SEISMIC STUDIES AND NUMERICAL MODELING AT THE HOMESTAKE MINE, LEAD SD

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ABSTRACT

Stresses around mine openings at depth can cause the surrounding rock to fail, releasing stored strain energy. When this happens, the rock may literally explode or "burst" into the opening without warning. As mining progresses deeper into the earth, the possibility of seismic events and rock bursts increases.

Researchers at the U.S. Bureau of Mines are currently studying seismic activity in three underground hard-rock mines in the United States: the Homestake Mine, Lead, SD; the Lucky Friday Mine, Mullan, ID; and the Sunshine Mine, Kellogg, ID. Waveforms from seismic events are recorded by personal-computer-based hardware and software. In addition, researchers are modeling the deep levels of the Homestake Mine using a finite-element code. These models generate stress and displacement values for a given loading condition. By studying in situ stresses and seismic activity along with actual stope sequencing, researchers can make correlations between stresses induced by mining and the frequency and magnitude of seismic events.

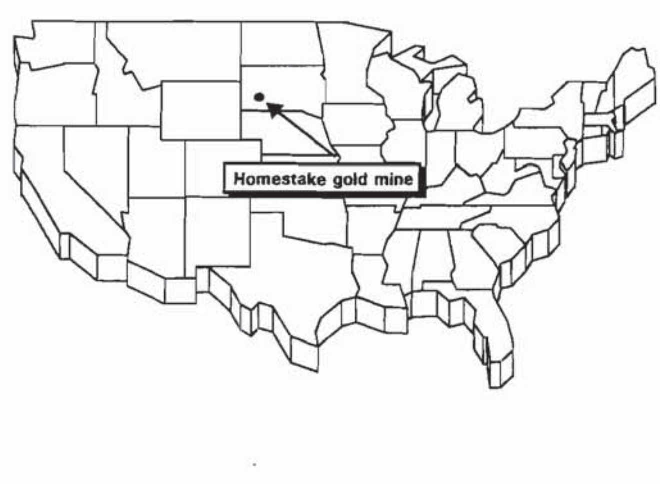
Information on seismic events coupled with results from finite-element analyses have increased understanding of rock mass behavior and the mechanisms that may lead to rock bursts. Optimization of stope sequencing designs as a result of these studies could reduce rock burst hazards.

INTRODUCTION

The Homestake Mine in Lead, SD (figure 1), is the oldest continuously operating gold mine in the United States. Opened in 1876, the Homestake Mine has produced over 37 million troy ounces of gold. However, as development of the ore body progresses, mining extends to greater depths. Because of greater stress in the deep levels of the mine, the potential for rock bursts increases, which emphasizes the need for thorough mine design. Nonetheless, even with careful planning and extensive support systems, the increased stress in the deeper levels may cause seismic events.

A seismic event is defined as a transient earth motion caused by a sudden release of potential or stored strain

Figure 1
Location of Homestake Mine, Lead, SD.



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energy in the rock. When a seismic event is sudden and violent and causes injury to people or damage to underground workings or equipment, it is referred to as a rock burst.

Between April 1990 and November 1991, the Homestake Mine experienced several seismic events that resulted in ground failures. Many of the events were large enough to be recorded by seismographs 145 km away near Gillette, WY. Following a Mine Health and Safety Administration (MSHA) investigation, a recommendation was made to Homestake personnel to install a system that would continuously record data on mine seismicity. In September 1992, the U.S. Bureau of Mines (USBM) entered into an agreement with the mine to install a seismic data collection system that would monitor the source of seismic activity in the deep levels of the mine.

SEISMIC MONITORING SYSTEM

HARDWARE

The seismic data collection system consists of an array of 16 accelerometers mounted vertically in the back on the 6950, 7100, 7250, 7400, and 7700 levels of the mine. Each accelerometer is wired to a junction box, which in turn is wired to a main junction box in the computer room on the 6950 level (figure 2). A 486 personal computer (PC) is used to record all data, which can be transferred to the surface via modem links. Girard and others (1995)[3] describe seismic monitoring systems in detail.

[3]Girard, J. M., T. J. McMahon, W. Blake, and T. J. Williams. Installation of PC-Based Seismic Monitoring Systems With Examples From the Homestake, Sunshine, and Lucky Friday Mines. USBM Spec. Publ. 01-95, 1995, pp. 303-312.

Figure 2
Underground Seismic Monitoring System.

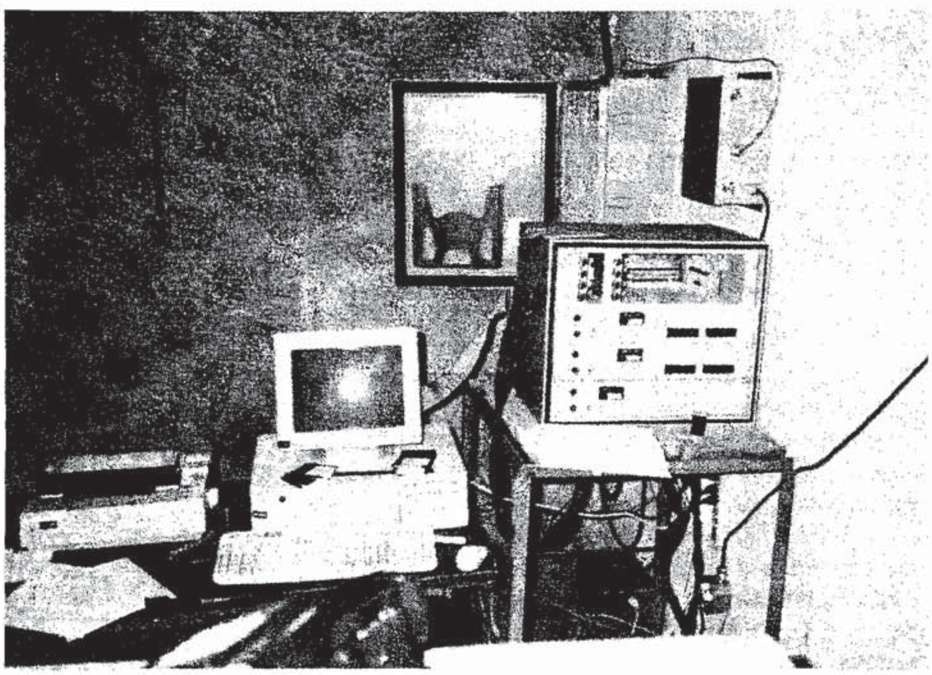
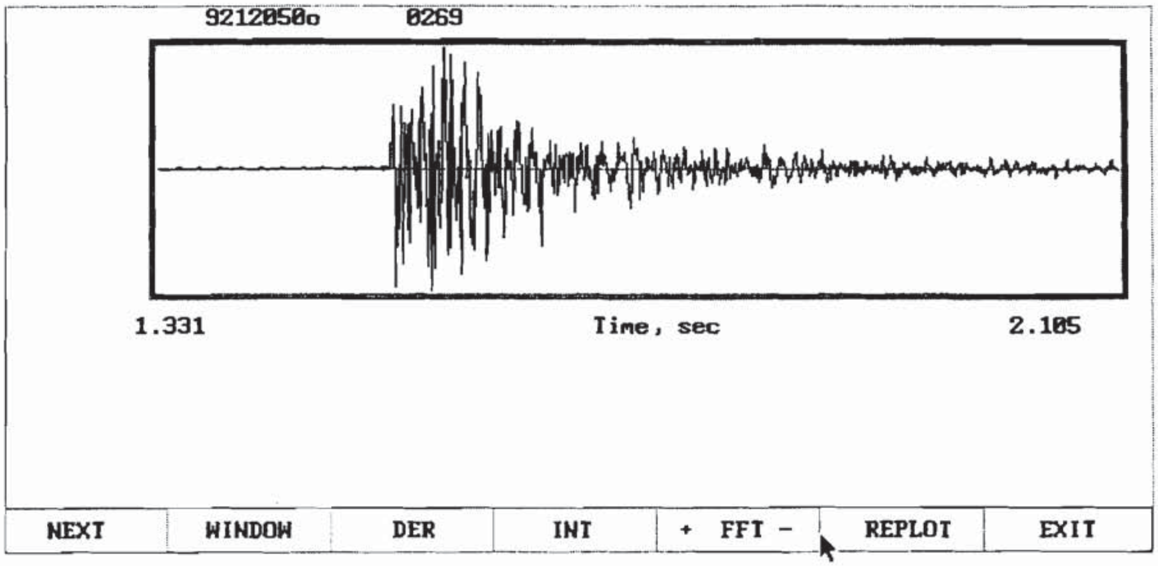


Figure 3
Computer Printout of Rock Burst Waveform.



SOFTWARE

A software program continuously monitors the information from each of the 16 accelerometers. If an event has sufficient energy, the recording system is triggered, and the waveform is stored on the hard drive of the PC. Figure 3 shows the typical waveform of an event.

By examining the digital waveform record, the arrival times of P-waves (compressional and dilatational first-wave motion) at each accelerometer can be picked. This arrival time information is used as input to a software program[4] that will compute the coordinates of the event location. Because solution accuracy is dictated by the solution method, the arrival time picks, and the mine's velocity structure,[5] an error residual on origin times for each event is also calculated and taken into account when performing data analysis. In addition, a measure of relative magnitude for each event is computed by averaging the maximum geophysical count of the waveform at each accelerometer. (This method for computing the magnitude is used because the mine does not have a seismograph installed.) A database is used to store event name, coordinates, relative magnitude, and time and date for all data recorded. The original waveform files are archived and stored on a magneto-optical platter.

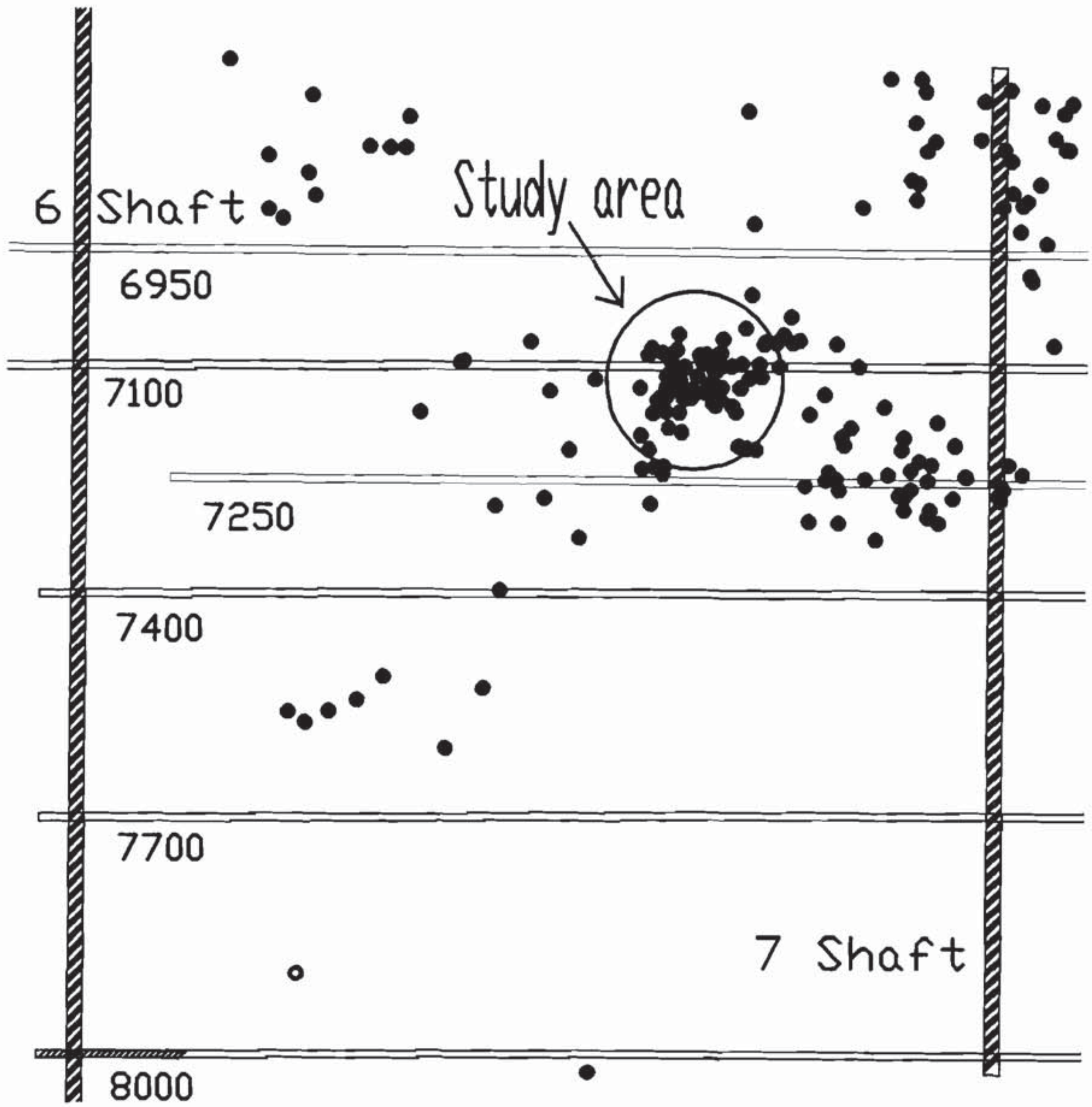
SEISMIC DATA

Since system operation began, approximately 1,100 seismic events have been recorded. Each event is located on mine maps, and a relative magnitude is calculated. By studying this information, areas of higher activity are targeted for detailed numerical analysis by the USBM. Figure 4 depicts several events plotted using the computer software program AutoCAD. The clustering of events represented by a circle in the figure was chosen as the focus of the finite-element analysis described in this paper.

[4]Blake, W. BBLOCK.FOR computer program, June 1985. Adapted from an original program CBLOCK.FOR by G. Swan and P. Rochon, CANMET, Feb. 1985.

[5]P. L. Swanson, L. H. Estey, F. M. Boler, and S. Billington. Accuracy and Precision of Microseismic Event Location in Rock Burst Research Studies. USBM RI 9395, 1993, 40 pp.

Figure 4
Computer Printout of Cross-Sectional View of Seismic Event Locations.



FINITE-ELEMENT ANALYSIS

Finite-element analysis is one of the many numerical modeling techniques chosen for predicting the behavior of a particular system subjected to a given loading condition. By performing a finite-element analysis of proposed mine designs, areas of high stress and potential mining-induced seismic activity can be located. Using stress analysis techniques allows researchers to vary stope size and sequences in an effort to reduce the occurrence of seismic events.

To perform a finite-element analysis, a model of the system under study must be created on a computer. A mesh is then created with a number of discrete elements. These elements are given numerical values equivalent to the material properties of the system under study. The appropriate loading and boundary conditions are applied, and the resulting stresses and displacements are calculated. Finite-element analyses generally require a large number of calculations. In the past, such analyses were carried out primarily on large mainframe computers or supercomputers. With advances in microprocessors and modeling software, engineers can now approximate complex systems using a PC. For this project, USBM researchers used a Pentium PC and a suite of software, including a finite-element analysis program, AutoCAD; DXF2ANSYS, a screen capture program; and a picture-editing program.

The first step in creating a finite-element model usually involves defining the geometry of the model. For this project, the Homestake Mine provided plans that included stope geometry, mining sequence, and mine geology. Three formations compose most of the rock mass: the Poorman Formation, the Ellison Formation, and the Homestake Formation. The exact formation geometry was simplified for analysis (figure 5A). The upper stope of the area under study is 2,043 m below the surface, and the lowest stope is 2,384 m below the surface. Figure 5B depicts the stope geometry predicted for 1994. This particular analysis focused on the mine's 44 pillar area. The mine plans were digitized and converted to an appropriate format for the finite-element model. This provided the finite-element program with line segments defining the stope geometry and boundaries of the three geologic formations.

With the model geometry defined, physical properties of the host rock must be specified. For this analysis, researchers relied on the material properties described by Pariseau (1985).[6] Next, an element type for the specific model was defined. A two-dimensional linear elastic anisotropic element with midside nodes was selected. This element type is desirable because the analysis performed is linear elastic and because elements with midside nodes are more accurate than elements without midside nodes.

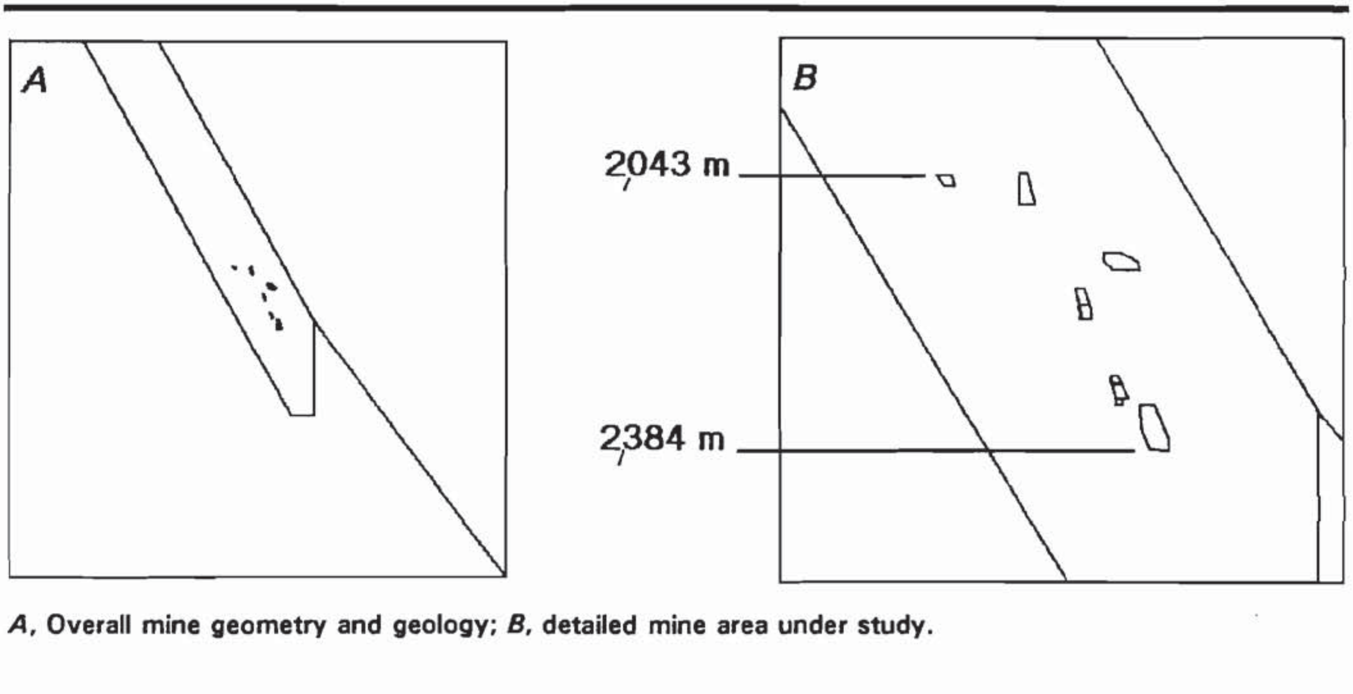
With the geometry and material properties defined, the finite-element mesh can be created. One of the difficulties that must be overcome when using finite-element analysis is determining mesh density. A very dense mesh will provide very accurate solutions but will also require greater computer resources. A very coarse mesh will obtain a solution using a minimum of resources but may not provide an accurate solution. Experience has shown that the mesh should be fine (at least five nodes) around mine openings. Away from a mine opening, the accuracy of the solution is not as critical, and a coarse mesh density is usually sufficient. The model must be large enough to avoid any boundary effects. Any initial mode size is estimated and an analysis run. If boundary effects become apparent, the size of the model is increased and the analysis re-run. Once the mesh parameters are defined, the program will automatically generate the finite elements (figure 6).

The next step in performing the analysis is to define all constraints and loads. This model is constrained along the bottom to anchor the model in space. Loading is applied to the sides to simulate the horizontal stresses that increase with depth and to the top to simulate overburden. These in situ stresses are described by Pariseau (1985).[7] Gravity loading is applied to simulate increased vertical stresses with increased depth.

[6] Pariseau, W. G. Research Study on Pillar Design for Vertical Crater Retreat (VCR) Mining (Contract JO215043, Univ. of UT). USBM OFR 44-86, Oct. 1985, 233 pp.; NTIS: PB 86-210960.

[7] See footnote 6.

Figure 5
Mine Plans.



***A*, Overall mine geometry and geology; *B*, detailed mine area under study.**

The analysis type was defined as plane-strain. This type prohibits the elements from deforming into or out of the plane of the model. To simulate stope sequencing between 1992 and 1994, the analysis was performed using multiple load steps. The first load step determined the in situ stress state before mining. The stresses and displacements obtained in this premining condition were then used as initial conditions for the second load step. This load step turned off, or "killed," the elements that represented the stope sections that had been excavated as of 1992. This provided the state of stress in the mine at the end of 1992. These stresses and displacements were used as initial conditions for the third load step. This third load step then modeled the excavations proposed for 1993. Again, the proper elements were killed, providing the stress state at the end of 1993. Finally, the stresses and displacements obtained from the third load step were used as initial conditions for the fourth load step, which computed the stresses and displacements in the mine at the end of 1994.

With the calculations complete, results were available for review. Figures *7A* through *7H* illustrate changes in safety factors around the mine openings. The safety-factor values were contained using the calculations as described in Pariseau (1985).[8]

In addition to safety factor calculations, the finite-element program will allow the user to plot principal stresses, vertical stresses, horizontal stresses, displacements, and a host of other solution parameters.

[8]See footnote 6.

Figure 6
Finite-Element Mesh.

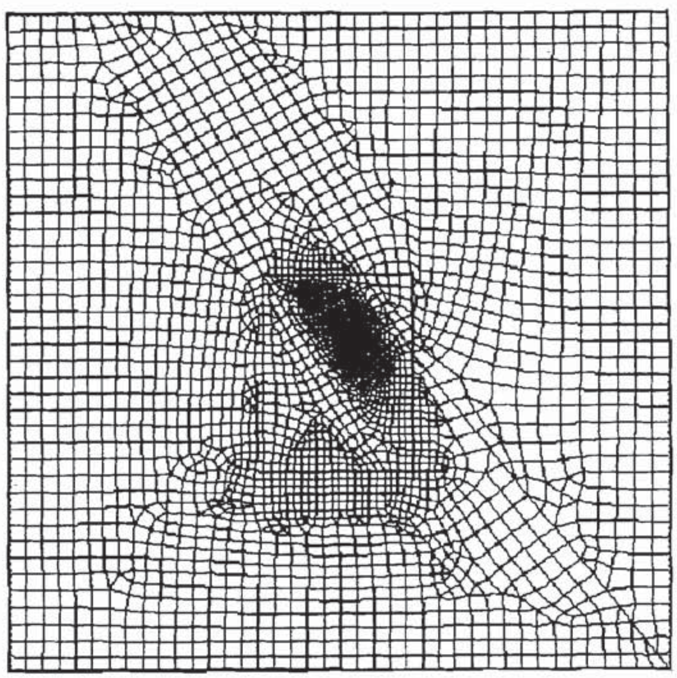
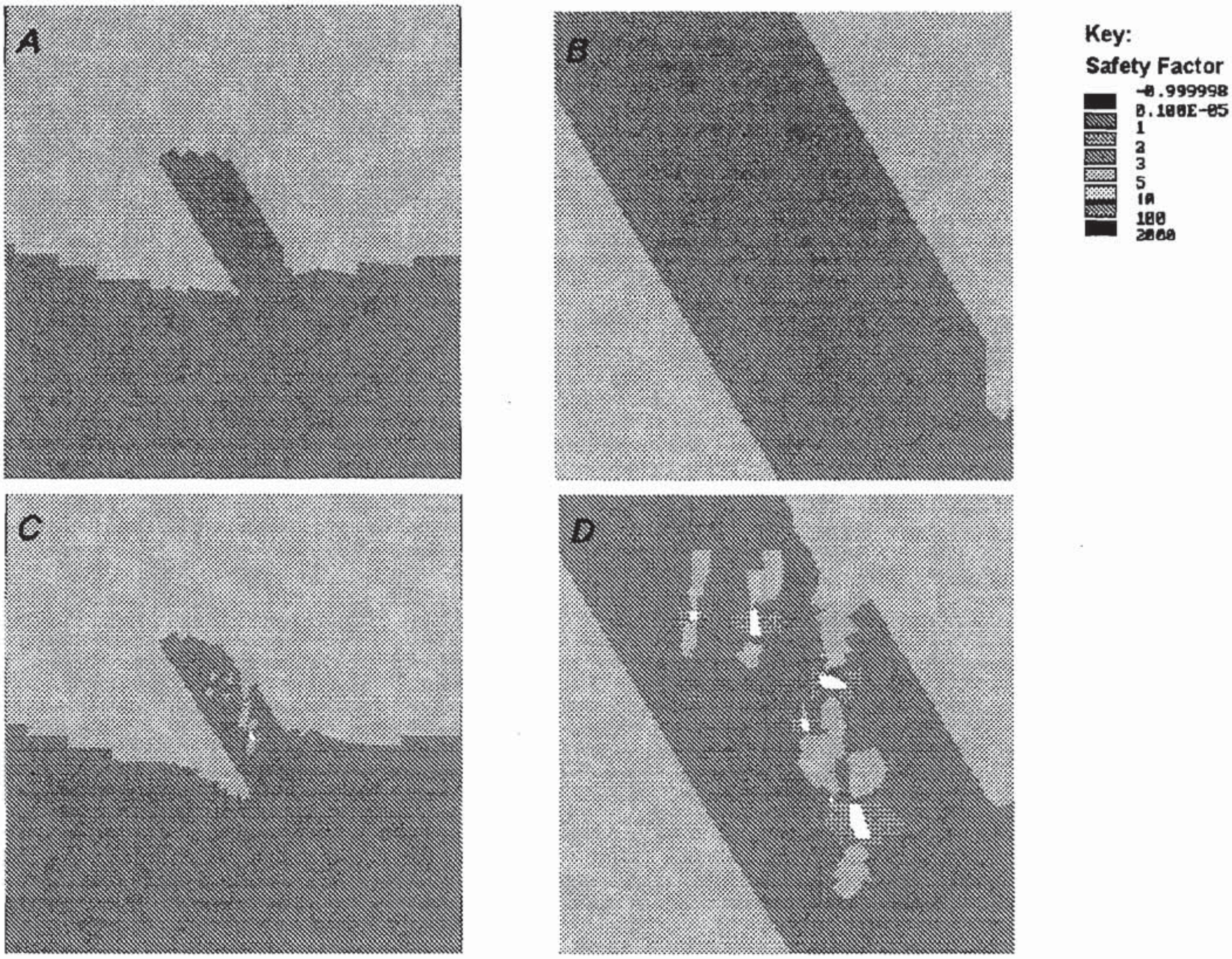
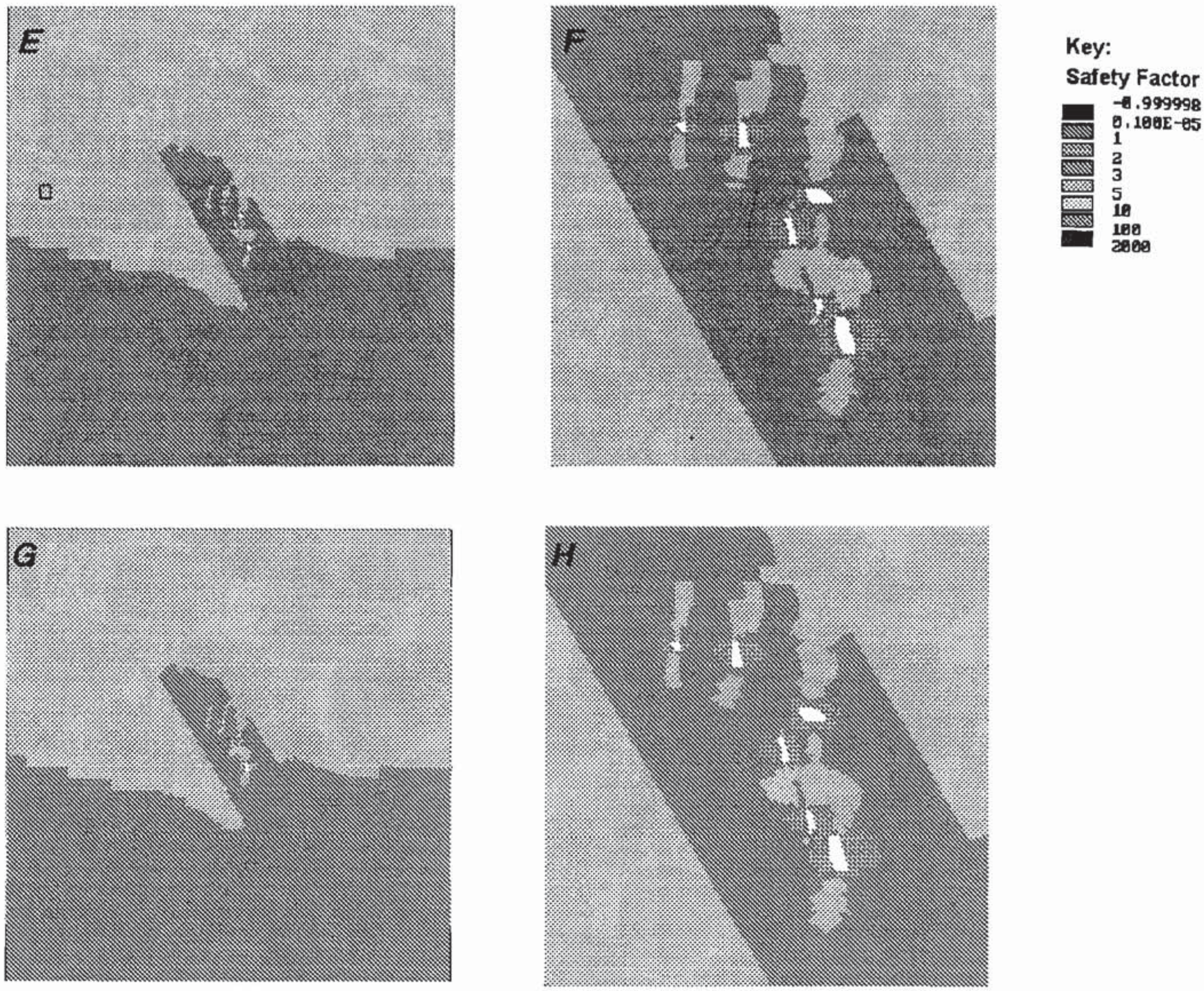


Figure 7
Safety Factor Calculations.



***A*, Load step 1; *B*, load step 1 closeup; *C*, load step 2; *D*, load step 2 closeup.**

Figure 7
Safety Factor Calculations—Continued.



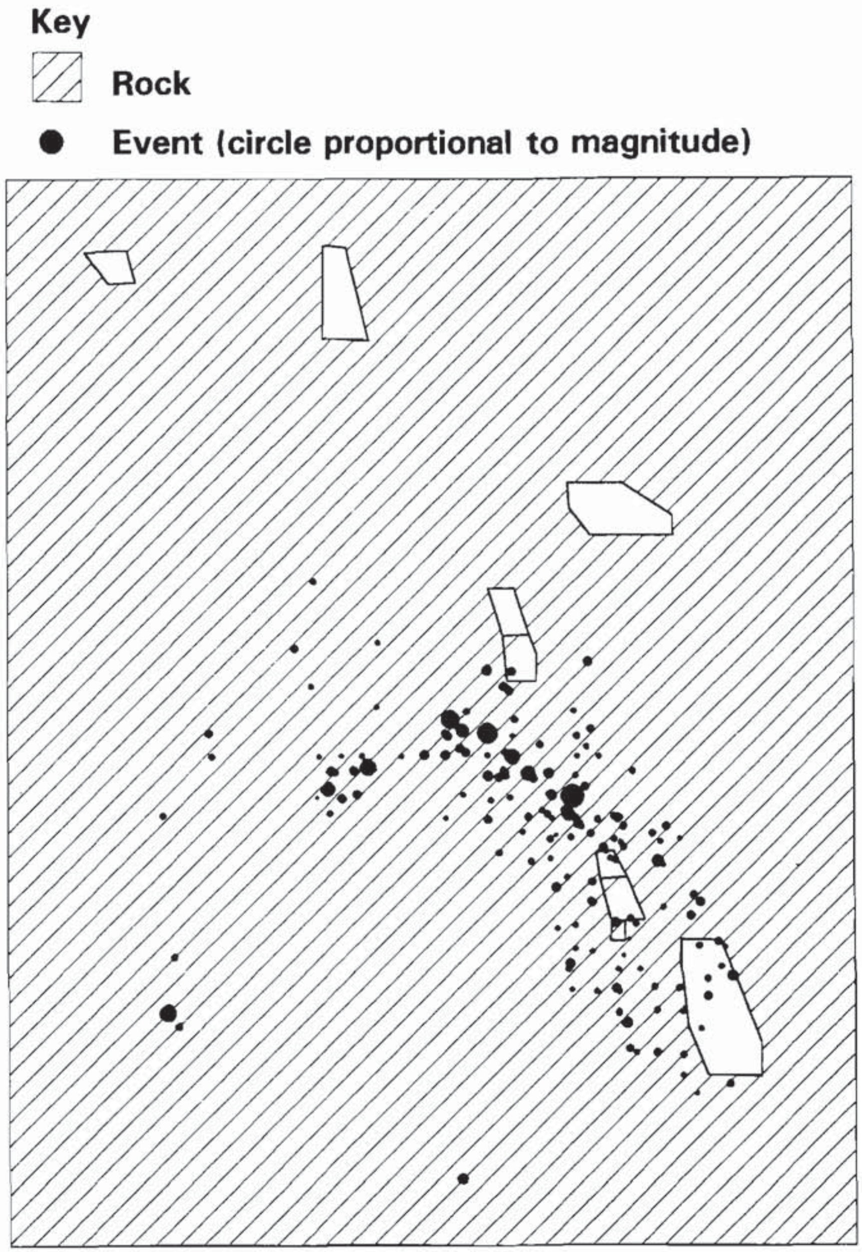
E, load step 3; *F*, load step 3 closeup; *G*, load step 4; *H*, load step 4 closeup.

ANALYSIS AND CONCLUSIONS

Figure 8 overlays all the seismic data from the 44 pillar that were recorded between September 1992 and October 1993. Regions of increased seismicity correspond to regions of lower safety factors as determined using the finite-element program. This finding may indicate a causal link between mining-induced stresses and seismic activity. However, while these preliminary results appear promising, the model was developed as a two-dimensional, linear-elastic analysis. A more rigorous analysis would require a three-dimensional model that incorporates failure criteria and more detailed information on actual mining sequences.

Combining data from seismic recording systems with stope sequencing information and numerical modeling results can be a powerful tool for mine design. Designers may use this tool to avoid mine layouts that could result in the creation of seismically active regions.

Figure 8
Seismic Events at 44 Pillar.



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