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Theses of Ph.D. Dissertation

Comparative analysis of natural and artificial seismic events

Márta Marótiné Kiszely

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Ph.D. School: Kitaibel Pál PhD. School of Environmental sciences

Head of Ph.D. School: prof. Dr. Csaba Mátyás

Program: Geo-enviromental Sciences
Head of program: Prof. Dr. László Szarka

Theme leaders: Dr. Erzsébet Győri
Dr. Márton Veress
Dr. Antal Ádám

1. Preliminaries

In recent years due to increasing number of modern seismological stations more and more earthquakes and explosions have been recorded and located in Hungary. In the determination of tectonic parameters for different regions the earthquakes should be separated from the explosions. This needs to analyze and identify the separation parameters of earthquakes and explosions.

The author selected two areas for study the features of natural and man-made seismic signals. The first one was the southern area of North Hungarian Mountains and the south part of Slovakia. The Piszkéstető (PSZ) seismic station is located here, on the second highest peak of Mátra Mount. The recordings of this station were used in cases of earthquakes occurred between July 2011 and 2013. This station also regularly recorded blasts originated from eight different quarries. One goal of the thesis was to analyze these earthquakes and explosions, and to study the separation facility of these two groups.

Another selected area was the Vértes Hills and its surroundings. In the northern side of Vértes, in Oroszlány occurred one of the most important earthquakes of the past 25 years in Hungary. The M_L4.5 mainshock was followed by more than 400 aftershocks. In the middle of this area, works one quarry in Gánt. These explosions were recorded regularly together with aftershocks by nearby seismological stations. The author studied the recordings of two stations operated in Csókakő (CSKK) and in Gánt (PKSG) to determinate the parameters of earthquakes and explosions between. The earthquake and explosion data used for the analysis occurred between 2011 and 2012.

The fundamental tasks to answer the following scientific questions:

1. What parameters can characterize the earthquakes and explosions originated in the North Hungarian Mountains and south area of Slovakia?
2. What parameters can characterize the earthquakes and explosions in the area of Vértes Hills?

3. What are the most excellent methods for discrimination the explosions and earthquakes?

2. Methodology, the work performed

The author applied comparative analysis in her dissertation. The recordings of PSZ station were used to analyze the earthquakes of North Hungarian Mountains and compared to explosions originated from eight different quarries. Temporal stability of parameters of earthquakes was also examined by comparing earthquakes data of two consecutive periods.

The blasts of quarry in Gánt were studied by seismograms of two nearby seismic stations CSKK and PKSG. The large number of events made possible to split the events into two parts in case of explosions and earthquakes too. The aim was to control the temporal stability of the parameters.

The author applied three groups of methods to analyze the characteristics of earthquakes and explosions.

1. Location of epicenter, depth, and temporal distributions.
2. Waveform analysis:
    a. Investigation of first motion polarity of P wave: compressional or dilatational.
    b. Analysis of amplitudes of P, S and Rg phases and their different amplitude ratios (filtered and unfiltered).
    c. Waveform correlation analysis.
3. Spectral analysis of different parameters included the following:
    a. Examination of modified spectrum caused by the ripple firing blasting technique. Study of the binary spectra and scalloping of spectra.
    b. Spectral slope and spectral ratio between the lower and higher frequency ranges, and the ratio of average and maximum value of the spectrum at given frequency range.

The author applied the Mahalanobis Distance (MD) for mathematical method that provides a relative measure of a data point's distance (residual) from a common point. The MD calculation was used to determine which parameters and their combinations proved the most suitable for the separation of earthquakes and explosions. Several uncertain or interesting events were discussed in both areas.

Hypocentral parameters of seismic events were published in the Hungarian Earthquake Bulletin for years between 2007 and 2013 and in the Hungarian National Seismological Bulletin 2011 and 2012 volumes.

The epicenter errors were determined by SEISAN seismic processing software. The waveform correlation studies were carried out in the MATLAB environment, with Gismo program package. The statistical Mahalanobis distances for different parameter combinations were also calculated using MATLAB function. The indication map of quarries was determined with zmap MATLAB program package. The maps were made using GMT (Generic Mapping Tools).

3. Results

3.1. General conclusions based on the location of the events:

In 10 km radius of the mines, there have been seemingly blasting events that were not certified by the mining authority. The errors of the calculated epicenters of the explosions sometimes reached of 5-10 km.

The confidence ellipses of epicenter calculation were highly elongated and in most cases the major axis was perpendicular to the straight line connected the permanent stations. The error in some cases was as high as 15 km.

The calculated depth of explosions in more than 90% occurred at 0 km. In the North Hungarian Mountains 5% and in the Vértes Hills 18% the earthquakes occurred shallower than 1 km.

The discrimination of earthquakes and explosions was not possible on the basis of the hypocenter data because of occurrence shallow earthquakes and the large horizontal error of epicenter.

3.2. Temporal distribution:

Most of the explosions in the North Hungarian Mountains and every explosion in the Vértes Hills were executed at workdays. For both areas could a time window could be defined when most of the explosions happened. A significant part of the earthquakes (the North Hungarian Mountains 36%, in the area of Vértes of 15%). occurred in this time window. However, the origin time of the event, does not provide sufficient information to filter out the explosions from catalogues.

The magnitude of half of the registered earthquakes was smaller than M_L=0.2 due to the very close stations to aftershocks (5-10km) in the region of Vértes. The diurnal distribution of M_L<0.2 earthquakes was affected by cultural noise of the area, at night more small events could be detected. From the nightly number of earthquakes – assuming uniform earthquake distribution 44% earthquakes M_L<0.2 missed from the daytime period.

The number of earthquakes originated deeper than 2 km was less at daytime hours. The registration circumstances of deeper events were favorable at night. The author estimated that 33% of the earthquakes deeper than 2 km were missed from the daytime period.

In the Vértes Hills a threshold magnitude (M_L = 0.2) could be defined, below which the daily registration circumstances became worst.

3.3. Analysis of arrival direction of P wave:

Theoretically the first arrival of the compressional P wave is expected - due to the impulsive and isotropic characteristics of explosions - at every station. In the North Hungarian Mountains the P wave arrival directions showed no significant difference between the earthquakes and quarry blasts. Similar number of compression and dilatation direction appeared in both classes. Uncertain arrivals showed up at the third of explosions, and almost the half of earthquakes.

In the case of explosions of quarry in Gánt the directions of P wave received on both stations were largely (over 75%) compressional, but some dilatational occurred also.

The direction of the P wave arrivals alone did not prove an appropriate parameter to discriminate earthquakes and explosions because of numerous observed dilatational first directions for explosions, and because of the uncertainty of the arrivals.

3.4. Amplitude analysis of the different phases:

It has been showed that the most effective discrimination result between the explosions and earthquakes were achieved by using the unfiltered P and S wave phases. In the case of Rg surface wave, the best separation showed in the filtered amplitude data between 0.5-1.5 Hz.

70% of the explosions and over 90% of the earthquakes of North Hungarian Mountains separated statistically properly from the other group using the P, S and Rg amplitude values and their different ratios in combination.

The successes of separation from earthquakes based on the amplitude data altered in the case of different quarries. The quarries of Nagydaróc and Nagylóc showed the best discrimination of characteristics of earthquakes, while the less discrimination showed the quarries of Bercel and Gyöngyössolymos.

In the case of the seismic events in the Vértes Hills, the statistical Mahalanobis distances between explosions and earthquakes based on P, S and Rg amplitude values separation was inadequate. The reason is that the amplitude parameters of the explosions at CSKK station almost and in case of PKSG station partially showed the values of earthquakes.

The explosions and earthquakes registered on CSKK and PSZ stations showed similar trend for S/P amplitude. The earthquakes excited more shear waves than the impulsive nature explosions. The PKSG station that is just 3 kilometers away from the quarry, the S/P ratio was higher in case of explosions due to the S and surface waves arrived almost simultaneously on the channels.

3.5. Analysis of the waveform similarity:

Major part of earthquakes has been proven similar to one another event based on the correlation analysis of waveforms recorded on different seismological stations.

The longer the distance of the station was from the epicenter the longer waveform may have been received, the phases became more separated, the P and S Coda waves developed. Therefore, the waveforms of the nearest station (PKSG) were shorter and showed more similarity to each other than the seismograms of further (CSKK) station.

The author found less similar waveforms between the explosions than between the earthquakes, despite the fact that the station, the site and depth of explosion were the same. This is because of every explosions had special pattern of charges (weight of charges, delay times and the number of holes). Unique high amplitude and low frequency Rg waveforms formed, which caused small cross-correlation values.

The explosions of different quarries formed different cluster(s). The clusters of earthquakes and explosions were never mixed with each other. Within the clusters the included events had different magnitudes; the size of seismic events did not affect the similarity.

In the case of clusters consisted of explosions of Recsk, Nagylóc and Gyöngyössolymos, appeared so seismic events that previously regarded as earthquakes or announced explosions. These events managed to connect to these quarries, so deteriorated the catalogue with misclassified explosions. Several events were included in different clusters, which hypocenter data could not be determined because of their small size, and only waveforms were available. In case of strict clusters these events could be linked to earthquakes, which had hypocenters. Thus, we got better values on the number of aftershocks.

Creating waveform database for each quarries, and continuously adding the seismograms of new blasts, a high portion of the explosions will be possible to filter out.

3.6. Result of the analysis of the spectra:

The scalloping of spectra and the time-independent modulations on the spectrograms – caused by the delayed fired technique – was observed in the most case of explosions. The presence of these signs in spectra has proven to be a good indication parameter of quarry blasts.

The analysis showed that the best separation parameter between the explosions and earthquakes in the North Hungarian Hills was the combination of *spectral slope* (between 1-4 Hz) and the *ratio of spectrum average and maxima* (between 1-10 Hz). On this basis, appropriate statistical separation showed up in 70% and 54% of the earthquakes and explosions respectively.

In the Vértes, the best discrimination was achieved by using together the spectral slope (between 2-24 Hz), and the ratio of spectrum average and maxima (between 2-24 Hz) and the spectral ratio between 1-10 Hz and 10-20 Hz rate.

In case of earthquakes recorded at CSKK station, the combination of the spectral and amplitude parameters increased the Mahalanobis distances for earthquakes significantly, but the degree of separation from explosion was not enough.

The various parameters of different quarry blasts discriminated differently from characteristics of earthquakes.

The Recsk, Nagylóc, Nagydaróc and Kisnána showed the the best discrimination while Gyöngyöstarján, Szalóc, Gyöngyössolymos and Bercel quarries showed the least ones.

The parameters of earthquakes – in the case of the two subsequent data systems, for these three seismological stations – showed that he average values of the waveform amplitude values differed greater while the spectral parameters differed lesser.

In the case of the two subsequent explosions data sets of CSKK and PKSG, the deviation of the parameters were much smaller than for earthquakes.

In the case of CSKK station the explosions and earthquakes were separated properly only for data system I on the basis of spectral data. The spectral parameters of earthquakes occurred in Gánt (2012 April)

in case of CSKK showed “blast-type” in case of PKSG showed transition values between explosions and earthquakes.

In case of the North Hungarian Hills events, the parameters of earthquakes occurred around Tenk (2013 April-July) differed from the parameters of other earthquakes. The parameters of earthquakes near to Tenk were similar to each others, and differed from the explosions.

Based on the results of the analysis, it is advisable to use longer period of data to determine the parameters of earthquakes. In the case of quarry blasts of Gánt, data were sufficient, since the values obtained from the two data systems deviated less than their standard deviation.

4. Applicability of the results

Correlation databases can be created from the blasts of different quarries, what allow reliable distinction of recent explosions and earthquakes. This method proved to be suitable for filtering a part of misclassified seismic events from the catalog. The waveform correlation analysis – in case of strict clusters – provides additional information about the spatial distributions of hypocenters.

The waveform correlation analysis is suitable for classification of several events without calculable hypocenter parameters, due to the few registering stations. We can get more accurate time distribution of aftershocks connecting these events to them.

It is possible to clean up the Hungarian catalog from explosions on the basis of the waveforms and spectral parameters for different blasts of quarries.

5. Theses

5.1

1) The use of geographical coordinates of seismic events for discrimination of earthquakes and explosions are limited due to their large horizontal errors. The use of depths of seismic events

are also limited due to the incidence of earthquakes with shallow focal depths (4% and 18% in Northern Hungary, and in Vértes Hills respectively).

2) A time window can be identified in the case of quarries when a substantial portion of the blasts occurred. However, part of the earthquakes happened in time window of the common explosions (36% and 15% in Northern Hungary, and in Vértes Hills respectively). The date of the seismic events did not provide sufficient information to filter out the explosions.

3) A threshold magnitude value (M_L=0.2) can be defined in the Vértes Hills, where the registration opportunities of smaller earthquakes have been deteriorated.

5.2

1) The direction of the first arrival of P waves for explosions in many cases were opposite to the theory: dilatational. For this reason, and because of many uncertainties first arrival directions were not considered to be a reliable separation parameter.

2) The best discrimination results were shown at the amplitude and the amplitude ratios of different phases, the unfiltered P and S phases, as well as the Rg phase was filtered between 0.5-1.5 Hz. The more phase and amplitude ratio were used together (log (Rg), log (Rg / P), log (Rg / S) and log(S/P)) the better statistical separation of earthquakes has been achieved. The blasts diverged in the degree of separation from the earthquake depending on different stations and quarries.

5.3

1) Scalloping were found in most of spectra of quarry blasts.The time-independent modulation caused by the delayed fired technique. These spectral features usually were good indications for the explosions. But because of several earthquakes with explosive-like spectra these can not be considered a reliable separation parameter alone.

2) The *spectral slope* (between 1-4 Hz) and the *ratio of average to the maximum of spectra* (between 1-10 Hz) together were proven

to the best separation spectral parameters in the case of North Hungarian seismic events.

3) The *spectral slope* (between 2-24 Hz) and the *ratio of average and the maximum of spectra* (between 2-24 Hz), and the *spectral ratio* (1-10 Hz/10-20 Hz) together were proven the best separation spectral parameters in the case of Vértes Hills seismic events.

5.4

1) Based on the correlation waveforms analysis of seismic events, the explosions of different quarries formed different cluster(s). The clusters of earthquakes and explosions were not mixed with each other. Creating waveform database for each quarries of North Hungarian Mountains, and continuously adding the new blasts, high portion of the explosions will be possible to filter out.
2) The waveform correlation analysis resulted in assigning such events into clusters that had no hypocenter parameters, due to the few registering stations in both studied regions. Connecting these events to the aftershocks sequence could reveal more accurate time distribution. Waveform correlation analysis – in case of strict clusters – provides additional information about the spatial distributions of the hypocenters.
3) Waveform correlation analysis showed that – in case of strict clusters – the distances between the members of clusters in many cases reached 15 km away from each other. The elements of strict clusters – according to the similarity theory – must be very close to each other within a few kilometers. This suggests that the error in the determination of epicenters could be up to 15 km because of the unfavorable station configuration in Vértes Hills region. Waveform correlation analysis gives additional information about the accuracy of the epicenters.

5.5

Using the waveform of phases, spectra and waveform correlation analysis of seismograms together, may discriminate the earthquakes and explosions with high reliability. However, based on the study, the most appropriate methods differ for different areas and stations.

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