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MICROSEISMIC DATA PROCESSING ASSOCIATED WITH MONITORING OF MINE SLOPE INSTABILITIES

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TRAITEMENT DES DONNÉES MICROSISMIQUES RÉSULTANT DE LA SURVEILLANCE DE L'INSTABILITÉ DES TALUS DE MINES

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RÉSUMÉ

La surveillance microsismique des travaux d'exploitation minière à ciel ouvert a été effectuée à la mine Cardinal River près de Hinton, (Alberta). La région choisie consistait en un talus très vaste qui faisait partie d'une couche tectonique de la période jurassique et qui contenait du charbon. Le projet était de nature expérimentale. On a fait une analyse des données dans le but d'étudier la possibilité d'utiliser certains paramètres pour prédire les effondrements, d'examiner la façon d'améliorer le système et d'établir la marche à suivre pour utiliser les résultats conjointement avec les résultats provenant d'autres systèmes de surveillance actuellement en service ou qui peuvent être utilisés à Cardinal River ou dans d'autres exploitations minières à ciel ouvert.

MICROSEISMIC DATA PROCESSING ASSOCIATED WITH MONITORING OF MINE SLOPE INSTABILITIES

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Synopsis

Microseismic monitoring in open pit operations has been carried out at the Cardinal River Mine near Hinton, Alberta. The target region was an extremely extensive slope in highly tectonised, jurassic, coal bearing strata. The project was experimental in nature. The aim of this data flow analysis is to examine the possiblity of using certain parameters as a prediction of failure, to examine where improvements seem possible in the system and how the results might be used in conjunction with other types of monitoring that are currently, or might potentially be used at Cardinal River or other open pit mine operations.

Introduction

This paper consists of two parts; a summary description of the microseismic work carried out by CANMET/CRL and USBM at Cardinal River and secondly the application of a data flow model to methodology of microseismic data capture and interpretation. The description of the site specific work concentrates of the attempt to interprete and process the raw data and to develop techniques that would enable operational decisions to be based on microseismic data.

Cardinal River Experimental Details

The Hardware

The hardware used for this project is that designed and built by the USBM and described in detail by Lepper, Poland and Mullis (1). The system allows for eight geophones to be used and for the transmission of results by VHF radio link from the pit to a suitable building. The processor is based on the Motorola 6800 device.

Installation

Monitoring took place for 28 days in June and July of 1984 on an active slope in the Cardinal River pit 50-B-C. Seven geophones were used on the slope which at the time had a depth of 100-140m. The geophones sites were difficult to access and the test was terminated when rolling debris caused failure.

Geotechnical Background

Cardinal River in common with other similar mines (Gregg River, Smoky River, etc.), are in highly tectonised strata where the rewards for engineering success are axially thickened coal seams and thick pods of coal. The penalty is highly active pit slopes and partially unknown and complex geology. Since the structures are localized, there is an extreme incentive to operate with the maximum possible pit slopes. These mines are generally making use of various geotechnical monitoring techniques, especially electro-optical distance measurement (EDM) and cable bolting of the lower parts of the slopes has been considered. The major influence of geotechnics on economics makes these mines extremely progressive with respect to trying new ideas. Mine management have become extremely able at "managing active slopes", i.e., experience has given them a good grasp of what rates of movements imply danger.

Microseismic Background

Clearly microseismic techniques can be expected to work best in rocks that show brittle properties, are good transmitters of elastic waves and have a known reasonably constant wave velocity. Clearly, this site does not fall under any of these descriptions; failure is relatively ductile, the fractured nature of the strata tends to attenuate the waves and the unknown structural geology especially the position of coal lenses suggests that the rock mass may be inhomogenous in terms of wave velocity. Fig. 1 shows the position of the geophone relative to the pit geometries at various times. It should be noted that if all the geophones were coplanar it would be impossible (mathematically) to determine whether events occur below or above the geophones. Since the geophones are not far from being coplanar small errors can `flip´ solutions so that they appear to occur in the air rather then in the ground, thus `airborne´ solutions are not figments of the machines imagination but reflections of true events.

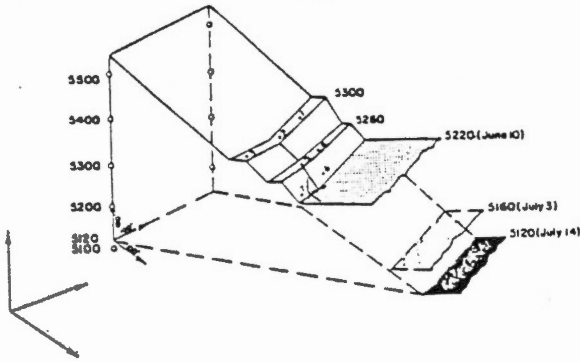

Fig. No. 1

MICROSEISMIC SLOPE MONITORING - DETAILS OF SLOPE DEVELOPMENT

Observations made during the test

EDM measurements as well as visual observations were made at the same time as the microseismic project. Fig. 2 shows time series data for EDM readings and microseismic data. Total slope movement was about 10m. Slip planes could be examined on occasions but one cannot relate these to magnitude on the Richter Scale since movement is by a series of stick-slip movements. They do, however, give an indication of the total amount of energy available for microseismicity in the period.

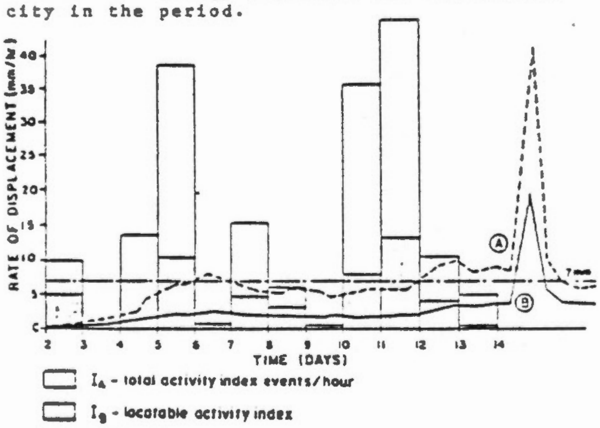

Fig. No. 2

DISTRIBUTION OF MICROSEISMIC ACTIVITY AND THE RATE OF DISPLACEMENT OF THE SLOPE

Event Trigger Error

An event is detected when the voltage from a given geophone exceeds a given level (i.e., is deemed to exceed the background noise) and a digital pulse is generated. Since the first arrival of the wave front is not the same as the time at which the noise level is exceeded there is some inherent error in the timing from this trigger mechanism.

Interpreting the Data from Cardinal River Slope Monitoring

As the data piled up from the experiment it became apparent that the paper output was difficult to use. Thus the data (or at least those events from which source locations were calculated was entered on a minicomputer (VAX 750) for analysis, although it was not clear at that stage what the analysis might be.

Multiple Occurences

Certain locations occurred several times as source locations (Fig. 3).

The first program written `boiled down´ these multiple occurences to a list of source locations and the number of events associated with these locations. This has two points of significance:

1) When displaying points it is desirable to know whether a symbol represents one or a number of points. Also, if one were analysing in real time one might attach more significance to an event from a known active area than an isolated event.

2) That multiple occurences can occur suggests that one is seeing a limitation in the source location system, one might expect to see slight differences between every pair of source locations.

Discretisation

The input channel converters respond to `clock´ signals and make a finite number of observations per second. These pulses discretise the source location in detection time space. When detection time space is mapped into cartesian coordinates the uncertainty associated with an event ceases to be a (5 dimensional) box shape and becomes the shape created by the intersection of paraboloid shells. The shape and size of these regions of uncertainty varies through the region and needs to be considered as a source of error.

Machine Accuracy

Electronic computation requires that a number system be used which limits the accuracy and precision of calculations. Should 16 bit integer arithmetic be used, one might be able to represent 65536 numbers as the number range -32767 to +32768. Fractions are not allowed thus round off errors can accumulate and the integer nature of the arithmetic may significantly restrict the number of possible output values (consider Table 1 with the process of division followed by multiplication). Recent developments in numerical hardware (numerical coprocessors) allow for high precision calculations at high speed. Three sources of errors are described in Fig. 4 a and b.

Cluster Identification

It was decided to classify source locations not only according to the number of occurences (which is likely to be a function of machine accuracy) but also as to the number of nearby locations - i.e., the extent to which they can be thought of as being part of a cluster. This program as with the multiple occurence program uses a linear search for each point processed - i.e., to determine how many near neighbours point N has in a file with X members one must make

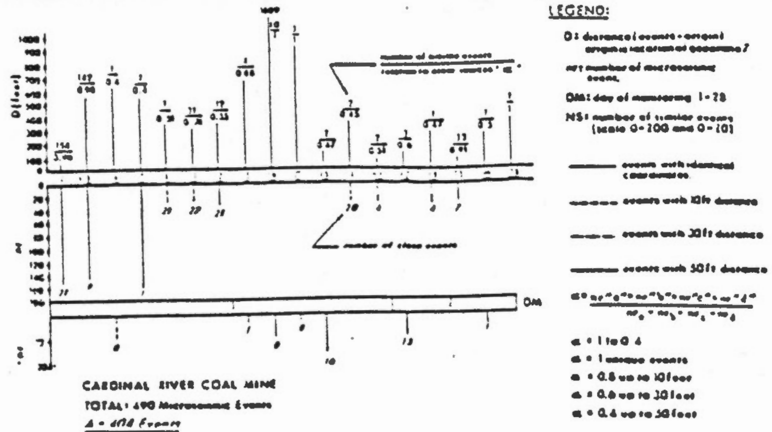

Fig. No. 3 MICROSEISMIC EVENTS RECORDED DURING THE TESTS

Time Descritisation Error

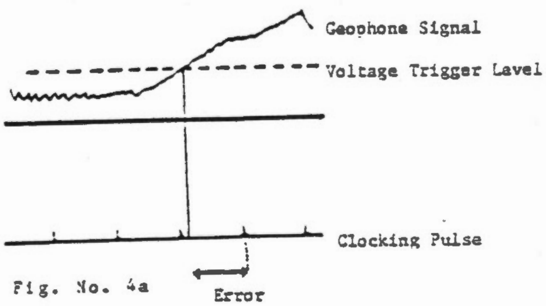

Fig. No. 4a

Event Trigger Error

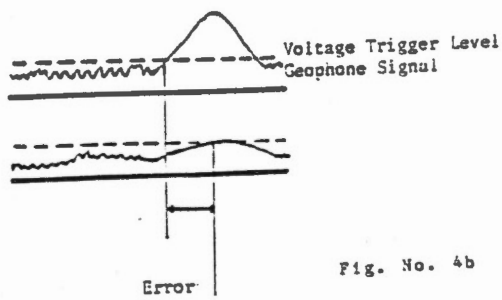

Fig. No. 4b

X-1 comparisons. To do this for each point in the file one must make X(X-1) comparisons. This obviously slows down the procedure rapidly as the file size increases. One possibility is to segment the data files according to the location so that one would only have to search the segments of the data file close to the point of interest. This requires a more complex file structure.

`Boxit´ Algorithms

Serious thought was given to the creation of a classification system based on user defined `boxes´. Conceptually and mathematically, this is simple. The problem lies with the user interface. The global coordinate system used is not parallel to the slope face. Thus, devising a simple way of inputing classifying boxes (which presumably would be expected to run parallel to the slope), was rather awkward. At the time, the laboratory did not have graphics terminals and it became clear that the program might actually cause more conceptual difficulty than it cleared up. It was felt, however, that there would be some merit in a `boxit´ program that had (a) a good graphics interface and (b) full logical capabilities so that, for example, a region `A´ may be defined that is the sum of regions B and C except where this intersects D. This would enable complex regions to be defined such as `close to ground surface´ or `above ground surface´.

Three Dimensional Plotting

There are a number of ways of representing three dimensional data, however, the primary issue is clarity of presentation thus the important thing is to give adequate visual `cues´ as to the position of sources but keeping the diagram uncluttered. This is really an artistic rather than an engineering problem, but it is important never the less. Fig. 5 shows an attempt at 3-D representation which was one of our most successful. It does however, give poor impression of the distance of each point from the ground surface.

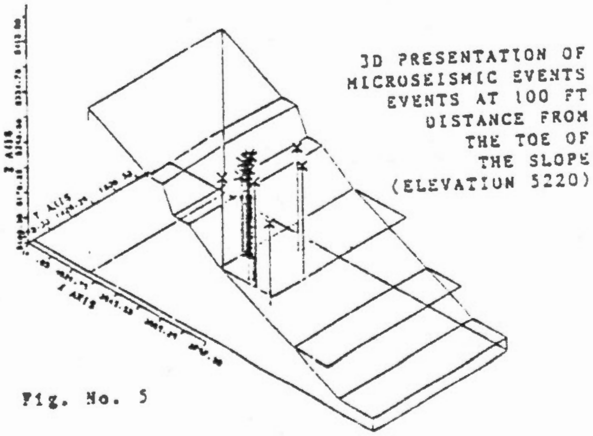

Fig. No. 5

Alternative strategies include changing the projection algorithm, changing the size of the event loction with depth into the paper or using `true three-D´ approaches:

1) Red green 3-D.

   In theory one could generate 3-D images in the manner of 1950's 3-D movies with the images for each eye being produced in a different colour with the observer wearing coloured spectacles. In practice it is doubtful if colour terminals have enough resolution for the subtle differential parallax to be adequately realised.

2) Stereo pairs

   There is no problem in generating stereo pairs which give a three dimensional effect when viewed through a stereo viewer. Plotters generally do have adequate resolution. Our experience is that this down not get around the fundamental `artistic´ problems and to get good three-dimensional effect one needs good graphical design as well as chosen projection parameters.

3) Rotation of the Graphic Image

   With improvements in graphics devices it may soon be a practical possibility to produce an image that can be smoothly rotated. This would give a strong three-dimensional effect.

Finite Element Analysis

Analysis of the slope was performed using the SAP 2D finite element package as described in the CANMET pit slope manual. This gives a 2-D elastic solution. We had to conclude that the indicated zones of high microseismic activity did not correspond to the predicted regions of high stress, presumably because of geological structures of which we were unaware. Never the less, it was felt that the predicted increase in stress levels with the various cuts was a useful parameter to describe the driving forces in the failure and microseismic processes.

The Place of Microseismic Monitoring in the Managerial Process.

One may hope that microseismic monitoring may yield three types of information that may be useable in the management of instabilities:

1) A general level of activity may reveal the range of level and the activity of the slopes. The general level of activity may be characterised in a number of ways;
   - the total number of events recorded i.e., the number of events interpreted as being above some threshold or background noise level.
   - the number of events being indentifed from two or more geophones.
   - the number of events that satisfy a criterion derived by processing: such as energy release or spectral composition.

2) The failure surface may be determined as it develops. One aim of the project described here was to be able to outline the mechanism of failure and thus be able to prescribe remedial measures such as anchoring, drainage or changing the excavation geometry. The plane that was generated by the experiment did not dip into the pit and thus was rather difficult to interpert. The failure surface may be determined both by a planar grouping of located sources and also by a knowledge of the source mechanisms; energy, orientation, displacement, etc.

3) Microseismic monitoring has a potential exploration value; structures may be revealed by their microseismic signatures prior to their participation in any failure process.

Introduction to Data-Flow Models

There are a number of paradigms used to specify computations of which the best known is probably the flow diagram. Data-flow is less specific from a procedural point of view but is appropriate here since we do not wish to determine which tasks should be computerised and which performed manually. The object is to summarize the various algorithms available and how they might be utilized to respond in real time to changes in microseismic behaviour and to effect the incremental design process. A data-flow model specifies the nature of the input and output data from a subprogram but does not specify how the calculation may be performed.

Data-Flow and the Interpretation Of Microseismic Data

In the example considered here the microseismic data was taken on paper tape and manually entered at a computer terminal. To produce three dimensional plots the coordinates of the pit slope were also entered as input for the plotting program. Finally, for the finite element analysis the coordinates had to be entered and converted into suitable 2D coordinates normal to the pit slope. The output from the analysis then has to be remapped back to the original coordinates.

The tool that is sought by the operators is a reliable predictor of failure giving 10-15 minutes warning or whatever time is required to evacuate men and equipment from the area of risk, and secondly, an evaluation of the slopes performance for use when comtemplating the design of a further cut. The former will be referred to as the safety assessment function and the later as incremental design.

Fig. 6 shows a conceptual data-flow map for these functions. The safety assessment process is really the merging of a number of different sources of data: Microseismic data which might arrive in real time, EDM and conventional geotechnical data (extensometer, piezometer, etc.) which arrives periodically depending on the perceived seriousness of the situation; and data on the mine geometry. To make sense of the data and to make the important decision on whether to evacuate the pit one would wish for a real time graphical output of the time series associated with each reading type and a three dimensional plot of measured movements and seismic sources. Currently, with EDM monitoring, a simple rule is applied in terms of

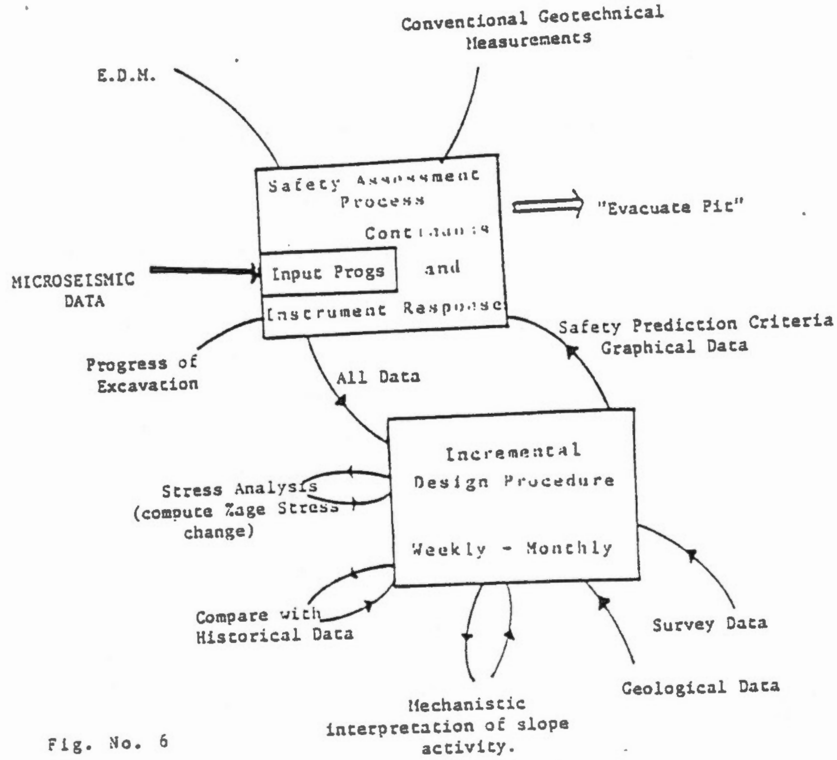

Fig. No. 6

MICROSEISMIC MONITORING DATA FLOW MODEL

rate of movement or acceleration (however a great deal of thought goes into the selection of the 'alarm' value). The more types of data available the more complicated the evacuation criterion. Most of the data types that the decision is based on are capable of throwing up errors so it is desirable to keep a human element in the process.

The incremental design function is taken to include all engineering judgements that determine the short term geotechnical procedure; the mining sequence (geology in these pits is partially discovered as one mines); updating the safety rules and slope design modification. Our experience with SAP 2D finite element analysis suggest that it would be an extremely useful tool in incremental design if the ergonomics were improved. Ideally, grid generation should be interactive and based on the geometric data used obtained from survey. Similarly, material properties should be available from a lithological lookup table. Also, graphical post processing is extremely desirable. Of the three or so weeks work involved with SAP 2D grid generation (working out appropriate coordinates for the grid generation program), material property selection, physically plotting grids and output, and writing output routines to compare values for different cuts took the bulk of the time, and this could largely be eliminated. Stress values from an elastic solution may prove to be highly useful when compared with other data - if the user interface is right. An example of the output is illustrated in Fig. 7. Most developers of FEM programs at least in the academic environment believe that the world is waiting for a better plastic failure model and do not perceive the ergonomic problems to the practicing engineer.

The microseismic source locations are probably of the most use in the incremental design function where some attempt can be made to identify patterns and perhaps deduce the likely mode of failure.

A critical issue, on which information suggested by FEM like the SAP 2D approach may be of importance, is the location of the geophones. Recent studies undertaken at Penn State by Dr. Hardy indicates that optimization of source location transducers may significantly enhance the accoustic emission image. This is associated with a relatively good knowledge of the structure and geomechanical data of the monitored area.

If one examines the input process of the microseismic data one sees a number of problems that can easily be automated. This consists of filtering the input values for obvious errors, classifying sources and compiling data into time series and other plots.

Filtering the Data

One may automatically discard data if it appears to come from outside the region of interest or if it appears to be the result of lightning, blasting, falling rocks, etc. Under certain circumstances one might choose to omit data from the set of source locations

FEM mesh:
. 1300 elements
. 1376 modes
. 3 types of materials

4 Models:
A - reference
B - softer materials
C - in situ stresses
D - without coal lenses

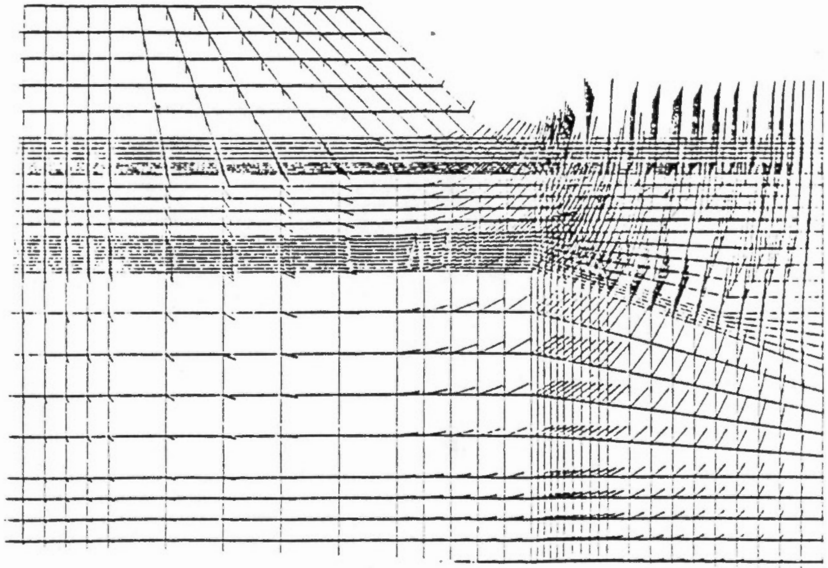

Fig. No. 7

DISPLACEMENTS EVALUATED BY FINITE ELEMENT METHOD - SAP-2D

(because it appears to be in the air) but not exclude it from the time series analysis.

The Classification of Events

Events can be classified according to the number of geophones on which they were detected, their energy, clustering characteristics or according to the region in which they occur.

Compilation

Time series and treed spatial plots can be created for a combination of categories.

Data-Flow Model of the Wider Microseismic Process:

One may consider the cybernetic implications of all aspects of the transmission and processing of seismic waves in terms of how information concerning the source event is transmitted or lost:

A) The Input Process: the seismic event

There are a small number of parameters concerned with the source event that one might wish to evaluate: - space-time coordinates (x,y,z,t), mechanistic parameters such as type (slip, impact, explosion,...), energy, orientation, slip length and maximum particle velocity at source.

B) The Initial Wave:

If events occured in an idealised isotropic elastic solid, the waves would maintain a simple wave front from which the above parameters could be estimated from a small number of sampling points (geophones). Under such conditions p and s waves only would be involved.

C) Seismic Wave Transmission:

A variety of processes occur that cause signal loss or convolution of the wave:

i) Reflection - partial reflection of seismic waves at material property boundaries causes convolution (an increase in the complexity of the wave as a function of the structure that it passes through).

ii) Refraction - refraction of seismic waves convolves the wave front by changing its shape and direction.

iii) Surface Waves - Love and Rayleigh waves are also created by the interaction of body waves with material property boundaries.

iv) Attenuation - wave energy is lost largely due to destructive interference around discontinuities. This reduced the signal to noise ratio (SNR).

v) Dispersion - dispersion is the tendency for waves of different frequencies to travel at different speeds. This tends to soften the peeks of pulse type waves and change the spectral make-up of the wave.

vi) Diffraction - this plays a role in attenuation and accounts for some non-linearity of wave path.

Many of the above effects could be compensated for is one had perfect knowledge of the rock mass and adequate numbers of geophones. If one could fully utilise the information obtained from microseismic data, one would learn more about the rock mass as one obtained more data - thus the location of ones first event might be revised in the light of subsequent data.

D) Transduction Analogue Electrical Signals:

Most geophones currently used for microseismic work are one dimensional, for example, they produce a single voltage output through the motion detected may or may not be in any direction. Thus there is a loss in directional information and the ability to discriminate between wave types. Geophones are deliberately selected for their frequency effects, for example, they are most sensitive to the frequency band of interest. Geophones can be thought of as points that sample a surface (the wave front), thus, if the wave front is a complex shape, we expect our knowledge to be incomplete. Geophone also record seismic noise (signals we are not interested in from machinery, etc.) and electrical noise is also compounded in the transmission system.

E) Analogue Transmission and Processing

The geophone signal is generally conditioned prior to transmission by cable, either to boost the power or merely, to adjust the impedence. This theoretically must introduce noise, however, for practical purposes the only noise noticed from this stage were erratic signals created by lightning.

F) Analogue-Digital Convertion

The voltage trigger wave front detector can be thought of as being a one bit analogue to digital converter. Clearly, this stage in the process disgards a great deal of information on the wave front as well as introducing the errors discussed previously.

<u>Implications of the Data-Flow Model</u>

The tantalizing thing about microseismic methods is that, in theory at least, microseismic waves carry enough information to determine a great deal about the failure mechanism causing the event and the strata through which the waves pass. In practice, most of the potential information is not obtained due to the following processes:

i Sampling and noise

The obvious improvements in this area would involve increasing the number of geophones.

ii Processing

The problem of processing is challenging and falls into the same class of problems as three dimensional vision and tomography. The present architecture demands that should a greater number of geophones be used the processor would have to work proportionately faster.

iii Distribute the processing

To construct systems that use more of the available data and/or larger number of geophones techniques must be employed to take the strain from the central processor. If each geophone contained a processor, information on events could be transmitted to the central processor as a "package" containing the geophones name, time of the event and other data. The central processor could then work on the "packages" rather more slowly and make use of additional information on the events and apply better error detection rules. The effective sampling clock rate would not be determined by the number of geophones or the central processor. Additionally, single channel techniques such as digital filtering can be applied within the geophone processor.

Conclusions

Microseismic monitoring of ground still represents a domain of expectation for geotechnical and mining engineers. To date several microseismic instrumentation systems have been developed in deep mines in Ontario in relation to rockburst hazard mitigation programs while the Cardinal River experiment represents one of the first extensive application for open pit operations.

Monitoring of pit slope instabilities by microseismic procedures have the benefit of a much larger volume of observation than point observation methods such as E.D.M. or extensometers.

The monitoring had the objective to identify and reduce mining risks related to slope instabilities which is important mainly when coal lies in the toe or below the toe area of steeply dipping seams.

The monitoring procedure was controlled by the dynamic nature of the mining operations, for example, the pit floor was lowered by about 30m in two phases of excavation.

The geometry changes resulted in significant stress and strain modifications. The paper refers to the attempts to handle the dynamic aspects of the monitoring and the implications of the associated stress modifications. Attempts were made to account for slope behaviour using a number of models. The mathematical models used are those referred to by the Canadian Pit Slope Manual, in particular SAP 2D, which is accessible to most mines in Canada. Particular problems are detailed which are specific to microseismic procedures and application of the data-flow model for processing accoustic emissions from a pit slope (Fig 8 and 9).

The field study was carried out as a joint project of CANMET* with the U. S. Bureau of Mines and the mine operator. Cardinal River Coal Mine was part of an evaluation of the applicability to geological structures. U. S. Bureau of Mines microseismic monitoring equipment developed especially for pit slopes was used.

*CANMET - (Canada Centre for Mineral and Energy Technology).

The intent of the paper is to inform the geotechnical community on some of the problems associated to microseismic procedures.

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(2) Early Warning of Slope Instabilities by Microseismic Monitoring, by M. Lepper and T. Vladut, Fourth Conference on Accoustic Emission/Microseismic Activity in Geological Strucutures, the Pennsylvania State University, October, 1985, p. 1-19.

Source location event analyer for early warning purpose

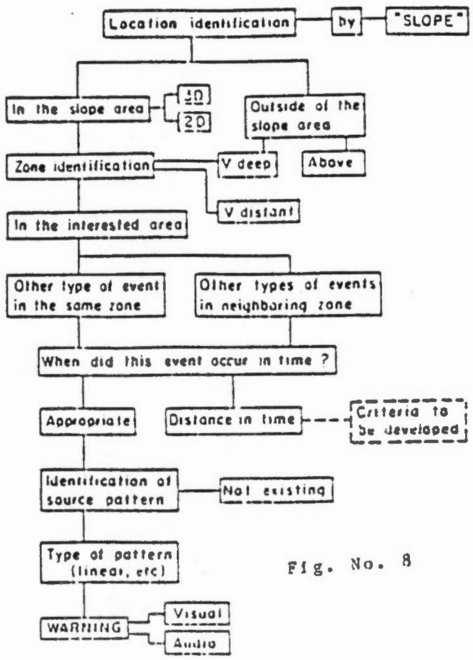

Fig. No. 8

Options in slope monitoring

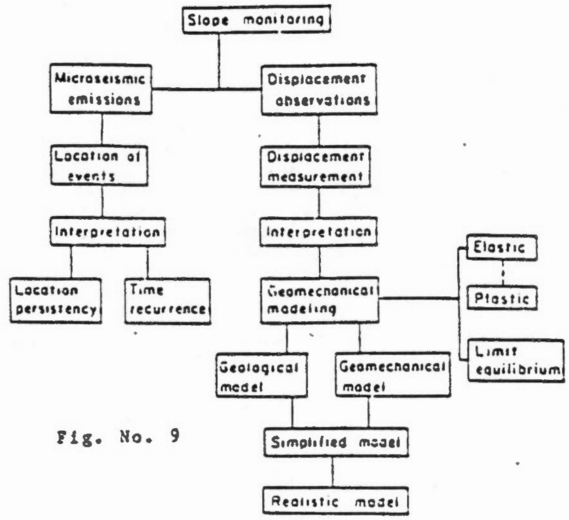

Fig. No. 9

The Effect of Round-off Error in Integer Arithmetic

Input Value	divided by 9 and rounded	Times 11
55	6	66
75	8	38
105	11	121
61	6	66
73	8	88
86	9	99
99	11	121
91	10	110
89	9	99
103	11	121
80	8	88

Wide range of input values ------------------ Maps into a select range of output values

Table No. 1