European Journal of Applied Sciences 1 (4): 47-52, 2009
ISSN 2079-2077

Discriminating Nuclear Explosions from Earthquakes at Teleseismic Distances

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Abstract: The discrimination between nuclear explosions and earthquakes is an important issue for the verification of compliance with a Comprehensive Test Ban Treaty. Several diagnostic techniques are examined for identifying earthquakes as events distinct from possible underground nuclear explosions. It has been suggested that, the differences between explosions and earthquakes are due to differences in source dimension, source time function, source mechanism and focal depth, or to combination of these. For relatively large magnitude events, effective discrimination appears to be possible at teleseismic distances. Several discriminations have been checked using Egyptian seismic stations (ESS) data. Complexity method has been used as a diagnostic aid for discrimination between natural earthquakes and nuclear explosions. It was found that, the complexity of natural events (earthquakes) is higher than of artificial events (explosions), therefore, natural earthquakes are more complex than nuclear explosions at teleseismic distances and separation is clear between both of them. Also, separation between earthquakes and explosions is observed clearly in the relation between body to surface- wave amplitudes.

Key words: Discrimination · Complexity method · Amplitudes · Artificial events

INTRODUCTION

Explosions happen instantaneously, in one spot, sending out seismic waves of approximately the same strength in all directions. Earthquakes typically occur when rocks slide against each other over a relatively wide area for a longer time and, as a consequence, will send out different seismic signals in different directions. The differences between these processes often can be seen in the observed seismic waves and used to distinguish earthquakes from explosions. The seismological differences are many bet not all of them are observable at large distances or are applicable to every earthquake and explosion. The basis of all discrimination criteria is the great difference between earthquakes and explosions as regards their relative generation of short and long period waves. Different techniques used for discrimination between nuclear explosions and earthquakes were reviewed by many studies [1-8]. From a physical point of view, it is expected that the spectra of earthquakes is more complicated and appears very different from those of explosions. Also, the energy released in the case of a natural earthquake is distributed in large frequency range. On the contrary, for explosions, energy is concentrated at higher frequencies. For nuclear test ban verification, reliable and efficient identification methods are essential. In recent years international seismic centers have located approximately 15000 events annually [9]. Discriminating possible nuclear tests from this number of events is a difficult task that has attracted the attention of many researchers during the last few decades. Several methods have been developed for seismic discrimination and a large amount of literature exists concerning the classification of seismic events [10-12]. The main focus of classification to day is on relatively weak events at regional distances. However, all areas are not within regional distances from closest seismic station. There still exist vast areas with insufficient station coverage for reliable regional seismic discrimination. Also, it is not guaranteed that data from all stations are always accessible. Consequently, there exists a need for seismic discrimination of teleseismic events, which is the scope of this study. Firing of a sequence of shots makes the P- wave from look complex like an earthquake and distorts the mb: Ms relationship if the size of explosions is steadily increased. The waveform complexity, describing the duration of the P- wave, seems to be critically dependent on focal depth, so that deep earthquakes have lower complexity values similar to explosions [13]. While complexity has been studied as a teleseismic discriminant

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[14-16], it has not been generally though that complexity could be applied at regional distances. However *Blandford* [17] has presented signals from events in Scandinavia that suggest that complexity could be used as a discriminant.

Description of Helwan and Aswan Seismic Stations: Registration of the seismic activity in Egypt started by the turn of last Century, in 1898. At Helwan (near Cairo, Egypt) two photographic recording World- Wide Standard Seismograph Systems (WWSS) were erected in 1962. A new seismological station containing a short- period moving coil seismograph with frequency analyzer and visible recording system (SP- FS) was installed on the same vault of the World- Wide Standard Station and operated at the end of 1972 [18].

By the end of 1975, a complete seismic station, with both long and short period seismograph system was installed at Aswan in the south. At Aswan station there are two sets: One set is long period of three components- vertical CVK- D and two horizontal CHK- D. This set was installed for recording seismic waves of far distant earthquakes and having a wide period band from 0.2 to 25 seconds with constant magnification of 1000. The other set is a short period of three components: One is vertical type CVKM- 3; the other two are horizontal type CHKM- 3. This set was installed to record seismic waves of near and local events.

Data Used and Magnitude Determination: The data set for this study consists of 19 nuclear explosions and 23 natural earthquakes in the magnitude range of about 4.7 to 6.6 recorded at Helwan and Aswan seismic stations operated by Egyptian National Seismological Network (ENSN). The events were selected from the International Seismological Center (ISC) and Earthquake Data Report (EDR) for the period from 1982 to the end of 2005. The propagation paths for these events range from approximately 17 to 86 Degrees.

Body- wave magnitudes were determined from long- period, vertical component seismograms at teleseismic distances, using one half the largest peak to peak motion found in the first 3 cycles of the P- wave at maximum amplitude. In this study, the body- wave magnitudes (mb) have been calculated by using the following formula [19]:

$$mb = \log (A/T) + Q + S$$

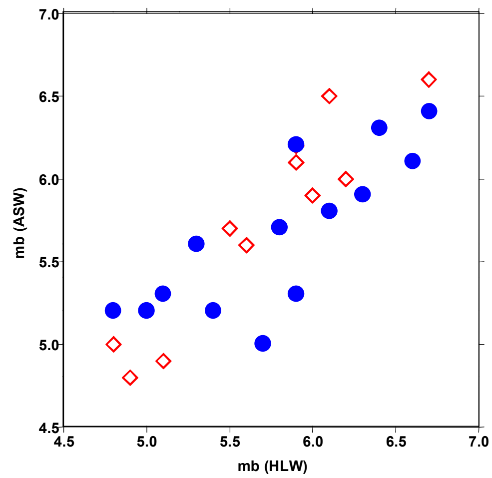

Fig. 1: Relationship between calculated mb (HLW) and mb (ASW) for the selected earthquakes (blue circle) and nuclear explosions (red square)

Whereas, A is one half of P- wave amplitude reduced to ground motion in microns, T is the period in seconds, Q is the distance- depth factor and S is the station factor.

Surface- wave magnitudes were determined from the amplitudes of the vertical component Raleigh waves and the standard IASPEI formula was, namely

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

Where Δ is the epicentral distance from the events to the station in Degrees and A/T is in microns per seconds.

Figure 1 is a plot between Helwan body- wave magnitudes mb (HLW) and those determined by Aswan seismic station mb (ASW), for the explosions and earthquakes used in the present study. Although there is some scatter in the data, but is a general agreement between them can be seen, especially in the large magnitude range. The scatter can be attributed to the difference in nature of the source whether natural or artificial and it should be affected by the local structure around the station. The third factor which may partially cause this scatter is the azimuthal difference in the ray path from the location of the event to Helwan or Aswan seismic station.

THE DISCRIMINATION METHODS

One of the most important problems in seismic monitoring is distinguishing underground nuclear explosions from other seismic sources. If a seismic event is large, the problem of discrimination is fairly straightforward. Explosions release their energy in a very small volume and produce primarily P- waves. In contrast, earthquakes represent the motion of blocks along a fault; the source dimensions are much larger for a given size than for an explosion and earthquakes produce large S- waves [20].

The reasons for identification are still not perfectly understood, it is suggested that the nature of the long- term displacement at the focus of an event control the marked differences in excitation of surface and body waves. Three various methods were used for the identification between earthquakes and nuclear explosions by using the records of Helwan and Aswan seismic stations, these methods are:

- Complexity method.
- Spectral P- wave amplitude method.
- Body- wave to surface- wave amplitude (Ap/As) method.

RESULTS AND DISCUSSION

Complexity Method: It is depends mainly on the displacement made by different frequency seismic waves. Complexity © can be calculated numerically by comparing the energy carried in the first five seconds of the seismogram of natural or artificial event. The following equation was used to calculate the complexity after Kelly [21] and Bormann [22].

$$\text{Complexity © } = \sum_{t=5}^{t=35} Am / \sum_{t=0}^{t=5} Am$$

Whereas, Am denotes the double amplitude as a function of time from one station for an event. The double amplitude Am in the formula varies with the type of recording station employed. Complexity © was calculated for the selected events after measuring the P- wave train amplitudes (from the first onset till 35 seconds) from Helwan and Aswan seismic stations. The complexities calculated from these stations are called C (HLW) and C (ASW) respectively.

To have a clear picture for the power of complexity method for identifying seismic events, the relationships between complexities © calculated at HLW and ASW stations are given in Figure 2. Also the relationship between mb and complexity for Helwan and Aswan stations are shown in Figure 3.

It is clear from complexity relationships that, there is no any confusion between the two different populations of earthquakes and nuclear explosions. The best discrimination between them is obviously clear in Figures 2 and 3. The discrimination is easier when mb is higher than 5.6. Also, the relation between P- wave magnitudes mb and complexity can be seen that, the complexity of earthquakes is higher than of the explosions, i, e. earthquakes are more complex than explosions and separation is clear between them.

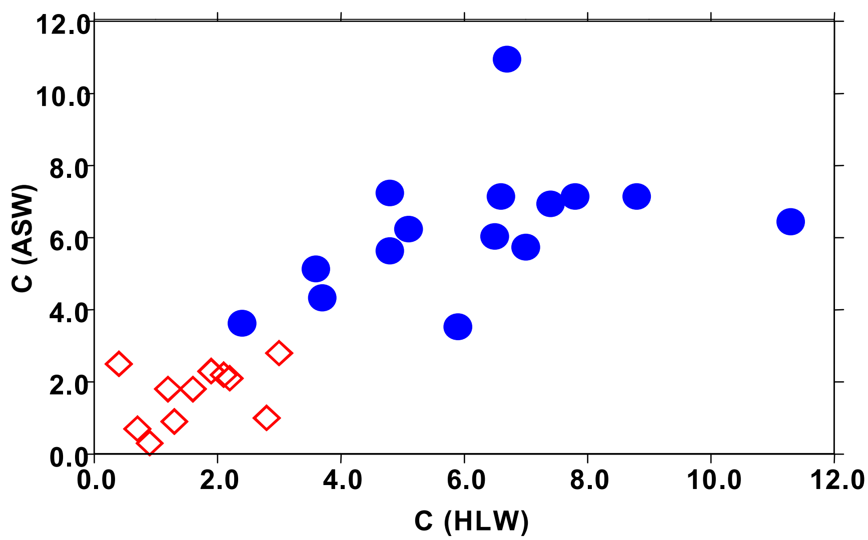

Fig. 2: Relationship between complexities calculated at Helwan and Aswan seismic stations for the selected earthquakes (blue circle) and nuclear explosions (red square)

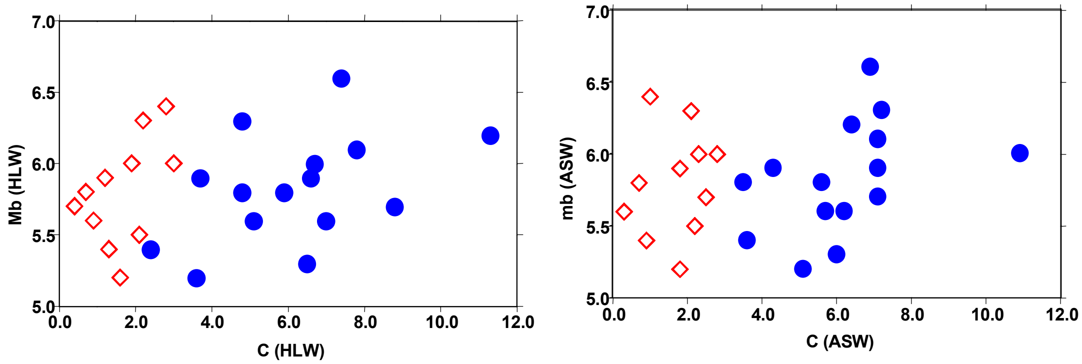

Fig. 3: Relationships between complexities and mb for Helwan and Aswan station

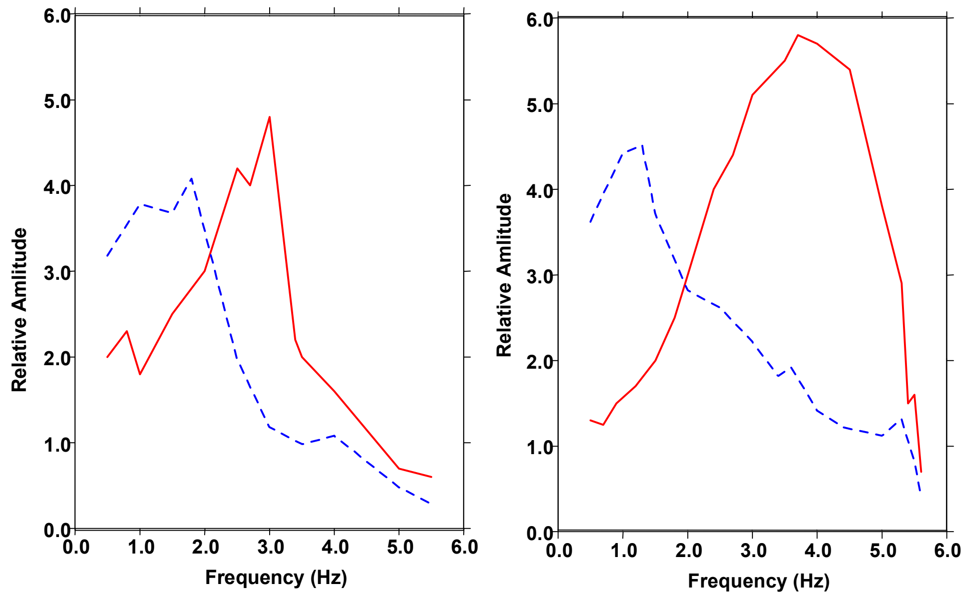

Fig. 4: Amplitude spectra from Helwan and Aswan seismic stations for explosions (Red line) and earthquakes (Blue line)

Results of individual discriminants are comparable to those *Taylor and Marshall* [23] presented for spectral ratios. When all the discriminants from all stations were examined a large variation in discrimination capability was found. Differences between Helwan and Aswan seismic stations were more significant.

Spectral P- Wave Amplitude Method: This method examined by many researchers [24,25] indicated that, one of the most useful diagnostic aid to distinguish between earthquakes and explosions is by using the relative amplitude of surface- waves that are generated for a given short- period P- wave signal.

Molnar and Wyss [26] reported that the best criteria for discrimination between earthquakes and explosions are based on spectral differences. At high stress drop, earthquakes radiate signals that are more similar to explosions than those radiated by lower stress events.

Figure 4 shows the relationship between frequency and relative amplitude of P- wave for nuclear explosions and natural earthquakes from the seismograms of Helwan and Aswan seismic stations. It is appeared that, the spectra were normalized and summed together to get a general view of frequency content of earthquakes and nuclear explosions obtained with each type of spectral computation. The summed spectra were used to select the frequency windows for spectral discriminants. These spectra for Helwan and Aswan stations are shown in Figure 4. The most profitable windows were selected automatically by testing all possible frequency ranges. Results varied considerably from station to station. The Helwan and Aswan stations seemed to have the strongest discrimination capability at low frequencies.

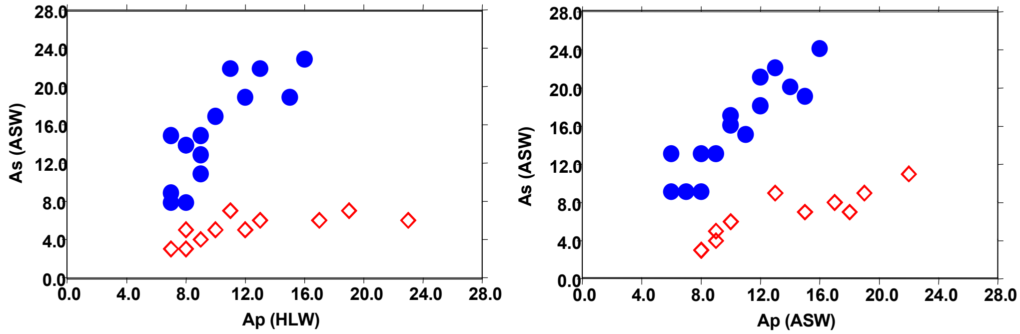

Fig. 5: Relationship between Ap and As for explosions (Red square) and earthquakes (Blue circle) at Helwan and Aswan seismic stations

Body to Surface Wave Amplitude Method: The ratio between body- wave amplitude (Ap) and surface- wave amplitude (As) is used for investigating the natural and artificial events. *Dahy et al.* [8] studied the discrimination between quarry explosions and local earthquakes occurred in Southern Aswan city using body to surface wave amplitude method. They were able to discriminate between them at local distances.

In the present study, the nature of interrelations among Ap- As for natural earthquakes which occurred in Asia and nuclear explosions fired in Former Soviet Union and China was investigated. By applying the relationship between body to surface wave amplitudes (Ap: As) from the records of Helwan and Aswan stations for the selected events (Figure 5). Figure 5 indicates that, nuclear explosions are clearly distinguished from natural earthquakes, especially in the large magnitude range where local effect on amplitude determination is considered to be minor. Since these events have almost the same epicentral distance from Helwan or Aswan station and lie in the same azimuth, then the separation can be mainly attributed to the difference in the source nature. Generally, it is observed that, body- wave amplitude for explosions are greater than those of earthquakes. Also surface- wave amplitude for explosions are less than those of earthquakes. This result can be explained that, in case of nuclear explosions most of the energy released is confined in the range of high frequency waves. On the contrary, for earthquakes the energy released is distributed in the large range of frequency. The degree of separation between earthquakes and explosions can change from region to region, but a generally valid observation seems to be that shallow earthquakes and underground explosions, with only few exceptions, exhibit different Ap (As) ratios. The parameters that influence the Ap (As) relation also seem to be understood.

In conclusion, the discrimination methods presented in this study was capable of correctly classifying nuclear explosions from the Former Soviet Union and China Test Sites and earthquakes from Asia Continent. The three basic discriminants that were employed were complexity, spectral P- wave amplitude and body to surface wave amplitude.

Using P- wave complexity method, it can use for identifying the two kinds of seismic events at low and high magnitude range and a good separation between earthquakes and explosions is observed clearly in this method. On the other hand, the amplitude spectra of nuclear explosions have a strong peak and simple pattern for the first onset. But in case of earthquakes, the spectra are more complicated and appear very different from those of explosions and radiation emitted by explosions should have more high frequency content than earthquakes.

From the relation between body and surface wave amplitudes determined at Helwan and Aswan long- period seismic stations as a discriminant criterion, it was possible to identify nuclear explosions from natural earthquakes.

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