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DEVELOPMENT OF A SEISMIC SYSTEM FOR THE DETECTION OF TRAPPED MINERS

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ABSTRACT

When a rockburst occurs, consequences can be of great importance both for the safety of the mineworkers and the extraction in progress. After the recent dramatic accident that occurred in Lassing, Austria (1998), where miners were deadly injured, the French national coal industry has initiated a project for the development of a system for the detection of trapped miners.

We have been asked to develop a system based on the location of microseismic events generated by miners on the sidewalls of a gallery. A preliminary estimate of the quarters and galleries where the miners are expected to be trapped allows the installation of seismic sensors in a sensible place. The system is designed for a real time acquisition and processing of any microseismic event recorded in the rock mass. This paper presents the description of the experimental equipment and results of the preliminary test conducted in the French national coal mining company (Charbonnages de France) test site.

INTRODUCTION

World history of post disaster survival and rescue operations shows that, after a rock fall or rockburst, early knowledge of the number of trapped miners and their location dramatically increases their chances of survival [1]. Such information could be obtained if there were some kind of communication between the trapped miner and the rescue team, or if location equipment were available. A fast location of the trapped miners, with a reasonable accuracy, increases the efficiency of the mechanised operations for the retrieval of the miners and reduces the time rescue personnel are exposed to a potentially hazardous environment. In many instances, rescue teams have risked their lives in areas where there were no trapped miners only to learn later that if the rescue effort had been directed into other areas of the mine, lives could have been saved [2]. This problem was emphasized for example in the 1968

explosion at the Consol Number 9 Mine in Farmington (US) [3] when the accurate location, the number and the condition of the trapped miners remained totally unknown until their rescue. More recently (1998), the worst Austrian mining accident since the 1940's happened in Lassing where ten miners were deadly injured when the talc mine caved in. A lack of information provided to the emergency services on the accurate locations of the buried miners contributed to delay the rescue operations.

Following this accident, the French colliery company decided to renew its equipment for the detection of trapped miners developed in the 1970's. The system was designed to work from a set of geophones deployed from the underground and provided a location from a graphical interpretation of seismic signals. Due to the development of new technologies and its expertise in the treatment and seismic data, we developed a system based on the same concept, using seismic sensors, with the objective to enhance the location accuracy whatever the gallery geometry.

This paper describes the existing systems for the detection of trapped miners, the main characteristics of the new developed system and its first experimental results.

STATE OF THE ART

Numerous trapped miners detection systems have been developed by the mining countries to match one or all the following objectives:

1. provide information so that rescue efforts could be initiated and directed toward the proper area in the mine;
2. guide the rescue team to trapped or injured miners who might be within a few metres but buried under rocks or obscured by smoke and debris;
3. keep the communication between the members of the rescue team when progress is rendered difficult by the smoke and debris in hazardous environment;

The purpose of this paper is to concentrate on point 1.

The principal requirement for the location of trapped miners is the set up of a communication between the buried and/or injured miners and rescue teams. This establishment of information through the rock mass can either be done by generating a noise source by striking the mine gallery or by carrying some kind of transponder or tag in the miners cap lamp battery. In the first case, a seismic based technique has to be deployed whereas a communication using electro magnetic waves is required in the second case. We recall in the following section the main principles of both techniques [4].

Electromagnetic methods

The potential to communicate with underground trapped miners was realised in the 1920's, when simple investigation of underground reception of Long Wave commercial stations where made [5]. Nowadays, the most commonly developed materials are based on the use of electromagnetic waves between a source carried in the miner's belt and an array deployed by the rescue team [6, 7]. The Integrated Miner Safety Device developed by CSIR[1] uses this technology, which appear to be very suitable for deep conditions in local hard rock mines. Using a tag transmitter with a 40-60 mW output and a 2.9Mhz operational frequency for the antenna, could provide at least 30 metres location range though the rock. The Bureau's Pittsburgh Research centre developed the Electromagnetic method considering the advantage of this technique for the voice communication [8]. Results from this technique showed that the probability of detecting a signal from an underground transmitter is 45 per cent at a depth of 3000 metres and 90 per cent when the depth is reduced to 1500 metres. Further developments by SELECTRONIC (called Sirius) in South Africa (1995) for through-rock communications were carried out using modulation of electromagnetic waves by the heart beat and/or the movement of human chest while breathing.

Seismic Methods

A limited number of systems working with the seismic method have been listed in the literature. The US Bureau of Mines in 1970, following the suggestions of the National Academy of Engineering [9], undertook the use of the seismic technique for the detection of trapped miners. The principles of this technique consist in the use of a network of geophones placed on the surface above the area where the miners are suspected to be trapped. As displayed on Figure 1, the miners are supposed to hit a part of the mine with any heavy object available in the surrounding. The generated seismic waves are then recorded on the sensors at the surface and the analysis of the travel time differences between the different sensors allows a location of the seismic noise. The resolution of an inverse problem trying to determine the best location with the only knowledge of the travel time of the seismic wave between a source and the receivers at the surface is highly dependent on two main parameters: the sensor distribution relative to the location of the seismic source and the choice of the velocity model.

This system, which is still maintained operational and deployed as one element of the Mine Safety and Health Administration, consists in the use of seven subarrays of sensors; each subarray is composed of either 7 or 24 geophones. Tests carried out at various sites have shown that the detection with a single subarray was sufficient to identify the signal as coming from an underground miner [10]. The identification can be more precise if several subarrays can detect the signal; a location becomes possible with at least three subarrays but a minimum of five is required for a reasonable accuracy (less than 300 metres). It appeared that the expected accuracy of a few metres for the positioning of the rescue borehole was not realistic and the main source of error was attributed to the topographic relief and geologic conditions that expectedly varied with position.

The equipment developed by "Charbonnages de France" followed the demands from France and Germany to the European Community in 1968 and 1973. One of the objectives was to

reduce the duration of the rescue the trapped miners by operating directly from the underground galleries rather than operating from the surface [11]. The main advantage of this technique is the reduced scale of the trapped miners search, limited to the vicinity of the rescue team gallery (less than a few hundred metres). Sensors were deployed along a line in the closest gallery to where the miners were trapped and the location procedure was based on a graphical interpretation of the seismograms (Figure 2). Depending upon the position of the source relative to the geometry of the sensor array, the accuracy of the location could vary from two metres (when the source was located in a gallery parallel to the geophones and at the position described on Figure 2), up to several tens of metres for perpendicular galleries. The paper graphical display of the seismograms was not constantly working and made the system not optimal for the purpose of the trapped miners rescue.

The new system, SYDEM (**SY**stème de **D**étection des **EM**murés)[12] developed for "Charbonnages de France" is based on the same hypothesis but uses state-of-the-art seismic acquisition and processing techniques.

SYDEM : SYSTEM INSTRUMENTATION

Equipment description

The operation of the system is displayed in . The signals generated by the miners are recorded on the seismic probes. The geophone used, the Geospace GS-20-DH with a at 28Hz – 1kHz frequency range, is housed in the seismic probe as well as the pre-amplifier. Signal is amplified with a selectable gain from 10 to 60 dB depending upon the *in situ* conditions and signal to noise ratio. The probes are inserted in 50 mm diameter boreholes and are coupled to the rock mass using a plastic wedge. The installation of the probes can be done for a borehole up to a depth of 5 to 10 metres. Metal cables fixed to the probes and wedges allow a fast

unclamping of the probes in case they have to be quickly removed due to a damaged borehole or a low signal to noise ratio. The analog signal is sent to the acquisition unit via a cable.

The acquisition unit is composed of a filtering unit that is switch-able by the operator in case of the presence of electrical noise in the gallery (50 Hz characteristic frequency). This initial processing step eliminates interference that would, in some instance, limit the system performance. Waveforms are then stored with a length sufficient for a full recording of the signal for P and S wave arrivals, at 16-bit, 15 kHz sampling. Once the installation of the seven probes has been completed, the data acquisition can be tested using an AUTOtest function. The response of the system to a ± 2.5 V spike is an essential control of the connection quality and satisfactory operation of each element for the acquisition after the installation.

The number of sensors for the triggering can be set depending upon environment interference (electrical or man-made) during acquisition. The acquisition is set by default to run continuously with an automatic display of the last recorded event. The automatic display option has to be unselected to perform interactive signal processing on the data. Waveform processing was manually done with the picking of the P wave on each channel of the event and the location algorithm is directly run from the acquisition software. The result of the three-dimensional location is automatically displayed on a graphical interface superposed to a drawing of the area of investigation.

All the system settings and the processing are conducted through a lap top personal computer connected to the main acquisition box. The acquisition unit is equipped with two 12 Volt batteries for an operation estimated at a maximum of 12 hours. The PC is limited to the of the battery life of 3 hours.

Location procedure

The location of a seismic source is often a complex issue due to the number of parameters affecting the solution, coming up from a non-linear problem, such as the number and

geometry of the sensors, accuracy of the velocity model and the *in situ* conditions. In the case of a location with an acquisition unit working from the underground excavation, the geometry of the sensor array is forced by the geometry of the gallery i.e. without any boreholes, geophones are necessarily deployed along a line.

It was possible to overcome the poor sensor coverage by using the hypothesis provided by Charbonnages de France that the system would be used in a case where the location of the trapped miners is unknown but in the limits of a given gallery. This assumption has allowed the development of a "grid search" procedure based on a comparison of calculated travel times with observed travel times (Figure 4). The gallery where the miners are suspected to be trapped is discretised with elementary volumes and travel times are *calculated* with straight ray paths for each gravity centre of the volume and compared to the *observed* travel times. The residual of the two travel times is defined as :

$$R.M.S. = (\Sigma (T_{\text{calculated propagation}} - T_{\text{observed propagation}} + T_{Origin}))^{1/2}$$

and it is chosen as the quality criterion for the location. A high value of the R.M.S., in comparison with the rest of data set, is an indication of a large discrepancy between the observed and calculated travel times. The principal origin of these errors is usually attributed to a wrong picking of the P arrival on one or several channels, and/or a significant difference between the effective velocity field and the propagation model. On the contrary, for a given velocity model and with the experimental uncertainties (wrong picking, errors in the sensor locations), the minimum of the R.M.S. criterion is chosen as the location of the trapped miners.

Seismic noise

Seismic noise can at times be a major problem with detecting small amplitude seismic signals. Since the signal from a trapped miner can be on the order of a few mV, a normal background

noise can perturb the signal. There are three common sources of noise typically encountered in the field: (a) natural seismic background noise, (b) manmade seismic noise, and (c) electric interferences. The latter may be readily eliminated by use of the 50 Hz filter previously discussed. Since natural and man-made seismic noises tend to vary widely as a function of the geographic location and time, it is not possible to make any predictions. The solutions adopted to overcome this problem are two fold: (1) use a stacking routine during acquisition in order to enhance the signal to noise ratio, and (2) apply a numerical filter adapted to the characteristic frequency of the noise during the processing.

The data analysis has shown the miners were not likely to strike identical shots at one point of the sidewall. This implies that stacked data should be used very cautiously as the addition of two different signals on the same channel may give a wrong waveform with strong uncontrolled artefacts, perturbing the true location of the trapped miners.

EXPERIMENTAL PROCEDURE

The SYDEM was tested in different geometries with several objectives: to evaluate the efficiency of the system to locate trapped miners, estimate the influence of local parameters such as noise sources and the velocity model, and make a first estimate of the necessary time for a complete installation of the system. Since the situation the miner will face in the case of a rock burst is very unpredictable, we have conducted location tests using various types of sources that a miner may typically have around him, such as metal bars, wood pieces and a plastic helmet.

Experimental site

The system was tested in two gallery configurations : (a) parallel galleries 60 metres long and 20 metres distant, and (b) two perpendicular galleries (Figure 5). The seismic probes were installed on the sidewall facing the trapped miner gallery. The spacing between the probes

was chosen to ensure the maximum coverage (10 metres average). The geology of the two test pillars is sandstone.

Different sections were selected in the trapped miner gallery in order to measure the location error. Four points were defined for each section, on the sidewalls (facing and opposite to the trapped miners gallery), the roof and the floor (see Figure 5c for notations).

Installation

When an alert occurs where trapped miners are involved, the following operations have to be undertaken prior to any actual seismic investigations :

- meeting of the rescue operating people;
- transport of the SYDEM to the gallery identified has being the closest to the gallery where miners are trapped;
- drilling of seven boreholes in the direction of the gallery of investigation;
- accurate survey of the borehole coordinates. The surveyors also have to provide the three-dimensional orientation of the trapped miner gallery in order to set up the discretisation grid;
- installation of the seismic probes and connection to the acquisition system;
- testing for successful installation (AUTOtest) and set up of the acquisition parameters (noise level, amplification of the signal, coordinates of the sensors, geometry of the experiment, acquisition data);

The required time for all these operations was measured to 4 hours before the first signals were recorded. This time, however, does not take into account a realistic delay for the transport of the equipment to an underground gallery with all the constraints this may suppose. A minimum additional time of 3 to 4 hours would have to be added.

If the detection had to be carried in a mine area with the standard 5000 V in the mine, an adapted 230 V power transformer would have to be installed in the mean time.

Results

Parallel galleries

In our tests the signals were recorded with a maximum amplification of 60 dB and 15 kHz sampling. A typical event recorded on a minimum of 5 channels is presented at figure 6. The signal frequency of the signals ranged between 150 and 270 Hz using a heavy metal piece as a source and 70 to 180 Hz with a plastic helmet. The trapped miner gallery was discretised with 0.5 m elementary cubes.

Due to the limited distances between sources and receivers in both experiments, errors in the picking of the arrival and in the velocity model are prone to significantly affect the accuracy of the location. The velocity model is usually unknown when arriving at a site. In this case we have compared the propagation model obtained from direct measurements (2000 m/s) with an indirect measure. A seismic probe located 5 metres ahead of the rest of the seismic line, noted S9 on Figure 5a, was placed in order to measure a travel time difference between sensor S8 and S2. For a ray propagating directly across the pillar facing the two sensors, a velocity equal to 1800 m/s was measured. In the case of parallel galleries, the 11 per cent velocity variation does not affect the location result by more than 10 per cent and can, so, be considered as a good approximation for the wave propagation model.

At each test points, miners were asked to hit a minimum of ten times in order to use the information provided by the stacked signals. Locations of some points in the different sections are presented in Table 1. The minimum location error is found when the miners are striking directly on the sidewall facing the sensors (point B2, C2 and E2). The difference for section D shots is not significant as the sidewall (shot point D2) is cemented with a poor coupling with the rock mass, causing a strong perturbation of the waveforms.

Errors on the other points in the sections (points 1, 3 and 4) are due to the variation in the velocity field. The basement of the trapped miner gallery is grouted and a higher velocity model estimated at 3000 m/s improves the location of the point B3 to less than 1.5 metres. In the case of the roof and the sidewall opposite to the seismic base, the distortion of the waveforms generated and travelling around the gallery up to the sensors cannot be taken into account in the location calculations and, as such, explains the discrepancy with the observed travel times.

Section	Point	Error (m)	maximum error (m)
B	1	4,2	5,3
B	2	0,9	1,3
B	3	2,5	5
B	4	3,0	7
C	1	3,0	4,7
C	2	1,5	3
D	1	2,3	3
D	2	2,2	3,5
E	2	1,0	4,3

Table I: Locations for parallel galleries at different points in the sections (see Figure 5a and Figure 5c for notations).

The different material tested showed a significant decrease of the signal to noise ratio (40per cent) and, thus, altered the quality of the picking. The soft materials used as sources like a miner helmet caused a decrease of the signal frequency. This induced an increase of the error in the location greater than 2 metres, and up to 7.9 metres when striking the sidewall with a miner safety shoe (Table 2).

	point	Error (m)	maximum error (m)
Metal support	B2	2,5	3,9
Helmet	B2	2,0	3,5
Plastic piece	B2	7,9	9,8
Rock lagging	F2	3,1	7

Table II: Location results with different materials for the source.

Perpendicular galleries

Three sections noted from G to I (Figure5b) have been defined in the trapped miner gallery and sources were limited to points 1 and 2. The average spacing between the probes is eight

metres. The locations calculated for the six points are presented in Table III. Errors are larger than in the case of parallel galleries and this is attributed to a combination of factors.

Firstly, the seismic array is perpendicular to the direction of the sources and the solution is highly unconstrained in the direction of the trapped miner gallery. Locations found in Table III were determined for a minimum in the RMS for various velocity models. The best location was found for a velocity model of 1450 m/s. We calculated that a ± 3 per cent variation caused a 30 per cent increase of the location error and a 10 per cent velocity variation an error in location of 300 per cent, less than 15 metres in this particular case.

Secondly, the signal to noise ratio in this part of the mine was significantly lower than for the parallel galleries due to a strong attenuation of the seismic energy (Figure 8). This caused an increase in the uncertainty in picking the P arrival. This can be overcome by choosing to pick the first peak, and good quality signals to be distinctly recorded on a smaller number of channels.

Point	Error (m)	maximum error (m)
G1	5,00	7,8
G2	3,0	4
H1	5,3	4,3
H2	1,7	4
I1	2,0	4
I2	3,8	5,5

Table III: Locations for perpendicular galleries at different points of the sections (see Figure5b for notations).

DISCUSSION

In a configuration where miners are confined to a 60 metres long gallery parallel to the seismic base, the SYDEM is able to provide a location of the miners with an accuracy better than 2 m in 70 per cent of the case and less than 5 m in 90 per cent of the cases. The maximum accuracy (less than a meter) is obtained when the miners are striking the sidewall facing the sensors. If the miners were hitting some parts of the gallery with non-rigid objects, we have always been able to detect and locate them within a 10 metres maximum error

around the true location. All these locations, however, are subjected to the choice of a velocity model as close as possible to the true P wave velocity in the rock mass. The addition of a shifted sensor from the seismic base line allows a good estimate of the velocity when we are considering a ray path travelling directly across the pillar.

The configuration of perpendicular galleries has shown a significant sensitivity of the location algorithm to the input velocity parameter. Further developments are currently in progress for the implementation of additional parameters to help the operator in the choice of the most probable location. These complementary calculations will be validated in a set of tests planned with more complex gallery geometries and in a coal environment.

CONCLUSION

The choice of a detection technique for trapped miners is motivated with the twofold objective of efficiency and accuracy. The other techniques reviewed in the literature were not sufficiently adapted to the requirement of "Charbonnages de France" and, thus, the adopted option was to improve the existing seismic based technique. Compared to the graphical system previously used in the French colliery, the SYDEM is easy to set up with a delay no longer than eight hours between the alert and the recording of the first signals. Its ability to conduct real time and continuous acquisition make this system a more adapted equipment for rescue operations. The accuracy of the system, shown on the tests described, is sufficient to make a decision on the drilling of a rescue borehole: close enough to the trapped miners but at a reasonable distance in order to not injure the miners with the drilling.

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FIGURES

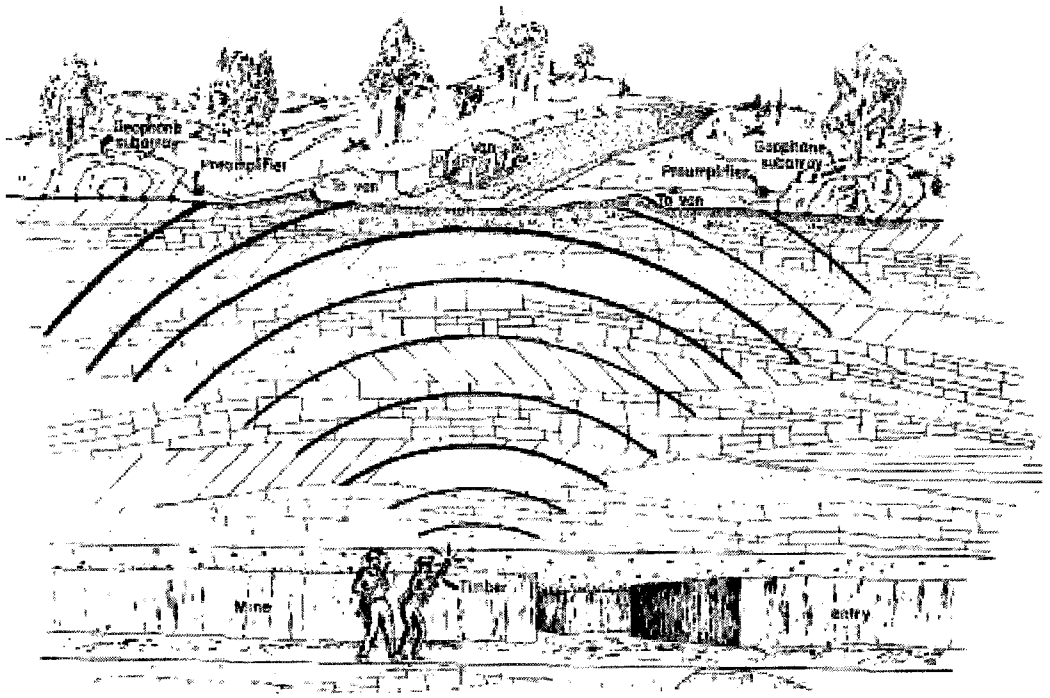


Figure 1 : Detection of trapped miners from a set of geophones deployed from the surface. The miners are hitting the sidewalls of the underground gallery and shot are located from the analysis of P-wave arrival times on the sensors. (from Dobroski and Stolarsczy, 1982).

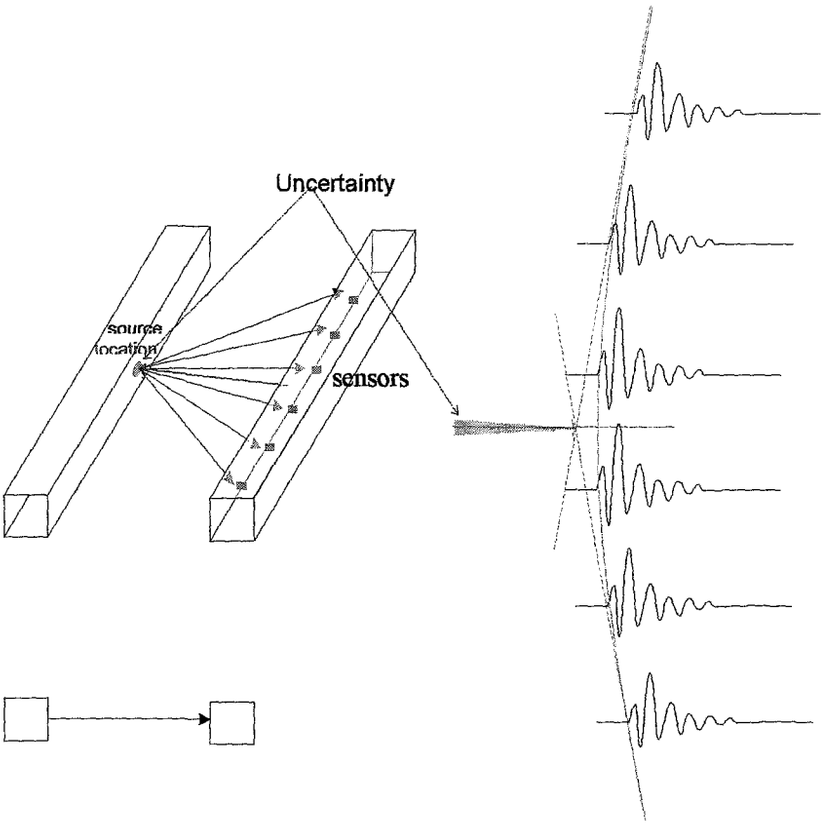


Figure 2: Graphical technique previously used at Charbonnages de France for the detection of trapped miners in a simple configuration. Two lines joining the P wave arrival times are drawn. The intersection of the two lines is indicating the direction and the location of the seismic source. Depending upon the experimental and picking errors, an uncertainty has to be estimated (Grisard et al, 1981).

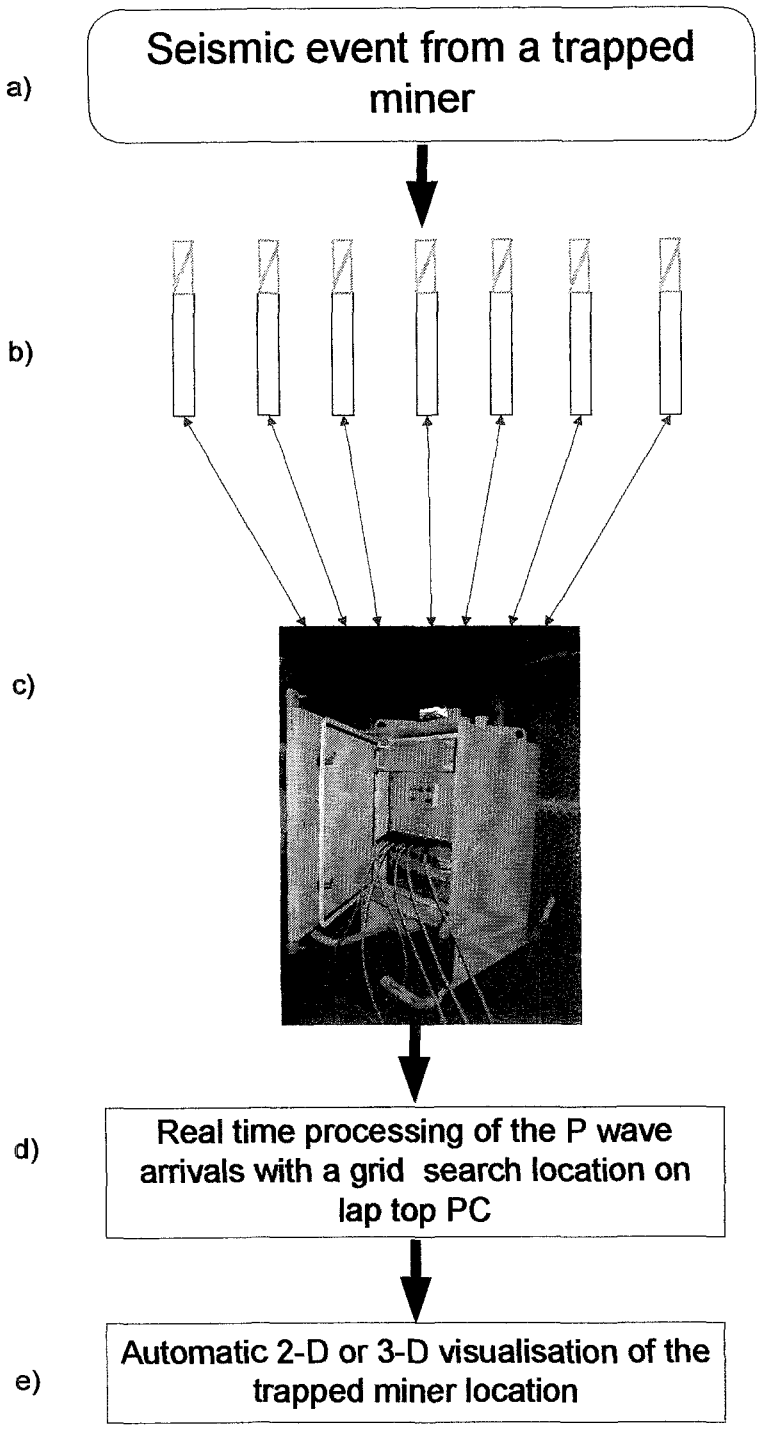


Figure 3: SYDEM operational description. (a) A seismic event from a trapped miner is recorded on the seismic probes. (b) Probes are clamped to the rock mass through a plastic wedge system. (c) The analogue seismic event is sent to the acquisition system for filtering and A/D conversion. (d) The analysis of the P wave arrivals on the PC provides locations of the trapped miner. (e) Automatic two or three-dimensional display of the trapped miner location.

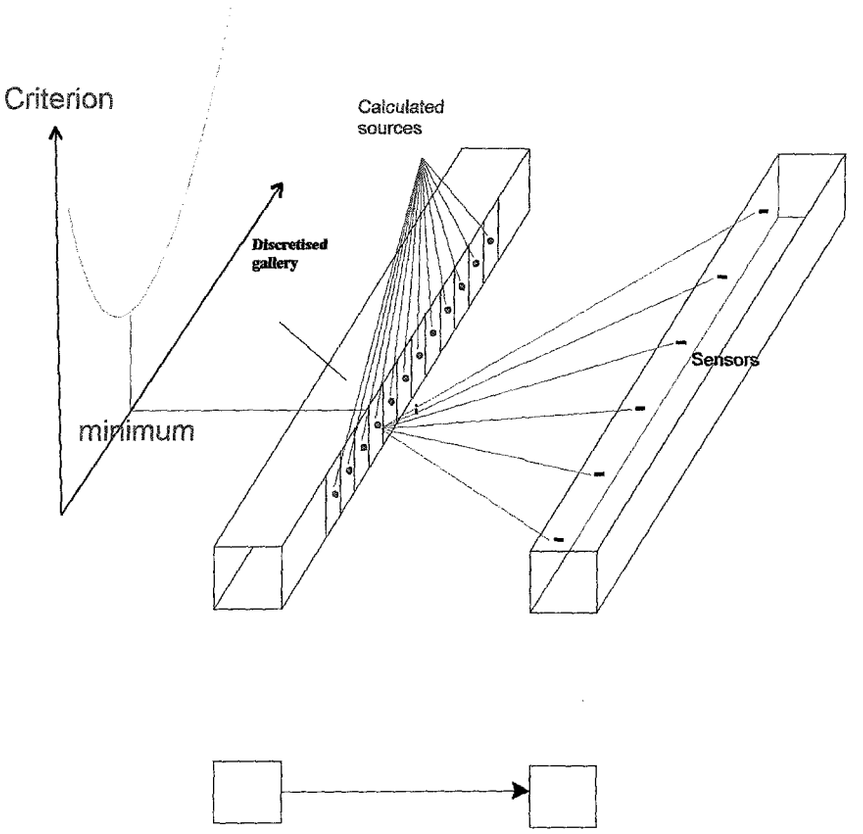
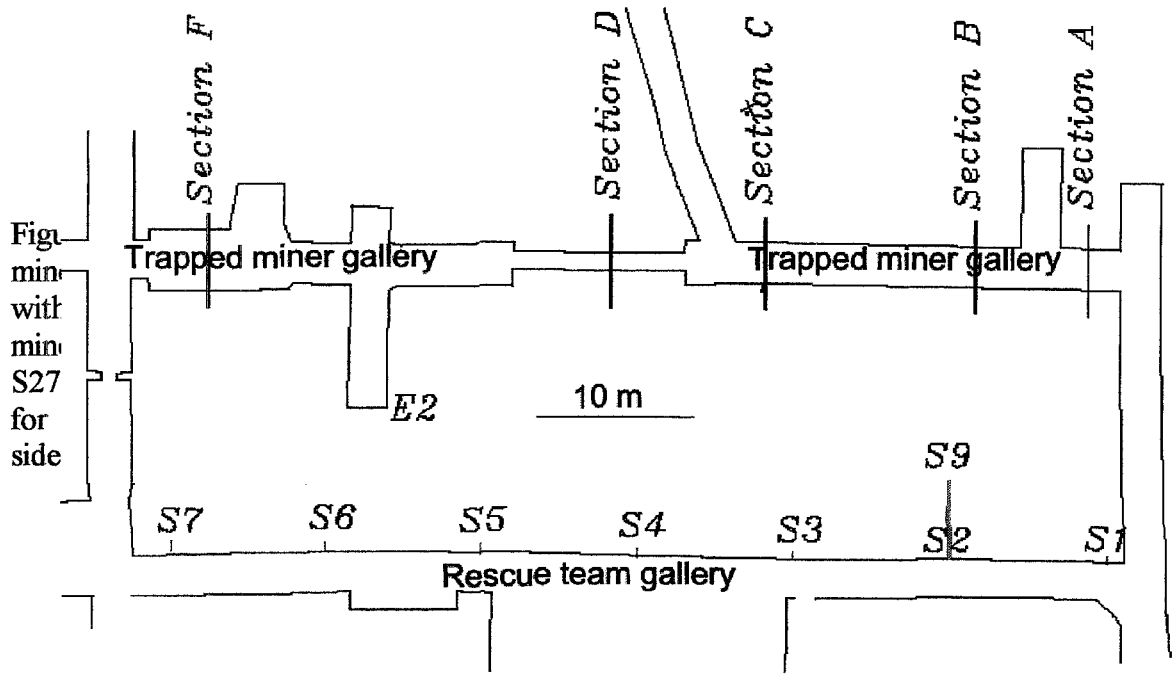
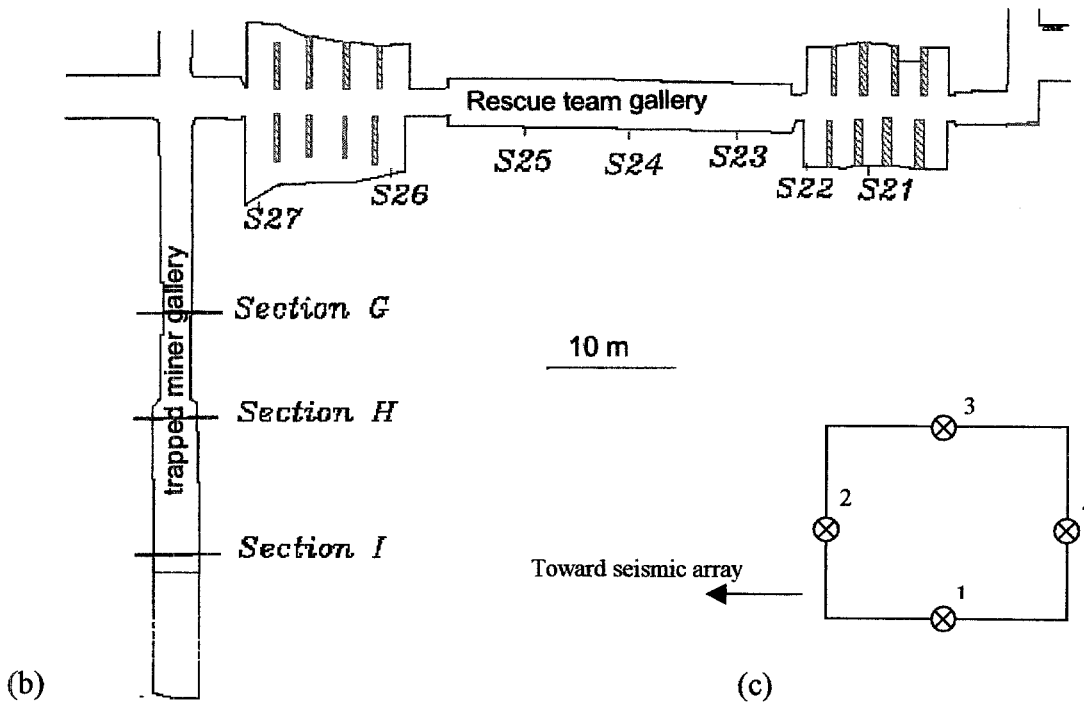


Figure 4: Grid search technique for the detection of trapped miners. A grid size is defined for the calculation of travel times in each pixel. For a velocity model and with the experimental errors, the minimum of the criterion between calculated and observed travel times is chosen as the location of the trapped miners.

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(a)



(b)

(c)

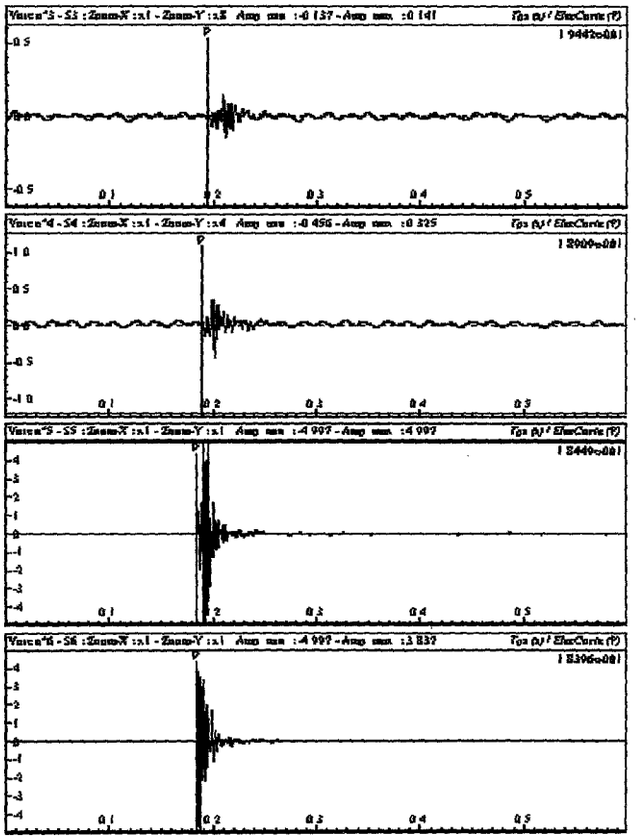


Figure 6: Example of seismic event recorded on four channels at shot point 2 from section E (sidewall facing the rescue team gallery for parallel galleries). The waveforms are 0.6 seconds long with a 15 kHz sampling frequency. The P-wave arrivals have been picked for a grid search location processing.

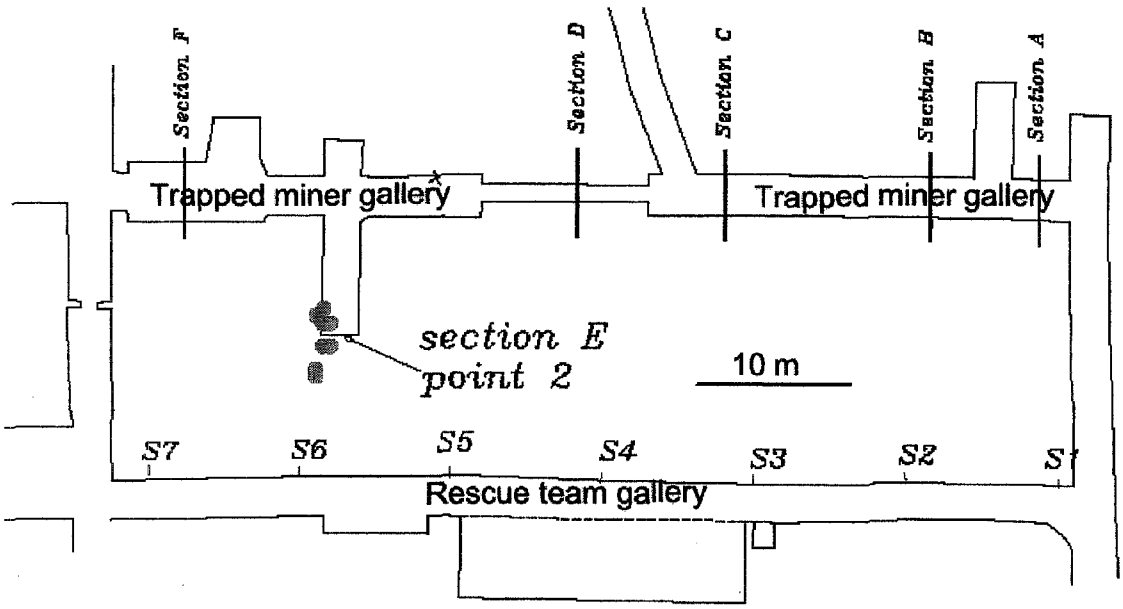


Figure 7: Plane view of the pillar for test 1 with parallel galleries. Results of the grid search location for the shots at the point 2 from section E in the trapped miner gallery are displayed with dots.

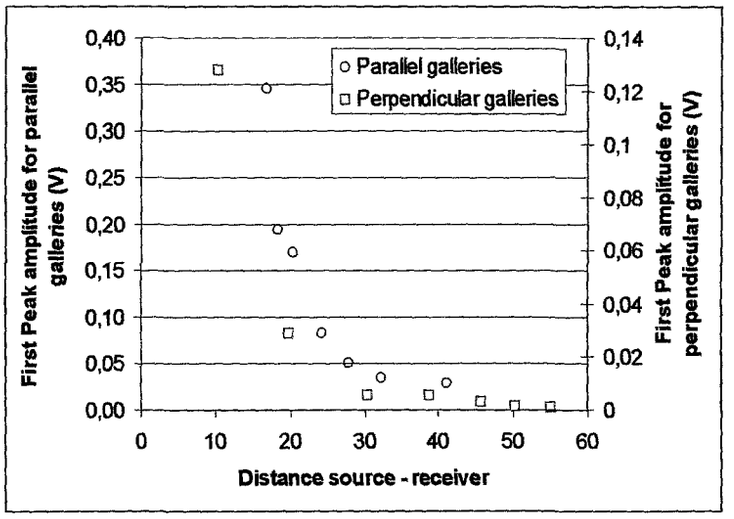


Figure 8: Energy attenuation of a seismic shot as a function of distance to the sensors for a shot recorded in the perpendicular and parallel gallery tests. The large decrease of the energy between 10 and 20 metres in the perpendicular galleries, compared to the parallel galleries, is attributed to a significantly damaged rock mass.