SEISMIC NETWORK OPERATIONS AT A DEEP UNDERGROUND COAL MINING DISTRICT IN WESTERN COLORADO (USA)

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An array of ten triaxial strong-motion stations has been installed on the surface above two underground longwall coal mines in western Colorado (USA). The district-scale network monitors mining-related and natural seismicity throughout an area of approximately 250 square kilometers of rugged canyon-mesa terrain. The real-time automated seismic event monitoring and notification tool features: password-protected Internet access to raw and processed data, web-client software that provides real-time graphical display of event locations, and email and paging notification of high acceleration levels and large magnitude events. This paper describes the network installation and the methods used to collect, process, and distribute seismicity information to its users and gives several examples of the collected data.

1 Background

Bowie Resources LLC, Mountain Coal Company, and the National Institute for Occupational Safety and Health (NIOSH) jointly developed a district-scale seismic monitoring network. The objectives of the network are to (i) distinguish and characterize seismic activity as either mining related or naturally occurring, (ii) implement a real-time event monitoring and notification tool, and (iii) collect data for use in research studies aimed at quantifying impacts from mining-related and natural seismicity. These potential impacts include dynamic rock mass failures such as coal bumps as well as strong shaking in the vicinity of critical structures such as impoundment dams, reservoirs, mine seals, mine openings, and steep slopes.

The first issue to be addressed in system design concerned the size of the area to be monitored. It was necessary to characterize seismicity throughout the current, former and future underground workings as well as nearby natural seismicity. It was also desirable to measure strong-ground motion in the vicinity of several earthen dams. For an array of these dimensions, conventional earthquake monitoring tools, including open-source software, could be used to characterize natural and mining seismicity and implement the real-time monitoring function. However, NIOSH's research interests require more detailed

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[1] The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health.

examination of failure mechanisms and strong-motion recording which necessitate additional measurements closer to the active workings. Use of temporary close-in stations that augment the district-scale network have been used to help meet this latter objective. This paper describes the development and application of the district-scale network.

1.1 Site Location

The North Fork Valley (NFV) longwall coal mines are located in western Colorado in an area where vertical elevation relief over the span of an individual mine approaches 1 km. Six minable coal seams are present with thickness ranging from 2 to 6 m. Maximum overburden in the district is approximately 0.8 km. Competent sandstone units are present with variable thickness and distance above and below most of the seams. This combination of overburden and stiff strong strata leads to the potential for coal bumps. Total yearly production from all NFV coal mines exceeds 17 million tons per year.

2 North Fork Valley (NFV) Network

2.1 Seismic Stations

Triaxial accelerometers (EpiSensors[2]) and 1-Hz vertical seismometers (L4-C) are co-located at each station to record strong and weak motions, respectively. Signals are digitized by nominally 24-bit data recorders (Altus K2). The recorders are configured to continuously stream four channels of waveform data at 100 samples per second, and locally trigger and save event data to compact flash cards providing backup in case of telemetry failure. Each station is equipped with a GPS receiver for time stamping.

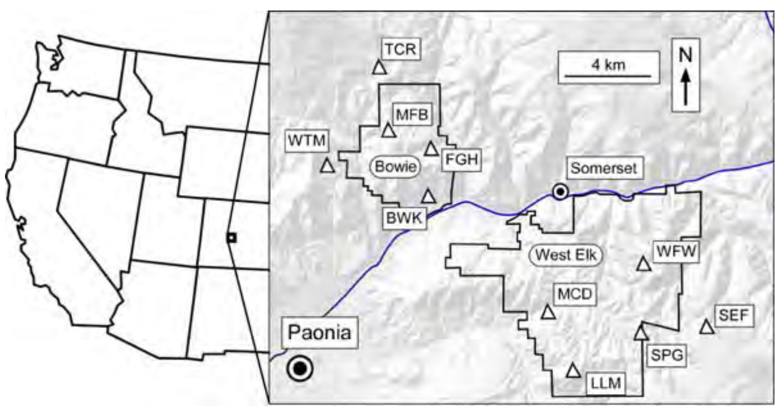

Figure 1. Seismic station locations (triangles) in North Fork Valley coal mining district of western Colorado. Lease boundaries marked by outlines.

Two groups of five seismic stations are centered around existing and/or future workings of the Bowie and West Elk mines (Figure 1) providing coverage of an area of approximately 250 square kilometers. To help constrain locations of naturally occurring earthquakes in the surrounding area, use is also made of data from a transportable array (TA) of broadband seismometers temporarily deployed as part of the EarthScope earth science project [1]. The average source to receiver distance for the nine nearest TA stations is 75 km.

2.2 Data communications

Continuous digital seismic waveform data streams are sent from each remote station to a central site in the town of Paonia equipped with a DSL Internet connection (Figure 2). Data transfer is achieved with license-free (in the U.S.) 900-MHz frequency-hopping spread-spectrum radios equipped with 10dB directional Yagi antennas. Radio interference issues have been experienced periodically with other nearby 900-MHz

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[2] Mention of specific products or manufacturers does not imply endorsement by the National Institute of Occupational Safety and Health.

data-comm networks that are used for ventilation and methane drainage drillhole monitoring and other networks associated with non-mining uses. The interference has been mitigated by appropriate antenna selection, positioning and RF-power level adjustments, and/or replacement of affected links with radios in the 2.4-GHz band.

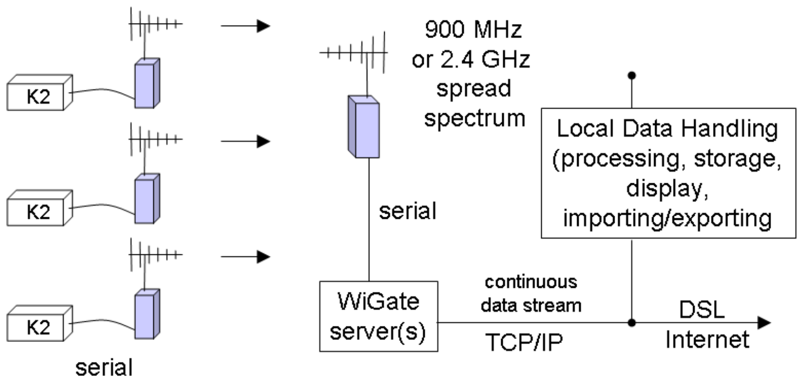

Figure 2. Data communications (serial/IP) network.

2.3 Data Processing

The open-source software Earthworm [2], developed by the U.S. Geological Survey (USGS) and other contributors, is used for a large portion of the data collection, processing, analysis and display functions. A wide variety of software modules are available, allowing one to custom build a system tailored to specific needs. Modules are available to stream real-time data from seismic instrumentation offered by numerous seismometer and recording-systems manufacturers (e.g. DAQ Systems, GeoTech Instruments, Guralp, Kinemetrics, Nanometrics, National Instruments, Reftek, Symmetric Research, Quanterra)[1].

In the NFV configuration, various modules on multiple Windows platforms automatically detect, process, archive and analyze seismic events, analyze ground motion parameters, distribute waveform data for redundant processing and backup, and provide alerting services. For on-line waveform storage Winston "waveservers" are constructed using the standard Earthworm Waveserver_V module or the MySQL-based Wave Server (WWS) Java utility [3].

Following software-based arrival-time picking, event locations are calculated using Hypoinverse [4] with a layered velocity model. Magnitude estimates are available from three separate sources: (i) the USGS's National Earthquake Information Center (USGS/NEIC) in Golden, CO (limited to the largest events), (ii) Mesa State Seismic Network (Grand Junction, CO), and (iii) those calculated within the automated processing (Hypoinverse coda magnitude).

2.4 Distribution of Data

Raw and processed data are made available over the Internet via a password protected web page. Access can be provided to all available data or a more limited subset, depending upon user privileges. Links are provided to data products such as helicorder records (12- to 24-hour single-trace recordings similar to paper drum recordings), triggered-event waveform files, summary event location/magnitude data, and peak acceleration values. An alternative open-source interactive helicorder-style module with useful spectrum display features, Swarm - Seismic Wave Analysis and Real-time Monitor [3], is also available. Waveform data from arbitrary time periods can be manually stored to disk in a number of different formats (e.g. SAC, SUDS, mini-SEED) by accessing the waveservers from anywhere on the Internet.

2.5 Event Monitor

A separate web server provides continuous reporting of seismic activity in the vicinity of the NFV network with near real-time displays of event locations, magnitudes and times of occurrence. It receives its data from Earthworm and is based on the CISN software designed for western U.S. earthquake monitoring and emergency management 24/7 operations centers (http://www.cisn.org/). Modifications to this software were made to provide additional control of the location quality of the displayed events. This increases the robustness of the event reporting and reduces the display of poorly constrained events when operating under wholly automated processing conditions. However, as with any automated system, it is not immune from errant mislocations; significant events are always confirmed by experienced users through manual inspection and, if necessary, re-processing.

2.6 Alerts

Timely notice of events of particular interest is provided by email and paging. Users receive email when specified levels of acceleration are met or exceeded at a given station, providing the opportunity to inspect critical structures or initiate other actions. In practice, it has been found useful, as a simple awareness measure, to set the threshold lower than any critical, or actionable, level in order to generate a stream of email that is proportional to the rate of large-event seismic activity. This also provides periodic confirmation that the notification system is working as intended. A second system email module is used to send messages about significant events to a nationwide paging service. Individual users can customize their own notification criteria by specifying values for acceleration threshold, minimum magnitude, and distance from stations of interest.

3 Example Results and Discussion

3.1 Mining Events and Natural Earthquakes

One of the initial goals of the network was to develop a better understanding of the relative amounts of natural earthquakes versus mining-related seismicity. Locally, seismic events with M $\geq$ 2.8 are fairly consistently reported by the USGS/NEIC. However, the typical location error is observed to be 8-12 km which is too large to allow discrimination between different mines in the area and discrimination from local earthquakes. Naturally occurring earthquakes (M$\leq$2.4) have indeed been recorded throughout the region by the NFV network but they represent less than one percent of the recorded activity.

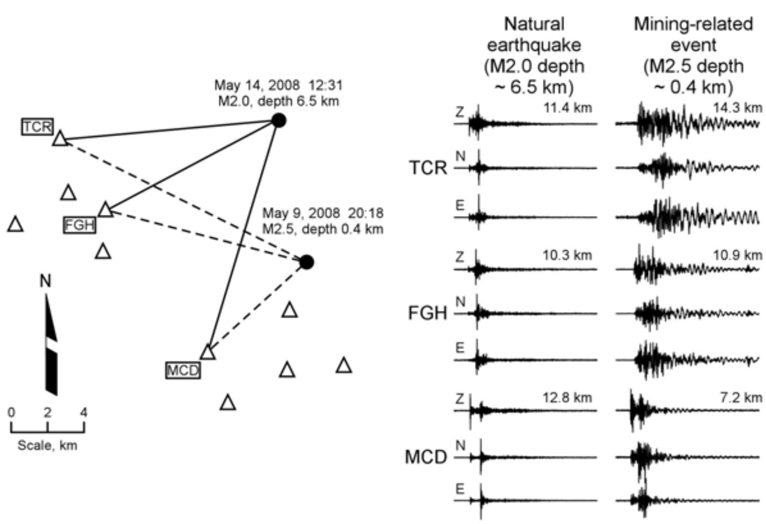

Figure 3. Comparison of waveform character observed for natural earthquakes and mining-related events.

Naturally occurring events are quite readily distinguished from the local mining events on the basis of their waveform character. Figure 3 compares waveforms observed at three strong-motion stations (TCR, FGH, and MCD) from both a local earthquake (M2.0) and a longwall mining-related event (M2.5). The natural event displays the classic tectonic earthquake signature with distinct P and S phases. The waveform signature of the mining-related event appears different: (i) the separation between P and S phases is not nearly as well defined, (ii) there appear to be several additional phases present, or complexity that is absent in the earthquake seismogram, and (iii) the frequency content across the entire waveform is generally lower for the mining event than for the natural earthquake.

The waveform characteristics in Figure 3 are typical for natural earthquakes and mining events observed by the NFV network. While differences in source mechanisms may exist – most NFV mining events exhibit dilatational first motions, much of the difference in waveform character in Figure 3 can be attributed to propagation path effects. A far greater proportion of time is spent travelling parallel to near-surface sedimentary layers for the shallow mining event in comparison to the much deeper natural earthquake. As a result, local earthquakes show minimal surface-wave generation and mining events show the strong influence of surface waves and near-surface layering.

3.2 Distribution of Seismic Activity

From May 2007 to January 2009, approximately 20,000 events were automatically detected, processed, and located. The level of activity is a strong function of mining operations, particularly deep longwalling. The temporal distribution of the larger events with $2.0 \leq M \leq 3.4$ is shown in Figure 4.

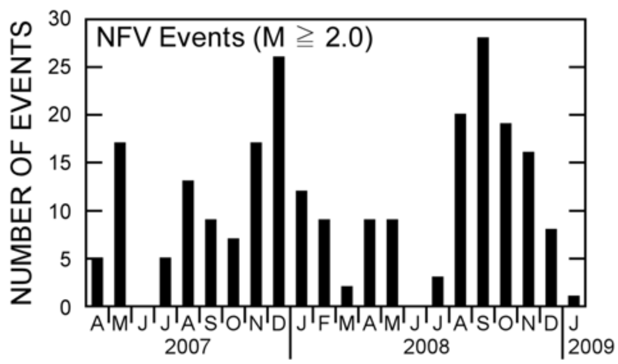

Figure 4. Temporal distribution of events in the North Fork Valley with $2.0 \leq M \leq 3.4$.

An example of the distribution of event locations for a single typical month (September 2008) is shown in Figure 5. Approximately 900 events occurred with a maximum magnitude of 2.8. No naturally occurring earthquakes were detected in this area during this interval. The strong event clustering to the east of the Bowie stations occurs in the vicinity of a third NFV area coal mine.

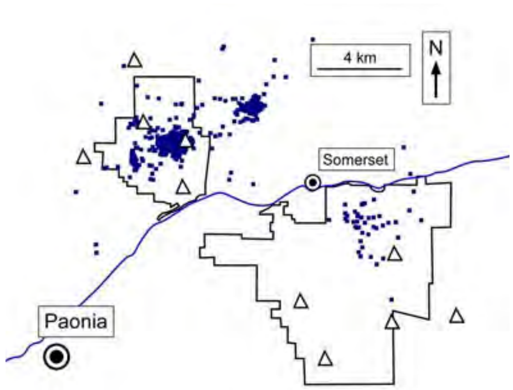

Figure 5. Distribution of event locations ($0<M\leq 2.8$) determined by the automated processing for the month of September 2008.

Automatically processed event locations on the scale of an individual mine are shown in Figure 6. Approximately 6,000 events with magnitudes between 0 and 3.4 were recorded at the Bowie Mine during the 3-month period from Nov 2007 to January 2008. During this time the longwall retreated a distance of ~700 m (white outline) in the B-seam. The high level of activity is a reflection of the consistently deep cover (>500 m), near-seam brittle strata and stress interactions with the previously mined D seam 90 m above. Figures 5 and 6 display event locations without regard to constraint on the size of location error.

3.3 Performance of the Automated Processing

The automated processing is largely successful in placing events into the appropriate mine and into specific work areas (i.e. longwall versus development sections, etc.). Scatter in event locations outside the longwall panel (Figure 6) is the result of both error in automated processing and the presence of other distributed sources such as development mining and continuation of events in old workings. There are also some outright erroneous locations due to events that occur close together in time producing overlapping arrivals which get assigned to the wrong event.

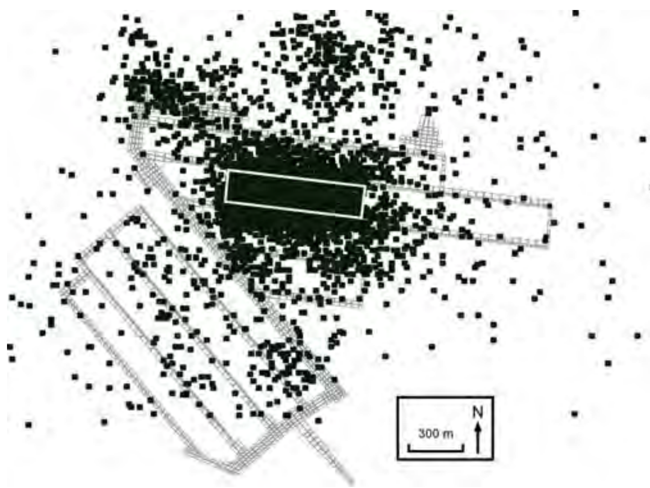

Figure 6. Automatically processed event locations for 3-month longwall retreat.

Manual arrival time picking reduces scatter in event locations, tightens up the clustering in the direct vicinity of responding mine structures, and is used when trying to maximize the understanding of the processes attending significant or damaging events. Other improvements in event locations for the automated processing are under development, including refinement of both mine-specific velocity models and station corrections and incorporation of multiple individual velocity models into the automated location process.

4 Summary

Bowie Resources LLC, Mountain Coal Company, and NIOSH have cooperated on a joint project to develop a digital wireless seismic monitoring network to collect background data on mining-related seismic activity in western Colorado and to implement a hazard monitoring tool. The ten station strong-motion array covers approximately 250 square km and provides an automated real-time monitoring capability using wireless serial and IP communications networks. To resolve details of the caving process, event depths, and interactions with specific strata in the vicinity of working faces requires augmentation of the network with a close-in fully three-dimensional distribution of additional sensors.

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