nuclear test from a nearby earthquake using the P/S ratios technique. They observed appreciable separation for the Pn/Lg and Pn/Sn ratios at frequencies in the range of 0.5-2 Hz but poor discrimination for Pg/Lg. Further, Pasyanos and Walter (2009) observed that use of P- and S- waves attenuation model of the lithosphere reduces the scattering in the P/S ratio and improves discrimination. The Pn/Lg discriminant at 1–2 Hz pass-band is obtained using broadband data of station NIL for earthquakes and the 1998 Indian nuclear explosion.

In the present study, the spectra of regional phases and their ratios to diagnose the nature of the source was utilized. Figure 3 shows the spectra of P, S and Lg phases (details of spectra are given in the subsequent section). It is clearly seen that the amplitudes of the P-wave spectra of the explosion beyond 1 Hz are 1-2 orders higher than those of the spectra of earthquakes. The S- and Lg phases indicate stronger energy in earthquake waveforms compared to those of the nuclear explosion. In all the cases the picked signals are beyond a threshold S/N ratio of 2. It is also clearly seen that the respective spectra of each phases are much larger in amplitude than their noise components (see in the top subplots of Fig.3). Figure 4, depicts the spectral ratio of the regional phases. The Pn/Lg (Fig.4a) for NE and EQ are quite distinct and are well separated in almost all the frequency bands of our analysis. Each spectra are fitted by a low order polynomial to estimate the trend of their variations. Further, the Pn/Sn ratio (Fig.4b) also have distinct characteristics within the analysis window. Hence our observations reiterate that the nuclear explosion has prominent compressional waves than the shear wave

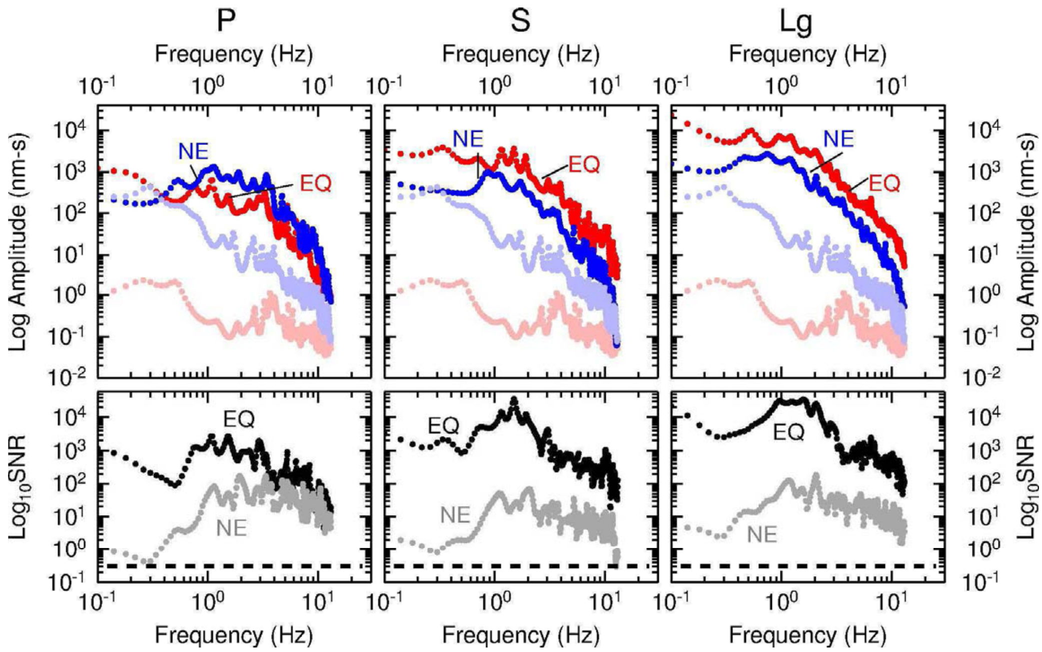

Fig.3. Signal to noise ratio analysis of P, S, and Lg phases for earthquake (red) and nuclear explosion (blue) are displayed. Each phases are indicated at the top of each sub-plot. The upper half of each panel represents the displacement spectrum (darker color) of respective phase and noise spectrum (light color). In the lower panels represent the signal to noise ratio in logarithmic scale for both the sources i.e. black: earthquake and gray: nuclear explosion. The dash line indicates threshold signal to noise ratio of 2.0.

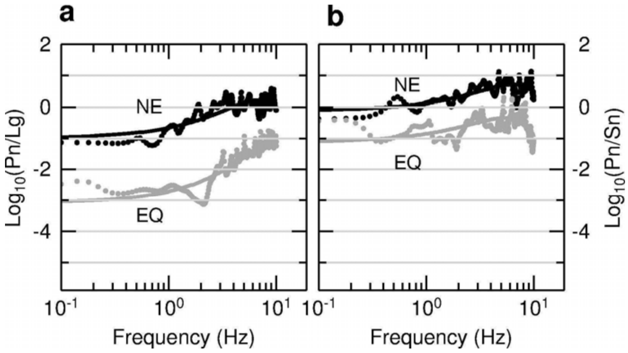

Fig.4. *S*pectral ratios (Pn/Lg and Pn/Sn) for the nuclear explosion (black) and the earthquake (gray). Pn/Lg and Pn/Sn ratios for explosion are higher than that of the earthquake. Discrimination between both kind of sources is clearly seen for all frequency range. However, for Pn/Lg separation is less for higher frequency but for Pn/Sn lower frequency (<0.2 Hz) both the sources are indistinguishable.

components. Also the generation of surface waves is quite low in amplitude in nuclear explosion than the earthquake source.

These types of discrimination discussed above are quite effective, however, one should also keep in mind the limitations of the interpretation which may be sometimes highly biased. The most important point is that the physical basis of these discriminants is not firmly established, and regional phases can be strongly affected by the heterogeneous structure of the lithosphere. Therefore, it is important to calibrate these discriminants at each of the monitoring stations. Lack of ground truth data for explosions further complicates calibration and discrimination using seismic waveforms.

SPECTRAL ANALYSIS FOR SOURCE PARAMETERS

The dynamics of earthquake and explosion sources can be studied with the help of source parameters. Displacement spectra are typically analyzed to estimate source parameters viz. seismic moment, corner frequency, stress drop, source radius, and moment magnitude. In the present study, we compute the spectra of P-waves arriving in a time window of 7 sec (1 sec prior to P) using Fourier transform. In the P wave spectrum, the amplitudes are higher for the explosion compared to the earthquake. On the contrary, the spectral amplitudes of S and Lg waves are less for the explosion. Since, weak S and Lg phases are observed for explosion data, we limit our analysis to the P phase only. Here, we employed a grid search scheme to estimate the source parameters. All possible values of seismic moment and corner frequency are generated in a grid space. For each pair, the theoretical displacement curve is obtained and compared with the observed one using equation (1). The pair that yields minimum least square error is considered as the optimal estimate. The error function is represented by,

$$E = \sqrt{\frac{\Sigma\,[D_{obs}(f) - D_{th}(f)\,]^2}{n}} \qquad (2)$$

where, $D_{obs}(f)$ and $D_{th}(f)$ represent the observed and theoretical displacement spectra, n is the number of data points. The best fit between the observed and theoretical is shown in Figs.5a and 5b for the earthquake and nuclear explosion respectively. Once the fit attains the minimum root-mean square value, we select those parameters as our estimated values. Baruah et al. (2015) demonstrated the effect of various parameters on the estimation of source parameters on the displacement spectra and suggested that the crucial input parameter is the attenuation value along the path. Hence the path attenuation from the published data was taken (Parvez et al., 2012).

From the estimated seismic moment and corner frequency the values of source dimension, stress drop and moment magnitude are obtained using empirical relationships and indicated in Table 2. The analysis reveals that the earthquake has a moment of ~$1.26\text{X}10^{17}$ (Nm) with a corner frequency of ~0.85 Hz, while for the explosion these values are ~$1.58\text{X}10^{17}$ (Nm) and ~1.18 Hz respectively. The static average stress drop for the earthquake is found to be ~41.25 MPa with an average source dimension ~1 km. The explosion has a slightly smaller source dimension of ~0.8 km. Using the relation of Hanks and Kanamori (1979), we estimate M_w for the earthquake and

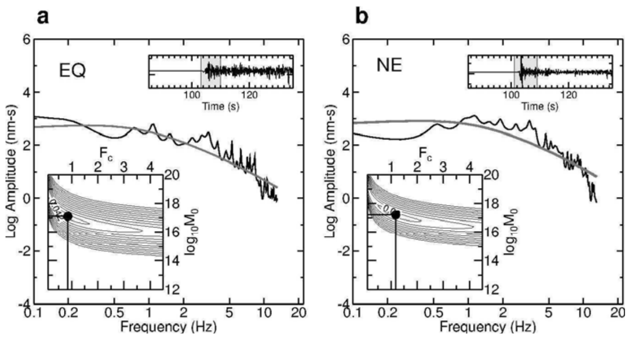

Fig.5. Spectral analysis of P phase to estimate source parameter. The black zigzag curve is the instrument corrected Fourier displacement spectrum of the P-phase for **(a)** earthquake and **(b)** nuclear explosion. Grid search result is shown by contour lines with estimated optimal parameters (moments and corner frequencies). The gray curve is the best theoretical fit for observed displacement spectrum. The gray shaded portion on the seismogram (as inset) show the P-wave time window taken for spectral estimation.

Table 2. Source parameters of the nuclear explosion and the earthquake estimated using a grid search method

Event	$Log_{10}M_0$	F_C (Hz)	Crack radius (km)	Stress drop (MPa)	M_W (present)	M_W (CMT)	M_S (present)
NE	17.2	1.18	0.793	-	5.4	-	3.57
EQ	17.1	0.85	1.101	41.25	5.3	5.1	4.31

explosion to be ~5.3 and ~5.4 respectively. Our estimate of the earthquake moment is comparable to the value of 5.1 reported in the Harvard CMT catalog. No such estimate exists previously for the explosion. Comparison of the displacement spectra of both the earthquake and nuclear explosion reveals higher corner frequency compared to an earthquake of similar moment. At higher frequencies, both the explosion and earthquake spectra decay proportional to the inverse of square of frequency (Aki, 1967; Brune, 1970; Wyss et al., 1971).

SURFACE WAVE MAGNITUDE

Magnitude determinations play an important role in the identification of earthquakes and explosions. Estimation of seismic moment, source radius and magnitude provide clues about the strength of the nuclear explosion and hence the yield, which is a key parameter in calibration of nuclear explosions. In the case of an explosion of comparable magnitude, the energy is mostly concentrated in higher frequencies (Kebeasy et al, 1998; Gupta et. al., 1999; Bonner et al., 2008), in contrast to energy that spans a wide range of frequencies during an earthquake. This in-turn implies that the earthquake possesses higher surface wave magnitude (M_S) than the explosion of same body wave magnitude (m_b). This observation is also supported by results from the present study (Figs.3 and 4). In order to estimate the surface wave magnitude, the Gutenberg (1945) relationship was used. At 20sec period, the maximum surface wave amplitude was measured to estimate M_S using the relation $M_S = a + b \log(\Delta) + \log(A/T)_{max}$. Here, a and b are constants depending on the region. Δ is the epicentral distance and A is the maximum amplitude in microns corresponding to a period T in seconds. However, such relation is strongly biased by the geology and tectonics of the region of interest. For the Indian scenario, Roy et al (1999) proposed a calibration formula $M_S = 2.75 + 1.51 \log(\Delta) + \log(A/T)_{max}$. Our estimated M_S value for the earthquake and explosion are ~4.31 and ~3.57 respectively. These estimates are quite consistent with those obtained earlier for the nuclear explosion (Roy et al., 1999 and Sikka et al 2000). Using the same station NIL, Douglas et al (2001) estimated the Ms value for the Indian nuclear explosion to be 3.2.

YIELD

The yield for the Pokhran nuclear explosion using the surface wave data from station NIL was estimated. The estimated yield of the underground nuclear explosion using the surface wave magnitude is ~50 kt. There are quite a large number of relationships to estimate yield from M_S (see caption of Figure 6 for various relationships). In this study, we use the M_S -Y relationship given by Murphy (1977) i.e. $M_S = 2.14 + 0.84 \log(Y)$ for Y<100 kt. Earlier, disparate estimates of the yield of the Indian nuclear explosion were obtained by different workers; ~60 kt (Sikka et al., 1998; Roy et al., 1999; Sikka et al., 2000), ~36kt (Zhao et al., 2005), ~15-20 kt (Douglas et al., 2001; Barker et al., 1998; Wallace 1998). Figure 6 depicts the yield estimates using different M_S relations for various nuclear explosion data. It is clear that most of the relations reasonably explain the

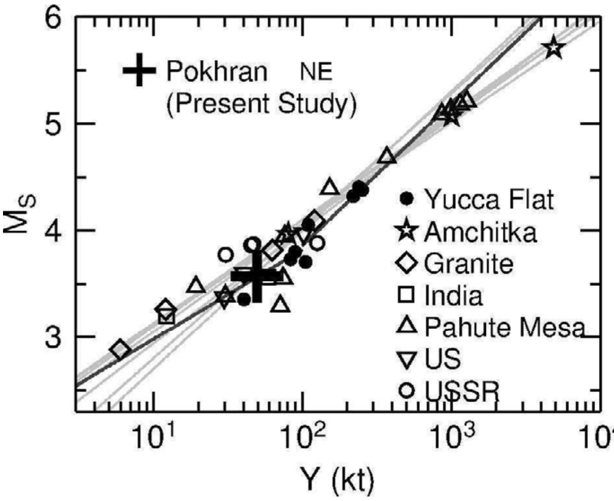

Fig.6. Various empirical magnitude (Ms)–yield (Y) relations* (gray thin lines). Worldwide estimation of yields from different nuclear explosion are also shown in different symbols (Marshall et al (1979). For comparison, our estimate of yield for Pokhran explosion from the present study using single station is denoted by thick black cross and that is quite consistent with the already reported values. The relationship used in the present study is by Murphy (1977) denoted by dark line.

* various Ms-Y relationships are,

a) Ms=2.16+0.95logY (Sykes and Cifuentes, 1984)
b) Ms=2.16+0.97logY (Sykes and Cifuentes, 1984; Marshall et al., 1979)
c) Ms=1.88+1.06logY (Marshall et al., 1979)
d) Ms=1.40+1.30logY (Evernden and Felson, 1971)
e) Ms=2.05+logY (Bache, 1982); Ms=1.56+1.24logY (Basham and Horner, 1973)
f) Ms=2.1+logY (Stevens and Murphy, 2001)
g) Ms=1.2+1.33logY for Y> 100; Ms=2.14+0.84logY for Y< 100 (Murphy, 1977)

observed data. However, at the lower and higher yield values they differ significantly in some cases. Murphy (1977) provided a relationship separately for yields below 100 kt and beyond 100kt.

As a note, it is emphasized that the yield estimation in the present study and recently done by others are based on the surface wave magnitude. In earlier days the yield estimations were mainly done using the body wave magnitude, but the body waves such as P waves generated in an explosion are effected by destructive interference (Sikka et al., 2000) and hence require corrections to compensate such phenomena. Moreover, the yield estimates using body waves differ from those obtained using surface waves which yield reliable estimates. On the contrary, Rayleigh waves from nuclear explosions are weak and generation of secondary surface waves due to tectonic stress release during an explosion make the yield estimation more complex (Stevens and Murphy, 2001). Yield estimation from M_S is accurate only when the event is large and at a closer distance.

CONCLUSIONS

The near and far field seismic displacements recorded by a seismic sensor are sensitive to the uncertainties in seismic magnitude and attenuation due to varied geology along the path and hence any quantification of the earthquake sources or calibration of nuclear explosions are not straight forward in the intermediate to regional distance ranges. Therefore, in order to calibrate the seismological data of the 1998 Pokhran nuclear explosion, we first studied the earthquake source and path characteristics using data of an earthquake of magnitude 5.1 Mb that occurred in the vicinity of the explosion site recorded by station NIL. We argue that such type of comparison of the source parameters places tighter constraints on the possible strength of the nuclear explosions. Since the present study has been done using single station-receiver pair, however, the good signa to noise ratio of our selected waveforms provide a consistent values of the various parameters. In the near future, we feel that such type of studies using many stations-events may provide a robust estimate.

The spectra of regional phases are used to compare the source parameters of the nuclear explosion and the earthquake using the seismograms and discriminate the passive and active sources. The discrimination is quite clear in all frequency bands of the waveform. Spectral analysis of both the sources reveal consistent source parameters. The earthquake and explosion have moments of ~$1.26X10^{17}$ (Nm) and ~$1.58X10^{17}$ (Nm) respectively, while their corresponding corner frequencies are ~0.85 Hz and ~1.18 Hz respectively. The static average stress drop for the earthquake is estimated to be ~41.25 MPa with source dimension of ~1 km, which is slightly higher than the source dimension of the explosion (~0.8 km). Further, the M_w for the earthquake and explosion are estimated as ~5.3 and ~5.4 respectively. The M_w estimate for the earthquake is comparable to that reported in the CMT catalog (5.1), lending credence to our M_w estimate for the explosion, which was hitherto not available.

The study of the surface wave magnitude reveals a higher value for the earthquake compared to the explosion, although the body wave magnitudes are similar. As described in the previous section, m_b:M_S technique provides an effectively discriminatory factor between earthquake and explosion. The present study supports the higher m_b:Ms for an explosion compare to an tectonic earthquake (Tables -1 and 2), akin to the previous observation from global studies (Steven et al., 1998; Steven and Day, 1985; Marshall and Basham, 1972; Levshin and Ritzwoller, 1995 etc.). Our estimate of the yield of the explosion based on the yield versus M_S relationship of Murphy (1977) is ~50 kt. From the study of the source parameters of the earthquake and comparison with that of the nuclear explosion, it is felt that the calibration of the nuclear explosion based on various uncertain parameters is not a straightforward task; however, comparing with the passive sources may provide some insights.

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