Real time stability control in uderground room and pillar mining
Controle en temps réel de la securité d' une mine souterraine exploitée par la méthode des chambres et pillier.
Fortwährende kontrole der stabilität eines unterirdischen, mit der Methode der Zimmer und Säulen, abgebauten Bergwerkes.

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ABSTRACT: In order to introduce large scale mechanization and increased productivity and ore recovery in an underground mine, the degree of safety has to be continuously monitored. The development, installation and evaluation of a real time data acquisition and control system for monitoring of roof deformation and stress changes, with strain gages, load cells and displacement transducers, in an underground bauxite mechanized room and pillar mine, is presented. A contiguous signal flow from the sensors streams to an interface and via an amplifier and a transformer reaches the computer, where data are interpreted. The system is rugged, reliable, easily installed and inexpensive.

RESUME: Dans le but d' introduire mécanisation a grande échelle, augmenter la productivité et obtenir aussi un haut degré de récuperation dans une mine souterraine, le niveau de securité doit etre continuellement controlé. Nous presentons le developpement, installation et évaluation d' un système pour obtenir, en temps réel, des informations indispensables qui concernent les déformations du toit et les variations des contraintes dans une mine souterraine de bauxite, exploitée par la méthode des chambres et pillier afin de les controler. Des signaux contigus, provenants des “sensors” coulent vers un arrangement qui les conditionne et en suite à travers un amplificateur et un transformateur arrivent a l' ordinateur pour être interpretés. Le système est robuste, facilement installé et relativement non couteux.

ZUSAMMENFASSUNG: Um in einen unterirdischen Bergwerk eine grössere Mechanisierung zu einführen und den Ziel die Produktion und den Erz Gehalt zu erhöhen, man muss den Grad der Sicherheit dauernd überwachen. Die Entwicklung, Installation und Schätzung eines gleichzeitigen Daten Erlangung und Kontrole Systems, für die Überwachung der Deformationen und der Änderungen der Spannungen mit Verwendung von Verzerrungs Gauge, Belastungs Zellen und Verschiebungs Transduktoren, in ein unterirdisches Bauxit Bergwerk, das mit der Methode der Zimmer und Säulen abgebaut wird, ist vorgestellt. Ein fortwährender Signal Lauf von den Sensoren strömt durch den Verstärker und den Transformator und reicht zu den Computer wo die Daten interpretiert werden. Das System ist kräftig, zuverlässig, leicht angelegt und relativ billig.

1 INTRODUCTION

The main bauxite deposits in Greece expand within the geosyncline of Parnassos-Giona-Helicon-Oiti mountains, the main axis of which has a northwest-southeast orientation. The deposits belong mainly to the uppermost third bauxite horizon, which is of diasporic type and is surrounded by fully stratified microcrystalline limestones. It is located approximately 750m above the sea level in a depth of 450 m with an average dip of 20^{o}, a W-SW/N-NE strike and an average thickness of 5.6m varying between 2-14 m. The hangingwall of the deposits consists of dark-coloured, rudistic, bituminous limestones of the Turonian-Senonian period. The footwall of the deposits consists of lower Cretaceous white limestones which are always establishing a characteristic angular unconformity with the hangingwall.

Extraction of bauxite is usually performed by mechanized room and pillar mining. Design of pillar layout and dimensions is based on pillar strength, which holds until the end of the depillaring stage. The immediate roof is reinforced by expansion shell rockbolts 2.1 m long. Intense and systematic rockbolting provides tensile and shear strength to the bedding planes of the hangingwall. Thus a massive and strengthened rock beam is established which prohibits roof failure and increases considerably the completed exploitation span. The latter is influenced by the pretension, length, spacing and stiffness of the rock bolting system.

Ground control is based on field observation of roof failure modes, in situ testing, performance monitoring and careful evaluation of the excavation stability especially during the depillaring stage. However, a number of controlled roof failures occurred, mainly during the gradual increase of the room dimensions at the depillaring stage. Most of the failures are related to rock mass weakness due to tectonic disturbances, weak or soft rock material, strata separation, clayey joint filling, high residual local stress field, high permeability, karstic erosion provoked by the delayed installation or the improper selection of the rock reinforcement system. The modes of failure observed are grouped (Economopoulos et al., 1993a) into nine types, i.e. critical joints, midspan or abutment tensile cracking, ineffective rock bolts, proximity to junction drifts, improper rock bolt spacing, low strength of the immediate roof rock material, peripheral spalling, karstic erosion and bent roof strata. The roof falls occurred as violent incidents of relatively short duration (up to 48 hours) with precursor indications such as noise from the roof and the pillars, fall of small sized rock particles, formation of tensile cracks on the roof (voussoir beam mechanisms) and bolt failure (Economopoulos et al., 1994). On the other hand, pillars in the affected area showed signs of heavy loading and spalling. The karstic voids, which are randomly distributed in the roof and the presence of faulted zones affect the stability of the limestone roof and of the bauxite pillars and render non predictability to the local mining conditions (Economopoulos et al., 1993b). These difficulties necessitate the use of innovative, low cost prediction and monitoring systems of the rock mass response due to the mining activities, in order to achieve higher extraction ratios without decreasing the safety standards of the mining operations.

Till now, only empirical observations and conventional low cost measurements were performed during the exploitation, such as vertical convergence, rock deformation, pillar surveillance and bolt pull out strength tests (Economopoulos et al., 1991). Roof-floor convergence measurements were executed from the beginning of the exploitation up to the final stage of retreat mining.

Measurements were taken from the mined out stopes and detailed observations were done in order to evaluate roof stability and pillar design thus improving the "natural support" system. Mechanical deformeters were installed, either vertically in the mine roof in order to measure separations between layers of limestone as a function of time or horizontally into the bauxite pillars for measuring their lateral expansion and monitoring their stability. Pillar joint survey was performed to a group of them in order to evaluate any modes of failure. The survey and the visual observation of the behavior of the bauxite pillars showed the dominant joint sets and provided important information for improving the mine-layout and the pillar design. The pull out tests were executed in order to test the performance of the expansion shell rock bolts, used in the mine.

2 INSTRUMENTATION

The system is installed in the underground bauxite mine for evaluation and verification of its performance, under real in situ mining conditions. It is used for continuous monitoring of roof response in a typical mining room from the beginning of extraction until the end of the retreating stage. The two important monitored variables are the roof deformation and the stress changes, measured through strain gages, load cells and displacement transducers.

Electric resistance strain gages operate on the principle that the resistance of a wire changes proportionally with strain. Strain gage systems are bonded to a rock or to a steel surface. Changes in the strain of the host material and the bonded gage are accompanied by changes in the resistance of the strain gages which are read by using a Wheatstone bridge electric circuit. Expansion shell anchor bolts are used mainly for roof support, the length of each bolt is 2.10 m and the diameter of the steel bar is 16mm and of the anchor head 35mm. It is decided to use these regular bolts and by mounting strain gages on them to develop modified strain gaged bolts for recording the in situ axial acting loads. After many trials and modifications, a low cost instrumented bolt was constructed (Figs. 1, 2). Initially, the bolt was slotted with a continuous cut of 30cm along its threaded end. Then, from the end of this slot, a flat surface of 7cm was machined on which two strain gages were placed, each one acting as a quarter of a Wheatstone bridge. The role of this slot was to allow the leads from the strain gage to pass through the threaded end of the bolt, thus protecting it from damage during fastening of the bolt nut with the impact wrench. Electrical resistance strain gages are chosen as they are ideal for precise strain measurements and inexpensive. For obtaining reliable measurements, both the correct adhesive and the proper mounting procedures have to be employed.

Initially, the flat surface where the strain gage will be located is carefully prepared. This preparation consists of taking away the eventually existing rust in order to obtain a smooth, but not highly polished, surface. Special solvents were employed to remove any traces of grease and to give the proper chemical affinity for the adhesive to the steel surface. Fully encapsulated k-alloy strain gages were used with an effective length of 0.350 inch. They have a resistance of 350 Ω, a strain gage factor of 2.05, an axial sensitivity of 2.03 and a transverse sensitivity of -0.0690. They were mounted using "M-200" adhesive. This gage - adhesive combination may produce valid strain measurements up to 60000 microstrain. The gages were mounted with their long axis parallel to the longitudinal axis of the bolt. After bonding the gage to the bolt, lead wires were attached so that the change in resistance could be monitored on a suitable system. Finally strain gages were covered with a rubberized coating "M-coat J" which provided an effective barrier against a high humid environment and protected installations from mechanical any damage. Prior to the application of "M-coat J", exposed electrical connections were covered with a layer of Teflon tape to provide insulation against any electrical leakage. To prevent penetration by water at the leadwire entrance to the coating protective coating "M-Coat B" was applied there to a distance of 25mm. The instrumented bolts were laboratory calibrated in a uniaxial tension machine to determine the voltage change directly with known applied axial load (Fig. 3). These results are used to analyze the data obtained from the underground testing. Underground testing of bolt loading was done in a room and pillar section of the bauxite mine, where two fully instrumented bolts were installed. This area is systematically supported with 2.1m long, 16mm diameter expansion shell rock bolts in 38mm diameter boreholes at 1.5m centers.

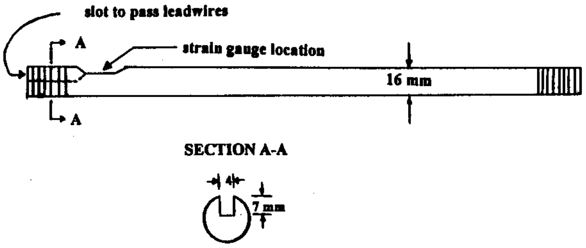

Figure 1. Strain gaged modified rockbolt.

Figure 2. Instumented steel bar.

The rock compression displacement transducer (Fig. 4, 5) measures the contraction of rock layers by detecting the relative displacement that has occurred between the roof surface and a specific anchor installed at the bottom of a 3m deep borehole. It has a rated output of 1mV/V (2000mε), a maximum excitation voltage of 10V, a bridge resistance of 350 Ω and a rated capacity of 50 mm. The instrument is calibrated locally (Fig. 6).

The load cell (Fig. 7) is used to measure loads on a rock bolt. It has a rated output of 1mV/V, a maximum excitation voltage of 10V, a bridge resistance of 350 Ω and a rated capacity of 20 tons. Its calibration is shown in Figure 8.

3 DATA ACQUISITION SYSTEM

The introduction and evolution of the modern personal computer makes possible for virtually everyone to take advantage of the flexibility, power and efficiency of the computerized data monitoring systems (Chilton et al., 1983). PCs offer high performance and low cost, accompanied with an easy-of-use. Thanks to a significant degree of standardization among PC and electronic manufacturers, a large family of hardware/software tools and application packages has evolved. In order to achieve optimal results during monitoring of the underground rock

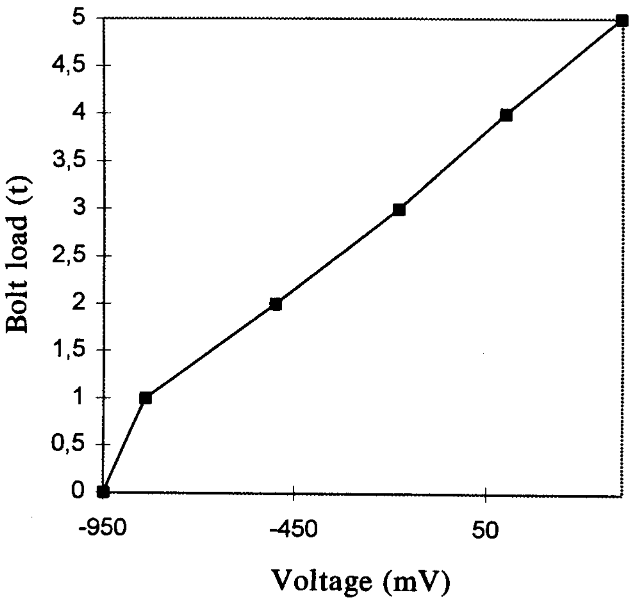

Figure 3. Calibration chart of the strain gaged bolt.

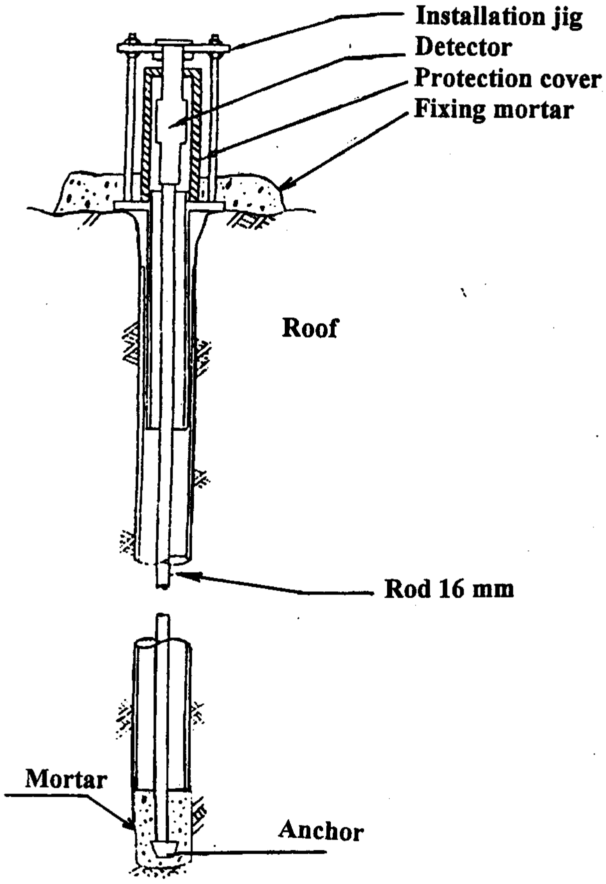

Figure 4. Rock compression displacement transducer.

mass behavior, the devices were based on the structure of "electronic" type system. Towards this particular aim, special strain gage transducers were developed during the research work. Such components "translate" the measuring value of the desirable parameter into an electric signal of appropriate scale, which is then transmitted through the necessary wiring to the data acquisition unit.

The basic structural element of the system consists of an PC compatible computer, in which all information from the sensors and the other devices were registered. This basic PC unit involves microprocessor, memory, power supply, etc., without any keyboard and output devices, such as monitors or printers and plotters. The structure of the system is shown in Figure 9. The main part of the system is based on a previous research work, focused on the development of an air monitoring system for diesel-powered underground mines (Kontothanassis, 1994). Resistance signals arrive at the system from primary strain gage sensors, which are measured as part of Wheatstone bridge circuit. A bridge is a symmetrical, four element circuit that enhances the system capabilities to detect small changes in the sensor. The strain gage sensors occupy two arms of the bridge and the load cell sensor and the displacement sensor one arm of the bridge, with the other two (or respectively three) arms being filled with fixed resistors. A differential voltage signal is developed across the arms of the bridge when the sensing resistor varies from their nominal value as a result of strain.

Signal entering in the system may include unwanted noise, which depends basically upon the signal-to-noise ratio. In general, it is desirable to minimize noise to achieve high accuracy. The major noise transfer mechanism includes conductive, inductive and capacitive coupling. The switching of high-current loads (i.e. booster ventilation fans) in nearby wiring can induce noise signals by magnetic coupling. Signal wires running close to AC cables can pick up 50/60 Hz noise by capacitive coupling. Allowing more than one power or signal path, ground loops can be produced that inject errors by conduction. The noise level induced, will depend upon several user-influenced factors, such as the input impedance of the data acquisition system, the signal source load impedance, the length, shielding and grounding of the lead-wires, the proximity to the noise sources and finally, the signal and noise amplitude.

Strain gage transducers are modeled by a current source (4-20 mA) for being inherently less sensitive to magnetically induced noise pick up than the voltage-driven devices. The maximum allowable cable length depends on a great number of factors, such as the signal noise type, the signal level, the cable type, the noise source type, the distance between the cable and the noise sources, the noise frequency and the required accuracy. Using a shielded wire cable, 4-20 mA signal, accuracy 0.5% and a bandwidth limited to 10 Hz, cables 400 m long are successfully used in

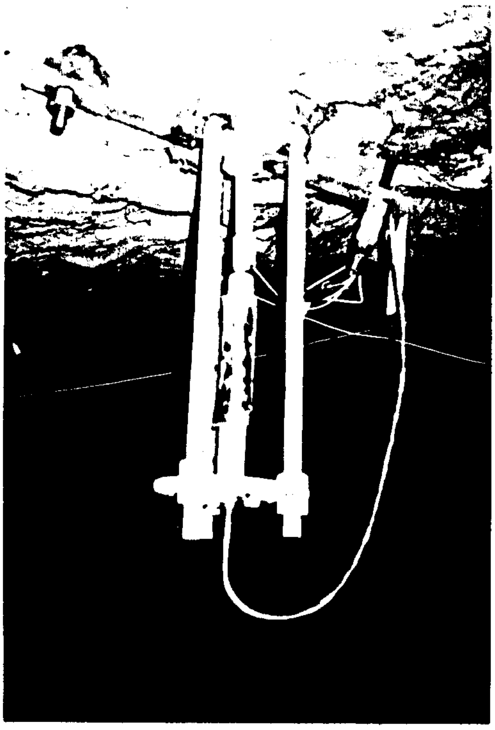

Figure 5. Rock compression displacement transducer installed in the mine roof.

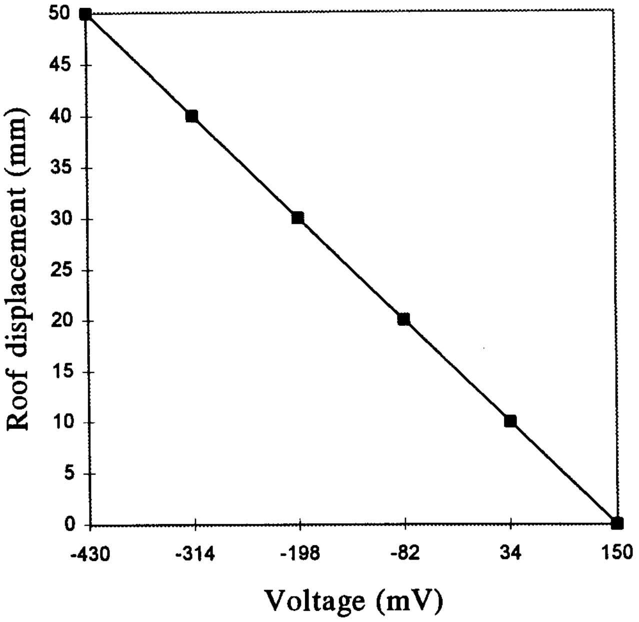

Figure 6. Calibration chart of the rock compression displacement transducer.

Figure 7. Load cell installed in the mine roof.

this typical underground mine environment. Generally, the allowable cable length L is given by using the following formula (Burr-Brown, 1990) :

$$L \propto \frac{I_s \cdot D_n \cdot C_f}{f_n \cdot A \cdot N_i}$$

where,
I_s : signal level,
D_n : distance to the noise source,
C_f : coupling factor, which is inversely proportional to the effectiveness of any shielding of the wires,
f_n : noise frequency,
A : required accuracy,
N_i : noise source intensity.

Due to the effect of signal conditioning on the quality of the input signal, the ultimate performance of the system can be greatly influenced by the type of conditioning employed for maintaining the overall accuracy. The signal conditioning interface includes current-to-voltage conversion, scaling, isolation and amplification. The output from the strain gages is converted to high level 4-20 mA signal at the source and then are converted back to a voltage at the measurement system, with a simple resistor of 250 Ω. For effectively increasing the signal-to-noise ratio, it is necessary to employ a special technique for attenuating 50/60 Hz noise, such as two-pole passive filter and furthermore, to design special software technique for reducing the effect of random, non-periodic noise sources by averaging the input data.

Analog isolation (capacitively coupled) is used to protect people and equipment from contact with high voltage. The fundamental function of an analog input system is to convert the analog signals into a corresponding digital format. The "analog-to-digital converter (A/D)" transforms the original analog input data into computer readable data (digital, binary code). In addition to the A/D, several other components are required to obtain optimum performance, such as an amplifier, a sample/hold (S/H) circuit, a multiplexer and signal conditioning elements. The dynamic ranges of the strain gauges have been under consideration, in the specific application. Dynamic range is the span, or difference, between the maximum full scale signal level and the lowest detectable signal. There is not necessarily a good correlation between strain gages accuracy and dynamic range, e.g. a 0.5% accurate transducer can have a dynamic range of more than 80 dB, thus requiring a converter with at least 12-bit resolution.

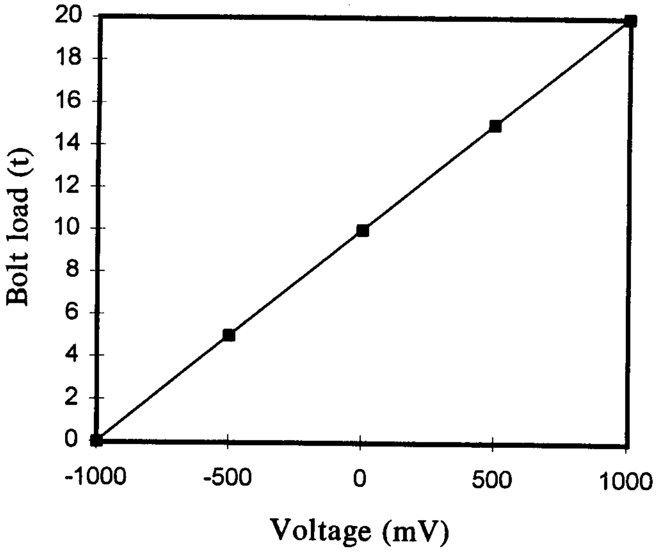

Figure 8. Calibration chart of the load cell.

The A/D converter requires a high-level signal in order to perform its best. An amplifier is provided to boost possible low-level signal to the desired amplitude, with several gain choices available, all under software control. The multiplexer is simply a switch arrangement that allows many input channels to be serviced by one amplifier and an A/D converter. Software can control these switches to select any one channel for processing at a given time. The function of the sample/hold is to grab the present value of the signal just before the beginning of an A/D conversion. This level is held constant, despite a changing input, until the A/D conversion is complete. Conversion time defines only the speed of the A/D converter, which is part of the total time required to measure a given channel. The true speed of the system is calculated at 10 kHz (input data every 1.6 μsec).

Even with the high-quality components mentioned above, it is desirable to pre-process the input signal. This task is called signal conditioning and is divided into two categories. Active signal conditioning includes amplification and isolation, while passive includes voltage division, surge protection and filtering. In the specific application, analog

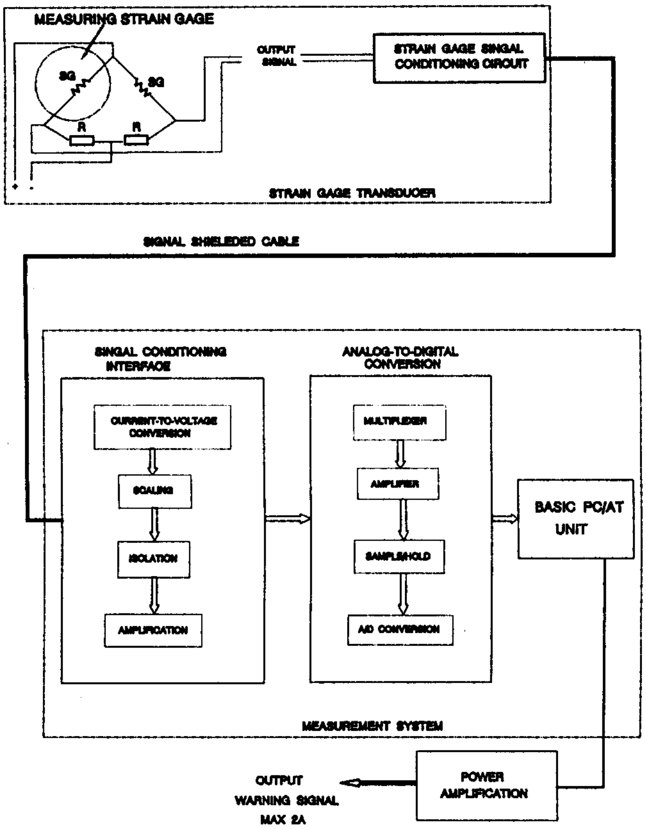

Figure 9. Structure of the system hardware.

output signal is required in order to activate external warning devices. In this case, a reverse process has to be followed. The output digital signal of the computer is translated into an analog electric signal of a discrete intensity value, through the circuit of Digital/Analog (D/A) converter. The D/A converter can supply up to 10 mA of load current (max 10 V), which is then driven to an external circuit of the signal conditioning interface (power amplification), that can supply up to 2 A of load current. This signal is able to activate the control switches of the desired device.

The computer is supplied with specific software in C language, developed for the particular application. It is noted that the undisturbed operation of the system, the storage of the measurements as well as the application of the appropriate criteria (for the control of the hangingwall and the support of the necessary decisions), are based on the above software. Polling is the simplest method for detecting a unique condition and then taking appropriate action (Fig. 10). This involves a software tool that contains all the required measurements, analysis, decision making algorithms and planned actions. The program periodically tests the system clock if it senses a transition. Whenever a transition occurs, the program samples each of the inputs and stores their values in a buffer. This buffer can then be stored in RAM, disk or other types of memory. Each time the program senses a clock "tick", the input is scanned and converted, and a new value is added in the buffer. The particular PC can support a data acquisition rate of 180 kHz, which is much faster than the converted rate of the whole system.

Certain specifications regarding the method of operation, the necessary power supply, the frequency of measurement, the environmental parameters, the required maintenance process of the sensors and the other components, are established during the design and development stage of the system. Part of the system is modified by specific components, which are used in similar applications, whereas the rest is developed from scratch. The proposed specifications consist a reference guide for the development or the selection of such systems. Moreover, any verification testing for the improvement of the technical standards of the system, will extent its application field.

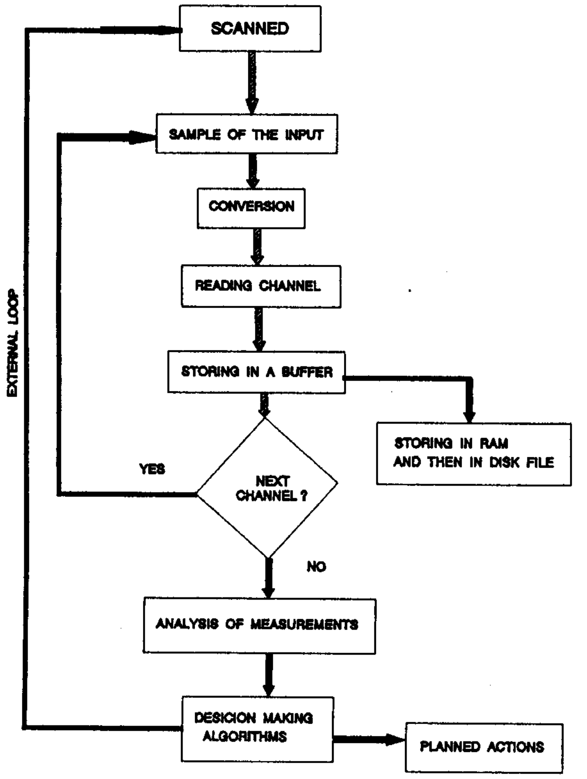

Figure 10. Structure of the system software.

4 MONITORING

Two instrumented bolts, an electrical load cell and a rock compression displacement transducer are installed and connected to a strain gage signal conditioning circuit (Fig. 11). The data are collected and stored on floppy disk of a PC located 60 m away from the face (Fig. 12). Figure 13 is a plan view of the underground test area. The system operates 24h/day and readings are taken at regular intervals, thus performing a continuous real time monitoring and control on the behavior of the limestone roof of the test area.

The system has operated for three months. During that period there were problems encountered due voltage drop, hard environmental conditions, cable cuts and incorrect installation procedures. Voltage drops during the initial stage caused incorrect readings and necessitated the installation of a voltage regulator. Hard environmental conditions such as humidity and dusty air damaged one drive of the PC and necessitated its replacement. Nevertheless, the rest of the hardware, which is installed into steel boxes for better protection, operates till now effectively. Detonations caused breaks to the cables from the sensors to the strain gage signal conditioning circuit. The correct installation of the instrumented bolt and the rock compression displacement transducer demands great care. Up to now the operation of the system fulfills the main requirements of a real time monitoring system. Typical measurements are shown in Fig. 14, 15 and 16.

5 CONCLUSIONS

A monitoring system is developed which is reliable and inexpensive. It fulfills the requirements of easy installation

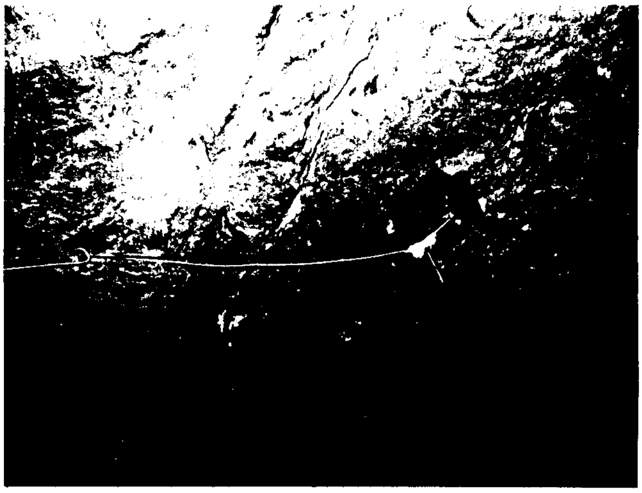

Figure 11. Strain gage signal conditioning circuit.

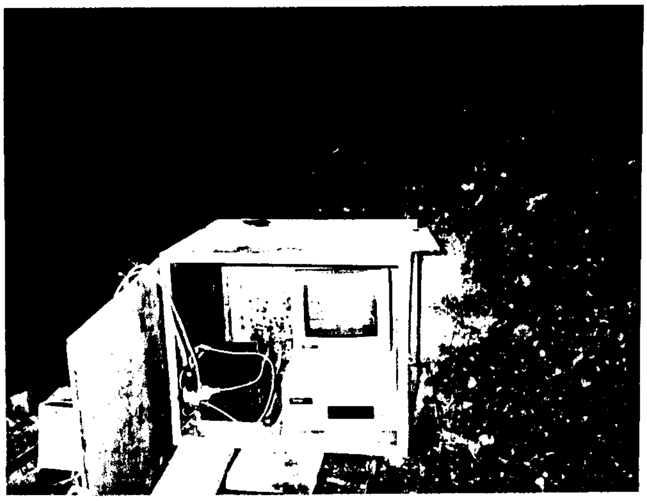

Figure 12. Measurement unit.

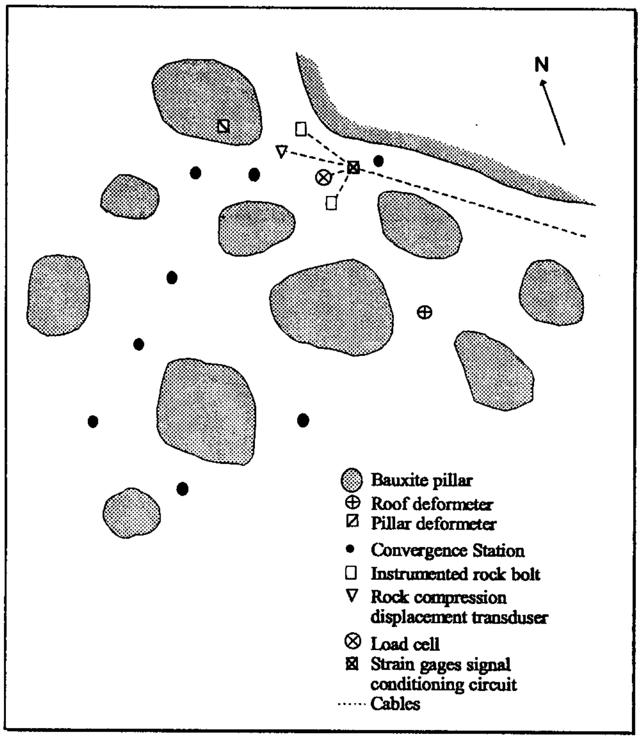

Figure 13. Plant view of the test area.

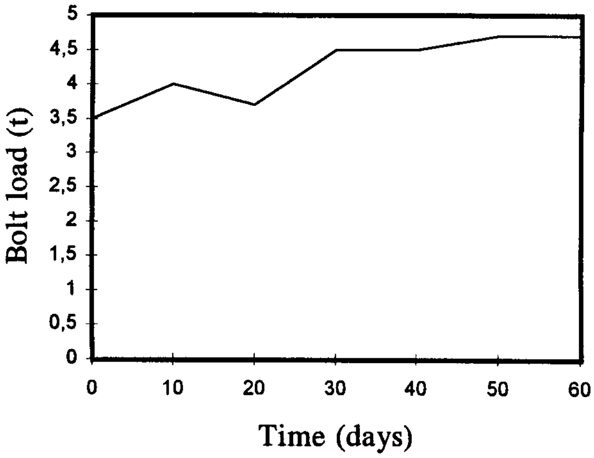

Figure 14. Instumented rock bolt monitoring results.

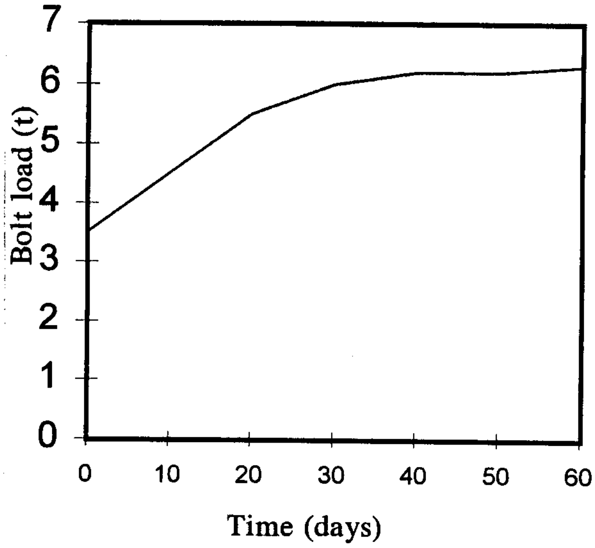

Figure 15. Load cell monitoring results.

even under adverse underground mining conditions, adequate sensitivity with accuracy of measurements, durability for the required period of monitoring and ease of reading. Reliable measurements are obtained in real time. The system may be operated by the foremen and the data may easily be read from the monitor or from the floppy disc. Thus the immediate availability to the engineer of specific geotechnical data, concerning bolt loads, stress changes and roof deformations, renders the system an alarm character which enhances the standard of safety in the mine.

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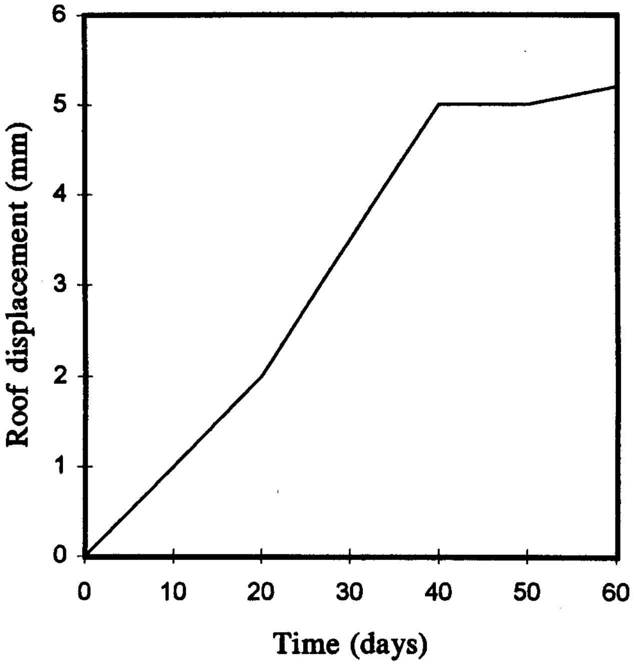

Figure 16. Rock displacement transducer monitoring results.

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