DETECTION METHODS FOR MINING EXPLOSIONS IN SOUTHERN ASIA

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-FG02-01-ER83341¹ and W-7405-ENG-48²

ABSTRACT

Weston Geophysical maintains a high-quality seismic research database for southern Asia consisting of detailed mining information together with seismograms recorded from mine blasts in northwestern India, southern Pakistan and the surrounding regions. This digital mining database contains data on more than 260 mines and mineral deposits in southern Asia, including information on location, geology, commodities, production, mineralogy, references, operator, and mining explosion resources. The waveform data consists of seismograms from several stations in southern Asia including NIL, ABKT, HYB, and GBA, in addition to data from proprietary stations.

We have employed complementary techniques to detect probable mining explosions. First, we applied the waveform correlation method (Harris, 1991) to data recorded in 2002 at each station of interest. Six clusters of mining events were detected between May and October 2002 near stations in southern, central and northwestern India. Second, a short-period Rayleigh wave ($R_g$) detector (Tibuleac and Britton; 2004, Britton et al, 2003) was developed for quarry-blast/shallow source, near-regional events. The $R_g$ detector was integrated into a semi-automatic event-detection and -location algorithm and applied on continuous data. The algorithm uses improved three-component frequency-wavenumber ($\text{fk}^3\text{C}$) single-station location techniques. We obtained better detection results and back azimuth estimates using nonlinear pre-filtering. We present continuous detection results from two proprietary stations in March and April 2001.

We are in the process of obtaining satellite imagery for the areas covering the locations of the mining clusters. The imagery, event locations, station locations, and information on the mines are stored in an ArcView 8.3 geographic information system (GIS) database in which the digital seismic waveform data are linked. The database is updated as more mining clusters are detected and supplemental information (satellite imagery, mining information) is received.
OBJECTIVES

The objectives of this research are to catalog the mining resources of southern Asia and to compile mine information together with mining explosion waveforms into a single digital database.

RESEARCH ACCOMPLISHED

Mine Database

Continuous broadband waveform data were obtained from the IRIS/IDA stations ABKT, NIL, and PALK. HYB waveforms were obtained from the Geoscope Network, and GBA waveforms were obtained through the Atomic Weapons Exchange (AWE) in the United Kingdom. The locations of these stations are shown in Figure 1, with proprietary stations indicated by P1 and P2 on the map and in this paper. Table 1 shows the dates of continuous data segments obtained from these stations.

In addition to obtaining continuous waveform data, information on the mines and mining districts surrounding these stations is being compiled. Supplemental information, such as satellite imagery, is imported into the database to aid in determining ground truth for the locations of detected mine blasts.

Table 1. Stations for which continuous data have been obtained

<table>
<thead>
<tr>
<th>Station</th>
<th>Network</th>
<th>Dates</th>
<th>Segment Length [days]</th>
<th>Lat (deg)</th>
<th>Lon (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABKT</td>
<td>IRIS/IDA</td>
<td>4/9/02 - 10/22/02</td>
<td>196</td>
<td>37.9</td>
<td>58.1</td>
</tr>
<tr>
<td>NIL</td>
<td>IRIS/IDA</td>
<td>7/2/98 - 3/3/99</td>
<td>244</td>
<td>33.7</td>
<td>73.2</td>
</tr>
<tr>
<td>HYB</td>
<td>GEOSCOPE</td>
<td>4/21/99 - 5/20/99</td>
<td>30</td>
<td>17.4</td>
<td>78.5</td>
</tr>
<tr>
<td>GBA</td>
<td>GEOSCOPE</td>
<td>2/1/1996 – 2/7/1996</td>
<td>7</td>
<td>13.6</td>
<td>77.4</td>
</tr>
<tr>
<td>P1</td>
<td>Proprietary</td>
<td>3/19/01 - 12/31/02</td>
<td>652</td>
<td>NW</td>
<td>India</td>
</tr>
<tr>
<td>P2</td>
<td>Proprietary</td>
<td>3/29/01 - 8/8/01</td>
<td>132</td>
<td>Southern</td>
<td>India</td>
</tr>
</tbody>
</table>

Figure 1. Location of IRIS/IDA (ABKT and NIL) stations, Geoscope station HYB, station GBA, formerly operated by the Atomic Weapons Establishment (AWE) at Blacknest, UK, and proprietary stations P1 and P2.
Detection of Mining Events from Continuous Data

Waveform correlation techniques. Two methods for detecting mine blasts are employed in this research. The first is the waveform correlation method (Harris, 1991). This method has been used on data from HYB, ABKT, GBA, NIL and the proprietary stations P1 and P2 (see also Britton et al., 2003 for an example of previous results at station P2). A simple STA/LTA detector was applied to twelve months of continuous data from proprietary station P1 as an initialization for the waveform correlation. Over 2000 detections were made for this period and the detected waveforms were correlated to a threshold of 0.7 into clusters of two or more events each. We developed subspace detectors for the six largest clusters (Table 2). These detectors were used to reprocess six months of the P1 dataset in order to find additional events in the six clusters. Events in these clusters are initially examined by eye, and if the events appear to be mine blasts (based on the presence of the Rg phase or repeated occurrence during daylight hours) then the events in the cluster are located. Figure 2 shows the locations of the clusters relative to P1. Figure 3 shows the detections, sorted by time of day, for a six-month period for each cluster. Figure 4 shows an example of events from each cluster.

Table 2. P1 cluster parameters. P and Rg back azimuth sample standard deviation was calculated only for events with detected Rg arrivals.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>Initial No. events</th>
<th>No. events used for cluster location</th>
<th>No. events with detected Rg arrivals</th>
<th>P back azimuth Sample Std. Dev (deg)</th>
<th>Rg back azimuth Sample Std. Dev. (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>25.1</td>
<td>74.9</td>
<td>88</td>
<td>39</td>
<td>33</td>
<td>11.2</td>
<td>11.5</td>
</tr>
<tr>
<td>3</td>
<td>23.5</td>
<td>73.6</td>
<td>30</td>
<td>14</td>
<td>5</td>
<td>10.3</td>
<td>6.23</td>
</tr>
<tr>
<td>4</td>
<td>24.4</td>
<td>73.8</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>7.4</td>
<td>7.1</td>
</tr>
<tr>
<td>5</td>
<td>22.9</td>
<td>73.5</td>
<td>35</td>
<td>16</td>
<td>-</td>
<td>14.2</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>24.4</td>
<td>73.9</td>
<td>12</td>
<td>7</td>
<td>4</td>
<td>4.1</td>
<td>8.7</td>
</tr>
<tr>
<td>7</td>
<td>24.8</td>
<td>73.7</td>
<td>21</td>
<td>6</td>
<td>4</td>
<td>12.3</td>
<td>12.2</td>
</tr>
<tr>
<td>Total events</td>
<td></td>
<td></td>
<td>208</td>
<td>98</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Only events detected by an analyst and with signal-to-noise ratio (SNR) greater than 1 were used for cluster location estimates. We calculated SNR as the ratio between the maximum P amplitude in a 3-sec window and twice the standard deviation of the noise (Der and Shumway, 1999) in a 10-sec window preceding the signal. The largest location outliers were discarded from each cluster. P and Lg arrival times were picked by an analyst, an Rg detector was applied and the events were located using semi-automatic methods similar to those described in the next section (Britton et al., 2003). Median values for latitude and longitude were calculated for each cluster. A comparison between the Rg and P back azimuth residuals for 98 events with Rg arrivals from five clusters in northwestern India recorded at station P1 is presented in Figure 5. We observe (Table 2) that sample standard deviations of back azimuth estimates using the Rg detector are comparable or better than single station P back azimuth estimates for all clusters (except for the four events in Cluster 6). A possible explanation is that the Rg phase often has larger amplitude than the P phase.

Most of the events in Cluster 2 were recorded between 0800 and 1000 UTC (13:30 to 15:30 local time). Less than half of the events in Cluster 3 had SNR > 1. Of these, five events had Rg arrivals recorded at times marked by arrows in Figure 3. Further investigation of events in Cluster 3 is necessary to find whether one or several mines are operating in the area. All the events in Cluster 4 had Rg arrivals and occurred between 0800 and 1000 UTC (13:30 to 15:30 local time). No Rg arrivals were found in Cluster 5 except for an event with SNR lower than 1. The events in Cluster 5 were recorded between 04:00 and 07:00 UTC (09:30 to 12:30 local time) or 1200 and 1500 (17:30 to 20:30 local time). Cluster 5 might be composed of two sub-clusters with different occurrence times. Three events without Rg arrivals were located apart from the other four events in Cluster 6 with detected Rg phases. Given the long durations of these cluster sequences (Table 2) and the consistency of the origin times, these sources appear to be mines. The fact that events from Clusters 2, 3, 4, 6 and 7 exhibit Rg phases, which are consistent with shallow sources such as open-pit mine blasts, supports this interpretation.
Figure 2. Single-station location of the six largest subspace detection clusters (blue squares) recorded at P1 between May and October 2002. Events for which $R_g$ was detected (suspected mine blasts) are plotted as black circles. Yellow squares represent locations of open-mine pits. All the other cluster events are plotted as open circles. The yellow star is the location of the Pokhran test site.

Figure 3. Clusters 2 to 7 event detections at station P1 sorted by time of day. Local time equals UTC plus 5.5 hours. Daylight hours (0600 to 1900 local time are highlighted). The arrows represent occurrence times for the Cluster 3 events with $R_g$ arrivals.
Semi-automatic detection of possible mining events from continuous data using an Rg detector. An alternate approach to the waveform correlation method is to continuously scan the station data for Rg arrivals without reference to known events. The presence of Rg on waveforms indicates shallow source depth, and when it is detected repeatedly during daytime hours, it is often an indication of mining operations. At this point we use only the P back azimuth in location algorithms. However, estimates of Rg back azimuth could be used for location of events with low SNR first arrival and large Rg amplitude. Thus, a complementary method used to detect small
shallow events (possible mine blasts) is the automatic $R_g$ detector (Tibuleac and Britton, 2004; Britton et al., 2003; Chael, 1997). When applied after non-linear pre-filtering, the $R_g$ detector code, using both polarization and amplitude information, produced back azimuth estimates comparable to the frequency to wavenumber three-component ($f_k3c$) single station $P$ back azimuth estimates when tested on clusters of well-located events in India (see also Figure 5 in this study).

**Continuous data processing algorithms.** The $R_g$ detector was incorporated into routines for semi-automatic analysis of continuous data. A first arrival ($P$) detector and the $R_g$ detection algorithm were applied to 10-min files. The $P$ detector code was designed for three-component data using an algorithm similar to the $R_g$ detector, modified for first arrival detection, and using a combination of Fourier and non-linear pre-filtering techniques. So far, the $P$ detector has only been used for qualitative information purposes. Based on previous studies (Britton et al., 2003), we decided to use non-linear pre-filtering before $R_g$ detection. The non-linearly filtered data consists of coefficients of a Continuous Wavelet Transform using the ‘Meyer’ wavelet. Due to its similarity to a sinc function, the Fourier transform of a Meyer wavelet is a boxcar, centered on the analyst-chosen period (1 sec for this region).

Once a detection was declared, we applied the WAVELET1.0 picker developed at Weston Geophysical by Tibuleac et al., (2003), to estimate $P$ and $L_g$ phase arrival times. Epicentral distance was estimated from the $P$ and $L_g$ arrival time difference using empirical, station specific formulas for station P1, and using the SSLOC3D single-station location method (Leidig et al., 2003) for station P2. The first arrival back azimuth was estimated using the $f_k3c$ method adapted from MatSeis (Harris and Young, 1997). Improvements to the $f_k3c$ method include: 1) non-linear pre-filtering using a “bior3.7” wavelet centered on the analyst-chosen $P$ period. 2) $f_k$ analysis in a sliding 1 sec window with a step of 0.5 sec, performed within 5 sec of the detected $P$ arrival to obtain the most stable back azimuth value estimation. Starting 2 min. before the detected $P$ arrival, 10 min. of waveforms were stored in the database for each event, using specific MATLAB–to–SAC conversion routines.

**Detection results for proprietary station P1.** The detection algorithms were applied to continuous data from station P1 recorded for 15 days in March and April 2001. The analysis resulted in 282 detected local events. Of these events, 35 had $R_g$ arrivals and were classified as possible explosions (orange circles in Figure 6). All the events with detected $R_g$ arrivals were located to the northeast of P1, in the direction of known local mines (yellow squares), except for five events located in the seismically active Bhuj region, near the Basantgarh Copper Mine. Examples of possible explosions recorded from northeast of station P1 are presented in Figure 7. The upper plot presents a suspected explosion, recorded on 8 April 2001, 08:31, followed by a similar, lower magnitude event, 43 sec later. Another typical event with an $R_g$ arrival, recorded on 5 April 2001, 08:13, also classified as a possible explosion, is presented in Figure 7, lower plot.

**Detection results for proprietary station P2.** The detection algorithms were applied to continuous data from station P2 recorded for 24 days in March and April, 2001. The analysis resulted in 156 detected local events. Of these events, 40 had $R_g$ arrivals and were classified as possible explosions. The majority of the events with detected $R_g$ arrivals were located to the northwest, in the direction of known local mines described by Britton et al., (2003). An example of suspected explosion detected northeast of station P2 on 3 April 2001, 09:12, is presented in Figure 8.

**GIS Database**

Waveforms of mine blasts detected by the waveform correlation and $R_g$ detection methods are linked through hypertext transfer protocol (http) to an ArcView 8.3 geographic information system (GIS) database containing information on event location, satellite imagery, regional geology, station information, and mine information. An example is shown in Figure 9.

Event locations are added to the mining activity tables. When the suspected mine blasts do not occur near known mines contained in the database, a literature search for mines in that area is initiated. Satellite imagery in the area of the event location aids in providing ground-truth locations for the mining events. Often, the event locations lie within 10 km of an observed pit. The images are geo-referenced and can be readily incorporated into GIS maps. The database now contains satellite imagery for four mining districts showing the locations of at least a half dozen open pit mines. We have been unable to obtain any blast confirmations from the southern Asia mines; therefore satellite imagery has become our main source of ground truth.
Figure 6. Location of suspected mine blasts (events with $R_g$ arrivals) detected in March and April 2001 at station P1. Events for which $R_g$ was detected (suspected mine blasts) are plotted as orange circles. Yellow squares represent locations of open-mine pits. Locations of event clusters estimated using waveform correlation methods are represented as blue squares.

Figure 7. Upper plot: Zero-phase Butterworth 4 pole, 0.6–5 Hz filtered waveforms for the 8 April 2001, 08:31:49 and 08:32:32 suspected explosions with $R_g$ arrivals. The first event ($P$ time lag 29 sec) was located 142 km east of P1. First arrival back azimuth was estimated to be 112 deg for the first event, located at 24.2 N and 74.1 E, and 109 deg for the second event, located at 24.3 N and 73.8 E. The $R_g$ back azimuth was estimated to be 105 deg for both events. Lower plot: An event recorded at P1 on 5 April 2001, 08:13:12. The estimated location of this event was 24.82 N and 73.21 E, 48 km northeast of P1. First arrival back azimuth was 67 deg, while the $R_g$ back azimuth was 63.4 deg.
Figure 8. Suspected explosion on 2001/04/03 recorded at 09:12:34, with an estimated location of 10.4 N and 77.7 E, 40 km northeast of P2. Back azimuth was estimated as follows: 57 deg (P) and 58 deg (Rg).

Figure 9. An ArcView interface window showing mining events detected near station HYB (blue, green and yellow circles), overlain satellite imagery and a digital elevation model. A window with event details and links to waveform data (right), and a window showing the attribute table for one of the events (left) are also shown.

CONCLUSIONS AND RECOMMENDATIONS

Information on mining activity around seismic stations in southern Asia is continually being compiled and updated. A combination of techniques, including waveform correlation and continuous data processing algorithms using single-station location methods and an Rg detection algorithm, was used to develop the mine database.
Continuous data have been analyzed using the waveform correlation method to detect events associated with nearby mines and mining districts. Waveforms from event clusters detected by the waveform correlation method at station P1 were spatially associated with nearby mines in the database. Additionally, the presence of Rg and the occurrence times during daylight hours confirm that these events are mine blasts. We observed that sample standard deviations of cluster back azimuth estimates using the Rg detector are comparable to f3C P back azimuth estimates. Therefore, using the Rg phase back azimuth for event location is a promising alternative using small SNR first arrival back azimuth.

An Rg detector was integrated into a semi-automatic event-detection and -location algorithm and applied on continuous data. The algorithm uses improved f3C single-station location techniques. We obtained better detection results and back azimuth estimates using non-linear pre-filtering. We presented continuous detection results at two proprietary stations in March and April 2001.

Detected waveforms are linked to an ArcView 8.3 geographic information system (GIS) database containing information on event location, satellite imagery, regional geology, station information, and mine information.

ACKNOWLEDGMENTS

We express our gratitude to Dr. Delaine Reiter and Mark Leidig for fruitful discussions and help on this project.

REFERENCES


