RECOMMENDED GUIDELINE FOR MONITORING ACOUSTIC EMISSIONS IN INSITU ROCK MASSES

1. Scope

1.1 The purpose of this recommended guideline is to describe the acoustic emission concept and its application to the stability monitoring of insitu rock masses. The guideline includes a brief history of the subject, a review of the basic theory, an outline of the associated monitoring techniques and equipment, and examples of a number of rock mechanics field applications where the acoustic emission technique has been applied. Since the technique is somewhat sophisticated, in comparison with most other rock mechanics field techniques, suitable references and a brief general bibliography are also provided to further assist those planning to utilize it in specific field applications.

2. Historical

2.1 In the late 1930's researchers at the U.S. Bureau of Mines (USBM), carrying out rock mechanics studies in a deep hard rock mine, observed that a stressed rock pillar appeared to emit micro-level sounds [1]. Later laboratory and field studies at the USBM verified that this phenomenon, which is often referred to in non-technical terms as "rock talk," is a measure of the mechanical stability of the rock material and/or the associated rock structure. The understanding of "rock talk," or acoustic emission as it is now more commonly called (Note 1), has developed considerably over the last 40 years [2]. Today it is utilized as a routine tool in a number of geotechnical applications and new ones are rapidly becoming apparent [3].

3. Basic Theory

3.1 AE Sources - It is generally known today that many materials besides rock emit acoustic emissions (AE) when they are stressed and/or deformed [3]. The phenomenon is commonly observed in most solids including soils, concrete, metals, ceramics, glass, and ice. In geologic materials the source of AE activity appears to be related to processes of deformation and failure which are accompanied by a sudden release of strain energy. Geologic materials are

Note 1--The terms microseismic activity, passive seismic activity, seismo-acoustic activity, subaudible noise, roof talk, elastic shocks, elastic radiation, stress wave analysis technique (SWAT), and micro-earthquake activity are also utilized by various disciplines to denote this phenomenon.

basically polycrystalline in nature. AE may originate at the micro-level as a result of dislocations, at the macro-level by twinning, grain boundary movement, or initiation and propagation of fractures through and between mineral grains, and at the mega-level by fracturing and failure of large areas of material or relative motion between structural units. The sudden release of stored elastic strain energy accompanying these processes generates an elastic stress wave which travels from the point of origin (source) within the material to a location where it is observed as an AE signal or a discrete AE event.

3.2 Frequency Character - The fundamental frequency character [3] of an observed AE signal depends on the nature of the source, the distance between the source and the detector (transducer) and the nature of the intervening material. Frequencies below 1 Hz have been observed at large scale field sites, whereas in laboratory studies AE signals have often been observed to contain frequencies greater than 500 Khz. Figure 1 indicates the frequency range over which AE and associated studies have been conducted. Figure 2 illustrates a number of typical AE events recorded at various field sites. Frequency analysis of an individual AE event indicates that it contains a spectrum of different frequencies. The form of the observed spectrum is a result of two separate factors, namely: the spectrum of the event at its source; and modifications incurred during its propagation from the source location to the point of observation (transducer location). Attenuation, which in geologic materials is often highly frequency dependent, plays a major role in modifying the AE source spectrum by decreasing the amplitudes of higher frequencies more than the amplitudes of lower frequencies. The ability to detect AE events at a distance from their source is dependent on the source amplitude, the source spectrum, the degree and frequency dependence of the attenuation, the distance of the transducer from the source, and the band-width and sensitivity of the transducer and the associated monitoring system.

3.3 Attenuation - As a general rule, attenuation increases with frequency, thus at large distances from a source only the low frequency components of the event will be observed. Furthermore, if the source spectrum of the event contains no significant low frequency components there will be a critical distance, or range, beyond which the event cannot be detected. A relationship between range and frequency, similar to that shown in Figure 3 is typical [3]. Normally the range vs. frequency curve, the form of which

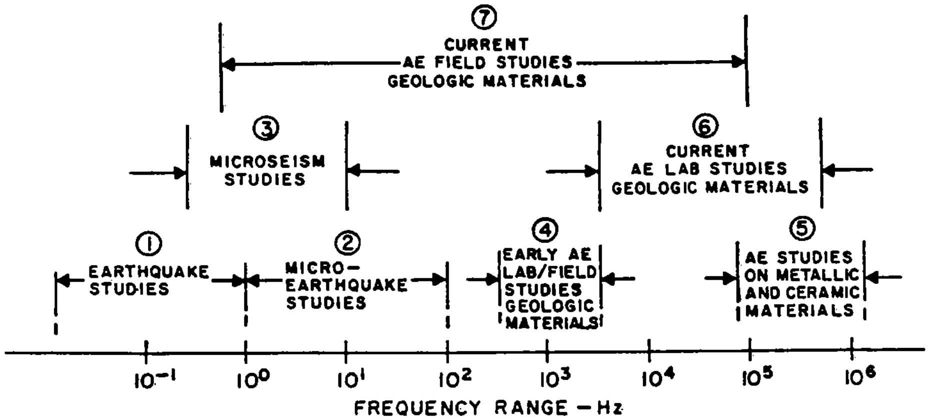


Fig. 1. Frequency range over which AE and associated studies have been conducted.

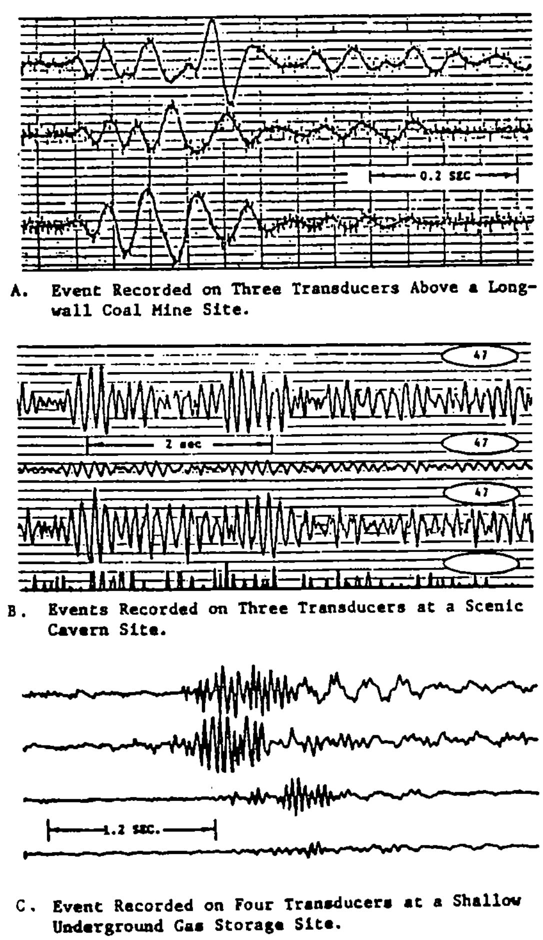


Fig. 2. Typical AE events recorded at various field sites.

depends on the characteristics of both the associated geologic material and the specific monitoring system utilized, will be more complex than that shown. The form of this curve is extremely important for the design of an optimum monitoring arrangement. For example, if the AE source spectrum was assumed to be wide, for example, containing components from 10 Hz to 200 kHz, the maximum range of the system would be approximately 6000-7000 m at the lower frequencies but only 5 m at the high end of the spectrum. The data shown in Figure 3 is also useful if it is desired to restrict the monitoring range of the system. For example, for the same source spectrum, by using a transducer only sensitive to signals of 100 kHz or higher, or by introduction of a suitable electronic filter in the system which would eliminate signals below 100 kHz, the range of AE detection would be limited to approximately 3-4 m.

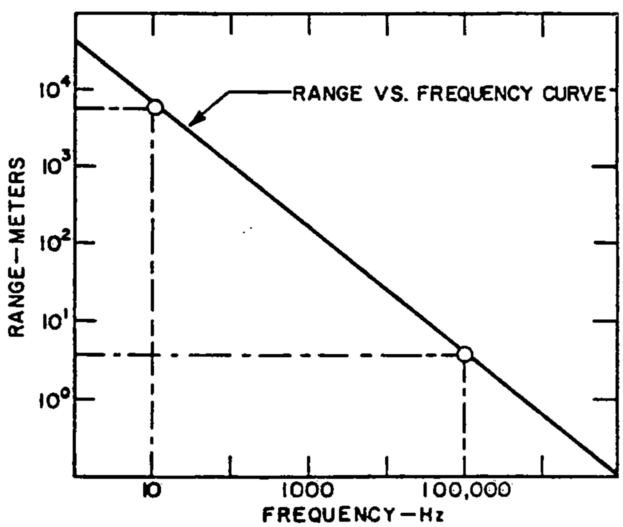


Figure 3. Typical range vs frequency data for AE signals.

3.4 Monitoring Systems - At a field site AE signals are obtained by installing a suitable transducer, or more often, a number of transducers (an array), in locations where they can detect any activity which may be originating in the structure under study. The minimum overall monitoring system involves the transducer(s), an amplifying and filtering system, and a recorder. Computer-based recording, evaluation, and analysis is very often used. Figure 4 illustrates a basic system which might be used, for example,

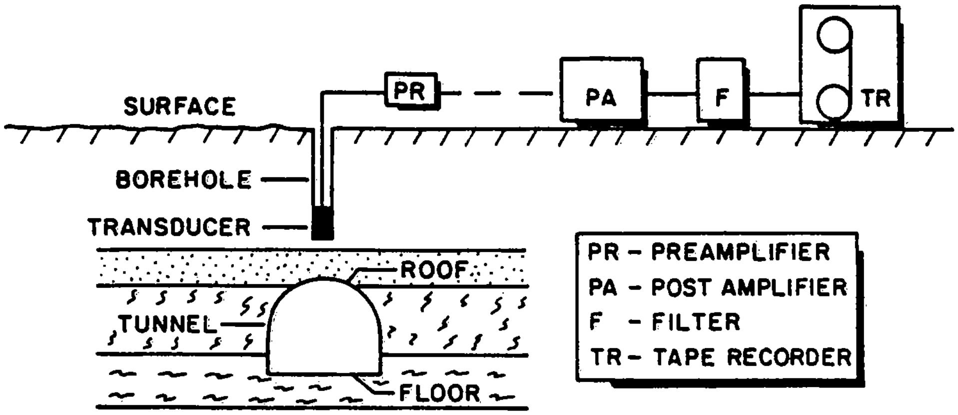


Fig. 4. Block diagram of a typical system for AE field monitoring.

to monitor the AE activity occurring in the roof of a shallow underground tunnel. In such an application the transducer could be firmly anchored in a suitable borehole a few meters from the tunnel opening. In this case the transducer would monitor the occurrence of typical AE activity. The output of the transducer, resulting from typical AE activity, is normally only of the order of microvolts, and it is necessary to amplify this small signal for subsequent recording. This is typically done in stages of amplification. The preamplifier is often of fixed-gain and located near the transducer in the circuit so the raw signal is boosted before long cable transmissions. The post- or primary amplifier provides most of the amplification and is usually controllable. A filter is also normally included in such systems in order to eliminate undesirable extraneous low and high frequency signals arising from such sources as excavation equipment and cultural activity. Past experience has shown that a magnetic tape recorder often provides the most satisfactory technique for recording AE signals, and allows the operator to analyze the recorded data at a later time. A system in which the AE signal itself is recorded is denoted as an analog-type monitoring system. In contrast, digital and parametric-type monitoring systems are available in which the analog AE signal is converted to a digital format. The digitized data is recorded and processed to provide a variety of AE parameters.

3.5 AE Parameters - In general, AE signals are randomly occurring transients whose characteristics depend on the specific field site (and the associated transducer array), and on the degree and type of instability active at the site. Figure 5 illustrates diagrammatically a section of typical AE data along with an expanded version of one of the events. Such data is most

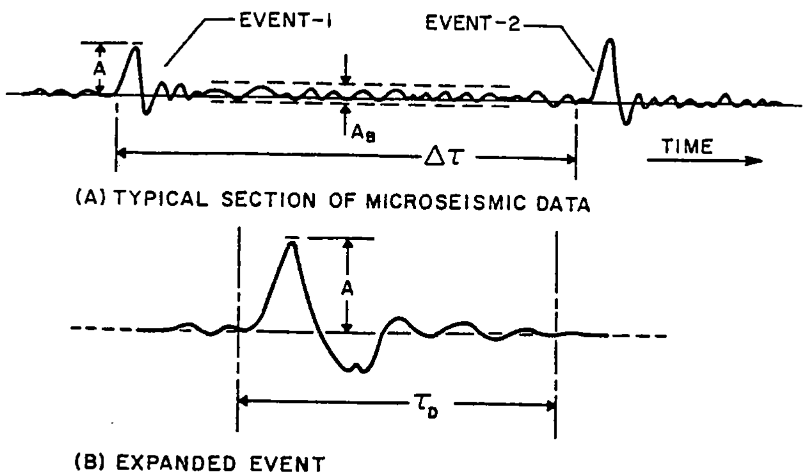


Fig. 5. Typical section of AE data and an expanded AE event.

commonly described in terms of the following parameters:

(1) Accumulated Activity (N) -- The total number of events observed during a specific period of time;

(2) Event Rate (NR) -- The number of events (ΔN) observed per unit time (Δt);

(3) Amplitude (A) -- The peak (maximum) value of each recorded event;

(4) Energy (E) -- The square of the event amplitude (A);

(5) Background Amplitude (A_B) -- The signal level present in the absence of well-defined events; A_B as shown is actually the peak-to-peak background amplitude;

(6) Signal-to-Noise Ratio (SNR) -- The ratio of the event plus background amplitude to the background amplitude.

In certain cases other AE parameters such as event duration (τ_D) and time-between-events ($\Delta\tau$) are found to be useful.

3.6 Source Location - One of the major advantages of the AE technique over other geotechnical monitoring techniques is its ability to delineate the area of instability. In general, source location techniques [3] involve the use of a number of monitoring transducers located at various points throughout the structure under study. Such a set of transducers is termed an array. Figure 6 illustrates, for example, a typical field situation where AE technique are being employed to monitor the mechanical stability of a large

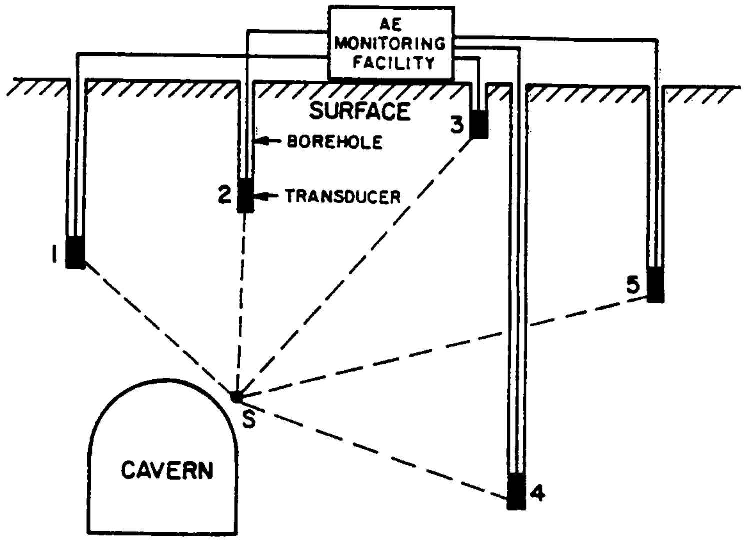


Fig. 6. Transducer array installed to monitor the stability of an underground cavern and to locate the source of any instabilities.

underground cavern. Here suitable transducers have been installed at accurately known locations, and data from these may be monitored during final cavern construction, installation of equipment, and subsequent facility operation. AE activity occurring during such an evaluation is detected at each transducer at a different time depending on the distance between the particular transducer and the AE source. The difference in arrival time between the closest transducer and each of the others yields a set of arrival-time-differences which, along with the geometry of the transducer array and the velocity of propagation in the material, may be used to determine the spatial coordinates of the AE source. Using the AE technique it is therefore possible to determine the location of any instabilities which may influence the safety and operating performance of the facility.

3.7 Important AE Concepts - From an applications point-of-view, the important AE concepts are as follows:

(a) AE activity originates at locations where the structure is mechanically unstable;

(b) AE propagates through the surrounding material undergoing attenuation as it moves away from the source;

(c) With suitable instrumentation such activity may be detected at locations a considerable distance from its source;

(d) The rate of occurrence and magnitude of the observed AE provides indirect evidence of the degree of instability;

(e) Observations obtained from a number of transducers (array) make it possible to determine the actual AE source location.

4. Monitoring Techniques and Equipment

4.1 The installation of a suitable AE field monitoring system necessitates consideration of the overall system, which includes the field site itself, the transducers (electro-mechanical characteristics, installation technique, and array geometry), and the monitoring facilities. It is important to realize that, at the input to the transducer, the mechanical signals associated with AE activity are often of very low amplitude (e.g., $v \approx 10^{-7}$ m/s in some cases) and extremely high-gain systems are required to convert these to usable electronic signal levels (normally 1-10 volts). System gains of x100,000 (100 dB) are common, thus requiring great care in the design, installation, and maintenance of AE monitoring systems. Furthermore, since only very limited data can be obtained using a single transducer (single channel system), most systems utilize a number of transducers (an array). Hence the associated monitoring facility involves a number of parallel channels (usually a minimum of five) and an associated multi-channel recorder. A list of AE equipment suppliers are included at the end of the guideline.

4.2 Classes of Monitoring - In general, there are two classes of AE monitoring, depending on the aims of the study and the number of transducers involved, namely: general monitoring and location monitoring.

4.2.1 General Monitoring - The aim of a general monitoring program [3] is to establish if AE activity is being generated in the general area of the structure under investigation, and to ascertain if this activity is associated with changes in various other monitored parameters such as slope motion, rate of tunnel advance, pillar loading, roof sag, tec. Figure 4 presented earlier illustrates a single transducer general monitoring system installed above a tunnel to evaluate the degree of roof stability. Since such monitoring involves only a single transducer, sufficient data is not available to determine the source location of the AE activity nor is a large volume of rock being monitored. The use of general monitoring is further complicated by the fact that there may be other sources of AE activity and background "noise" at a specific field site which are unrelated to the structure under investigation. These include electrical transients, excavation equipment, vehicular traffic, blasting, low-level tectonic seismic activity, etc. Unless activity from such sources can be effectively eliminated using selective filtering or by limiting the range of the system, the use of general monitoring may be unsatisfactory.

4.2.2.1 General Location Monitoring - The location of unstable zones in a large structure is only possible if location monitoring [3] is carried out using a suitable array of transducers. A minimum of four transducers are required for epicenter location (location on a horizontal datum), with source depth undetermined; and a minimum of five transducers are required for three-dimensional, or hypocenter location. For example, Figure 6 presented earlier, illustrates a five transducer array for hypocenter location of AE events associated with an underground cavern. Provided suitable AE signals are detected by all transducers, it should be possible to locate the three-dimensional coordinates of the source(s). Accurate source location is only possible if the transducer array effectively surrounds the structure being investigated, both in the vertical as well as the horizontal plane. This condition is usually easily satisfied in the horizontal plane. Suitable distribution in the vertical plane is more difficult and costly and, as a result, there is often a tendency to utilize a nearly planar array. Such a planar array, however, will introduce large errors in the calculation of the vertical source coordinates.

4.2.2.2 Example of Basic Source Location Calculation in Three Dimensions

Background - An AE transducer array and source point are schematically represented by Figure 7. The unknown coordinates of the source S are X, Y,

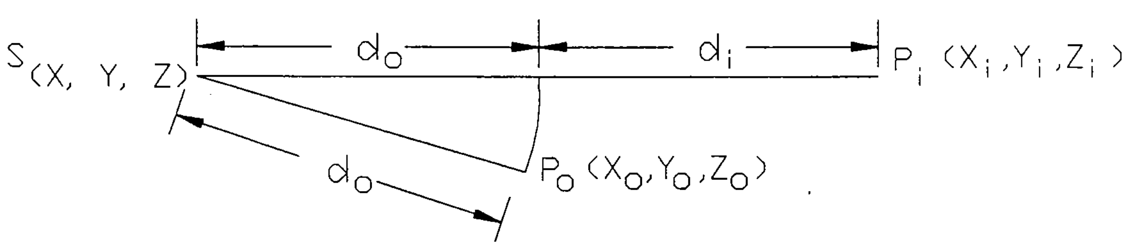


Figure 7. Schematic of Transducer Array and Source Point.

and Z; the coordinates of the receiver R_o where the first AE arrival is captured are X_o , Y_o , and Z_o ; the remaining receivers of the array R_i have coordinates X_i, Y_i , and Z_i. The velocity of acoustic propagation V in the solid, (assumed) homogeneous and continuous geologic mass is unknown, as is the distance d_o between S and R_o. Therefore, there are five unknowns (X, Y, Z, V, and d_o) requiring a minimum of five independent measurements and relating equations. The AE must be received at a minimum of five receivers with the initial time-of-arrival defined as $t_o = 0.0$ seconds and that particular receiver designated as R_o . Observe that the designation of R_o and t_o then makes distance d_o not entirely independent of X, Y, Z, and V. The velocity V can be determined by initial calibration of the array to the site. The three basic desired unknown coordinates can be calculated by the set of equations (presented without derivation) as follows.

$$A_i X + B_i Y + C_i Z = H_i \quad \text{(for } i = 2, 3, 4\text{)} \qquad \text{Eq. 1}$$

where

$$A_i = 2(a_1 /d_1 - a_i /d_i) \qquad \text{Eq. 2a}$$

$$B_i = 2(b_1 /d_1 - b_i /d_i) \qquad \text{Eq. 2b}$$

$$C_i = 2(c_1 /d_1 - c_i /d_i) \qquad \text{Eq. 2c}$$

$$H_i = (k_1 /d_1 - k_i /d_i) \qquad \text{Eq. 2d}$$

$$(i = 2, 3, 4)$$

and

$$a_i = X_o - X_i \qquad \text{Eq. 3a}$$

$$b_i = Y_o - Y_i \qquad \text{Eq. 3b}$$

$$c_i = Z_o - Z_i \qquad \text{Eq. 3c}$$

$$k_i = d_i^2 + X_o^2 + Y_o^2 + Z_o^2 - X_i^2 - Y_i^2 - Z_i^2 \qquad \text{Eq. 3d}$$

$$(i = 1, 2, 3, 4)$$

The values for d_i are obtained from (1) measurements (or assumptions) on the values(s) of V_i and (2) the AE raw data in the form of successive elapsed times of arrival et_{oi} of single AE events at each receiver R_i after first arrival at receiver R_o.

$$d_i = V_i \, et_{oi} \qquad \text{Eq. 4}$$

$$(i = 1, 2, 3, 4)$$

The array calibration for propagation velocities is performed by artificially generating an impulse at each receiver point and measuring the time elapsed to arrive at each remaining receiver point. Given, for example, the minimum five-receiver array for three dimensions:

$$V_{mn} = d_{mn} / et_{mn} \qquad \text{Eq. 5}$$

(for m = 1, 2, 3, 4, 5
and n = 1, 2, 3, 4, 5)

where et_{mn} is elapsed time-of-travel from source m to receiver n
and $d_{mn} = [(X_m - X_n)^2 + (Y_m - Y_n)^2 + (Z_m - Z_n)^2]^{1/2}$ Eq. 6

An unknown, possibly anisotropic, model of velocities along each inter-receiver path (V_{12}, V_{13}, . . . , V_{35}, . . . , V_{mn}) is determined from the independent path lengths d_{mn} and measured times-of-travel et_{mn}. Less rigorously, an assumption may be made of V being isotropic and a single measurement of that velocity will suffice. Least desirable, the value of V (assumed isotropic) may be inferred from the site lithology.

Available Data for Example - An array of receivers R_i is installed in a rock mass at the following coordinates, X-axis being EW, Y-axis being NS, and Z being positive elevation.

Receiver	X, ft	Y, ft	Z, ft
1	100.0	200.0	150.0
2	100.0	300.0	150.0
3	200.0	250.0	150.0
4	150.0	250.0	250.0
5	150.0	250.0	50.0

Calibration is performed with a sound impulse at each successive receiver point which is, in turn, received at each other receiver point. The calibration data is as follows.

Source-to-Receiver Ray Path	Path Length, ft	Elapsed Time, seconds	Velocity, ft/sec
1-2	100.00	0.01430	6993.0
1-3	111.80	0.01585	7053.6
1-4	122.47	0.01760	6958.5
1-5	122.47	0.01745	7018.3
2-3	111.80	0.01600	6987.5
2-4	122.47	0.01750	6998.3
2-5	122.47	0.01755	6978.3
3-4	111.80	0.01595	7009.4
3-5	111.80	0.01590	7031.4
4-5	200.00	0.02855	7005.3

The differently oriented ray path velocities do not seem to indicate anisotropy. The velocity of propagation (compressive wave) is characterized as isotropic with a mean value of 7003 ft/sec and a standard deviation of +- 26 ft/sec. On 2 December 1990 the record depicted in Figure 8 is recovered

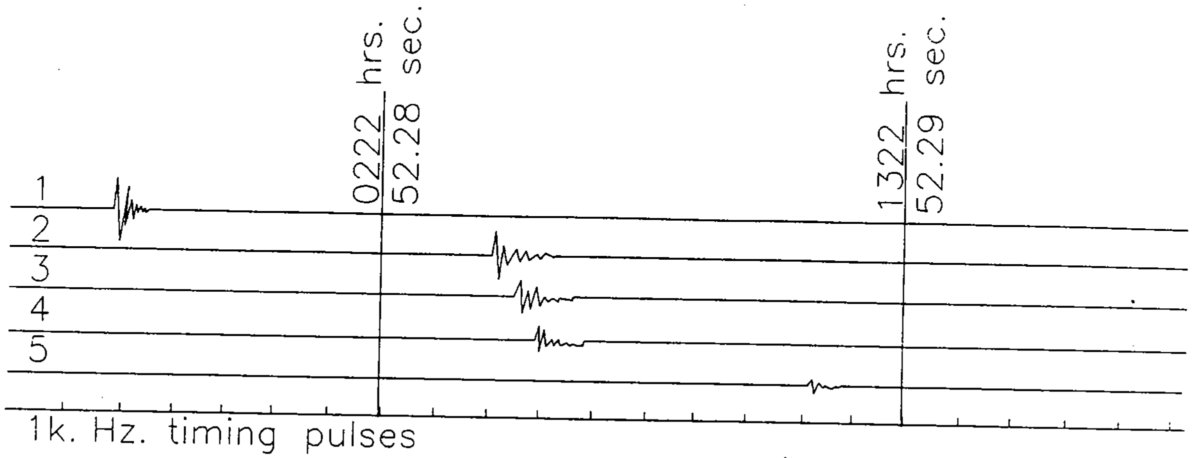


Figure 8. Modeled 5-channel AE record for example of source location calculation.

indicating five channels receiving a discrete AE event. The measured data are read as 'Raw Time of Arrival' at each receiver and, after observing R_1 as the first arrival, elapsed times at successive receivers are determined.

Receiver	Raw Time, hr:min:sec	Receiver	Elapsed Time, seconds
1	02:22:52.27495	0	0.00000
2	02:22:52.28210	1	0.00715
3	02:22:52.28255	2	0.00760
4	02:22:52.28295	3	0.00800
5	02:22:52.28820	4	0.01325

From Equation 4 and V = 7003 ft/sec:

$$d_1 = (7003)(0.00715) = 50.071$$

$$d_2 = (7003)(0.00760) = 53.223$$

$$d_3 = (7003)(0.00800) = 56.024$$

$$d_4 = (7003)(0.01325) = 92.790$$

From Equations 3:

$$a_1 = 100.0 - 100.0 = 0.0$$

$$a_2 = 100.0 - 200.0 = -150.0$$

$$a_3 = 100.0 - 150.0 = -50.0$$

$$a_4 = 100.0 - 150.0 = -50.0$$

$$b_1 = 200.0 - 300.0 = -100.0$$

$$b_2 = 200.0 - 250.0 = -50.0$$

$$b_3 = 200.0 - 250.0 = -50.0$$
$$b_4 = 200.0 - 250.0 = -50.0$$
$$c_1 = 150.0 - 150.0 = 0.0$$
$$c_2 = 150.0 - 150.0 = 0.0$$
$$c_3 = 150.0 - 250.0 = -100.0$$
$$c_4 = 150.0 - 50.0 = +100.0$$

$$k_1 = (50.071)^2 + 100^2 + 200^2 + 150^2 - 100^2 - 300^2 - 150^2$$
$$= -47492.9$$
$$k_2 = (52.223)^2 + 100^2 + 200^2 + 150^2 - 200^2 - 250^2 - 150^2$$
$$= -49667.3$$
$$k_3 = (56.024)^2 + 100^2 + 200^2 + 150^2 - 150^2 - 250^2 - 250^2$$
$$= -71861.3$$
$$k_4 = (92.790)^2 + 100^2 + 200^2 + 150^2 - 150^2 - 250^2 - 50^2$$
$$= -6390.0$$

From Equations 2:

$$A_2 = 2[(0.0/50.071) - (-150.0/53.223)] = 3.7578$$
$$A_3 = 2[(0.0/50.071) - (-50.0/56.024)] = 1.7849$$
$$A_4 = 2[(0.0/50.071) - (-50.0/92.790)] = 1.0777$$
$$B_2 = 2[(-100.0/50.071) - (-50.0/53.223)] = -2.1154$$
$$B_3 = 2[(-100.0/50.071) - (-50.0/56.024)] = -2.2094$$
$$B_4 = 2[(-100.0/50.071) - (-50.0/92.790)] = -2.9166$$
$$C_2 = 2[(0.0/50.071) - (0.0/53.223)] = 0.0$$
$$C_3 = 2[(0.0/50.071) - (-100.0/56.024)] = 3.5699$$
$$C_4 = 2[(0.0/50.071) - (100.0/92.790)] = -2.1554$$
$$H_2 = [(-47492.9/50.071) - (-49667.3/53.223)] = -15.3187$$
$$H_3 = [(-47492.9/50.071) - (-71861.3/56.024)] = 334.1767$$
$$H_4 = [(-47492.9/50.071) - (-6390.0/92.790)] = -879.6459$$

The final system of equations (Equations 1) to be solved is:

$$(3.7578)X + (-2.1154)Y + (0.0)Z = -15.3187$$
$$(1.7849)X + (-2.2094)Y + (3.5699)Z = 334.1767$$
$$(1.0777)X + (-2.9166)Y + (-2.1554)Z = -879.6459$$

The system may be solved in any convenient manner; by Gaussian elimination the solution for the AE source coordinates is:

X = 119.93 ft, Y = 220.29 ft, and Z = 169.99 ft.

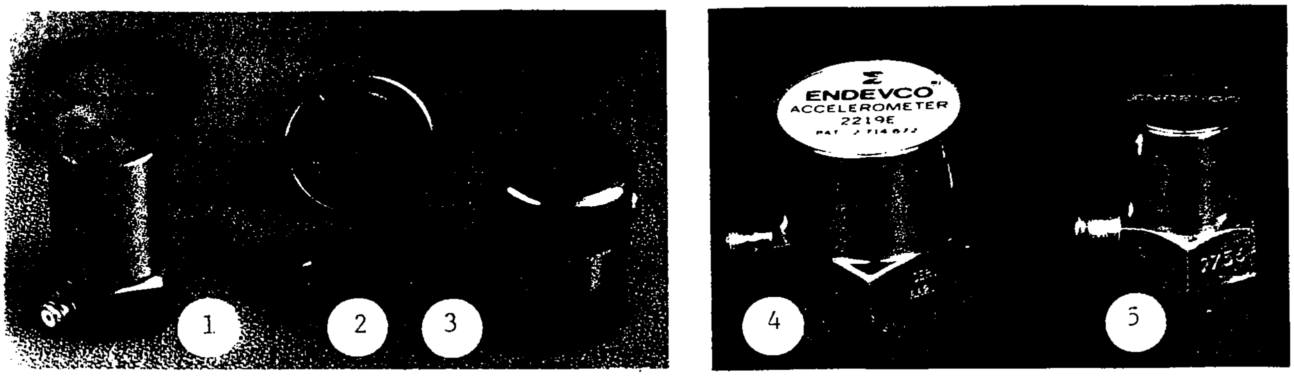
<u>Comments on the Example</u> - To construct the example the velocity used was 7000.0 ft/sec and the source coordinates were (120.0, 220.0, 170.0). Note the

precision of the original example raw times was +- 5.0 x 10^{-5} sec (+-0.05 millisec). This precision is realizable in actual practice but requires much care in equipment selection and reading the recorded data. The artificial record is somewhat unrealistic because of an exceptional signal-to-noise ratio and the absence of additional and confusing recorded impulses from other sources (AE or otherwise). The computation was manually performed; in reality, computer/calculator codes would be used, perhaps using more sophisticated algorithms. The modeled rock mass and associated velocity model pre-supposed straight-line ray paths of propagation with no refraction, curvature, or reflection; joints and nonhomogeneous strata would be more likely in real geology.

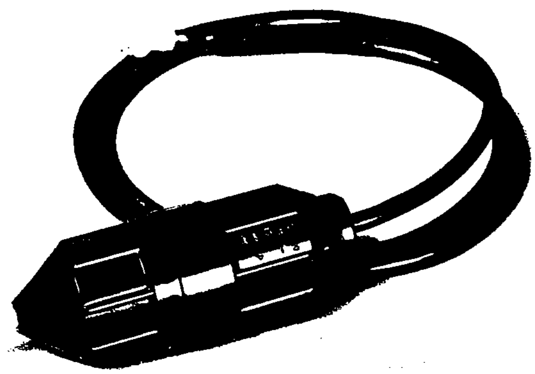
4.3 AE Transducers

4.3.1 Transducer Types - The purpose of the transducer [3] is to convert the mechanical energy associated with an AE event into a suitable electrical signal. When a geologic structure is loaded, mechanical (acoustic vibration) signals are generated due to localized deformation, and/or failure at areas of high stress concentration. AE activity at a specific point in the structure may be detected by monitoring the displacements, velocities or accelerations generated by the associated mechanical signals at that point using a suitable transducer. Where signals containing relatively high frequency components ($f > 200$ Hz) are involved, accelerometers are usually employed. In contrast, low frequency signals ($f < 1$ Hz) are usually detected with displacement gages. Signals between these extremes (1 Hz $< f <$ 2000 Hz) are conveniently detected using velocity gages (geophones). Typical geophones and accelerometers have sensitivities in the range 40-400 V/m/s (Volts per meter/sec) and 2-100 mV/g (milliVolt/gravity), respectively. Figure 9 shows a number of typical AE transducers. A limited number of field studies have also been conducted using hydrophones as AE transducers [4, 5, 6]. Such transducers are effectively ultra-sensitive pressure transducers and when installed in a fluid-filled borehole they sense the presence of minute pressure changes in the borehole fluid resulting from acoustic waves occurring in the surrounding strata.

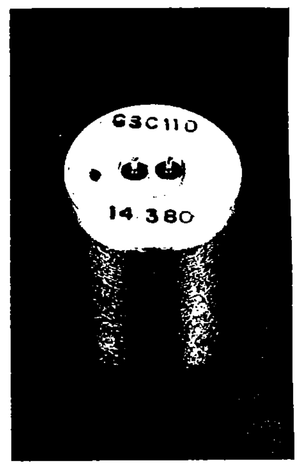
4.3.2 Transducer Installation - In general, optimum transducer location will depend on a number of factors including, among others, the size and depth below surface of the structure under study, the thickness and properties of the overlying strata, the expected energy of the AE events to be detected, whether general or location monitoring will be employed, the desired source



(A) Accelerometer units.
[1, 2, 4 & 5 are flat response-types; 3 is a resonant-type]



(B) Marsh-type geophone unit.
[(C) shows associated sensor element]



(C) Basic geophone sensing element.

(D) Large, high-sensitivity geophone unit.

Figure 9. Typical commercially available AE transducers.

location accuracy, and the funds available. It should be noted that there appears to be no single transducer location or array geometry which is suitable for all studies; experience has shown that these must be tailored to the specific application. In a number of cases, transducers have been installed underground in tunnels, shafts, caverns, and mine workings. Such installations involve mechanically locking or cementing the transducers into boreholes, mounting them to underground supports such as steel arches or rock bolts, or clamping them to a plastic or metal plate previously cemented to the roof or walls of the opening [3, 7]. Figure 10 illustrates a variety of methods of underground transducer mounting. In a number of field situations it is more desirable, and often necessary, to install transducers from the ground surface overlying the structure under study. A number of such installation techniques [8, 9] are shown in Figure 11. These are suitable for monitoring structures located near-surface and at depths of less than 200 m. For structures at greater depths special techniques are normally required [10]. When it is desired to monitor exposed structures such as rock slopes, and dam foundations and abutments the transducers may be installed directly on the structure, or in shallow boreholes, using various of the techniques illustrated in Figures 10 and 11.

4.4 <u>AE Monitoring Facilities</u> - After the required transducer or transducer array has been installed, suitable facilities must be provided to monitor the associated AE activity. A wide variety of equipment has been developed by various workers in the geotechnical field for this purpose [11, 12]. General monitoring may be carried out using a single channel system. However, when source location information (location monitoring) is required, a suitable multi-channel system must be utilized. In general, as illustrated in Figure 12, a single channel system, regardless of its apparent complexity, consists of only three major sections, namely, the transducer, the signal conditioning unit, and the readout unit. In such a system, AE activity

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Note 2--Two types of accelerometers are employed in AE studies. At frequencies up to 50 kHz most are of the flat response-type (sensitivity independent of frequency). At higher frequencies resonant-type accelerometers are employed in order to obtain the sensitivity levels necessary to overcome the high attenuation experienced at such frequencies.

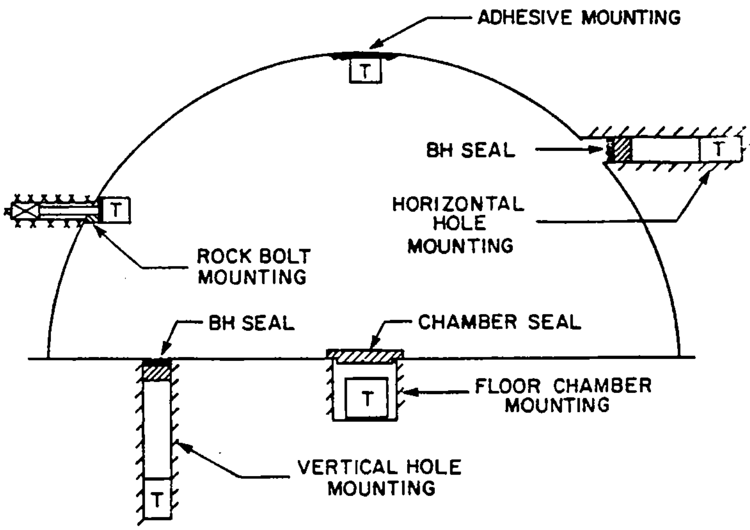


Figure 10. Various methods employed for underground mounting of AE transducers. (T - transducer)

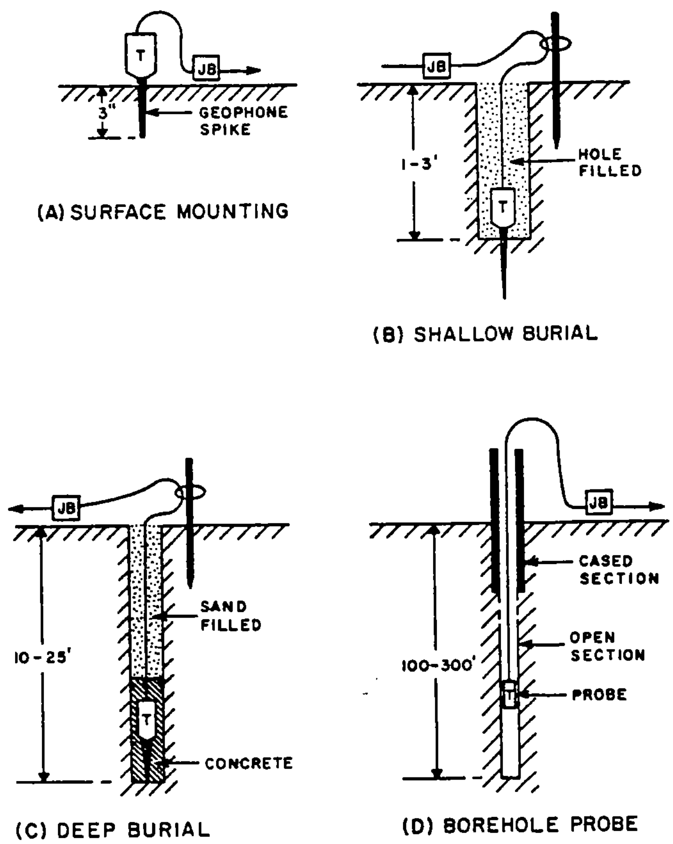


Figure 11. Various methods for surface installation of AE transducers for structures located at depths less than 200 m. (T - transducer, JB - Junction Box, Length Conversion Factors: 1" = 0.025m and 1' = 0.305m)

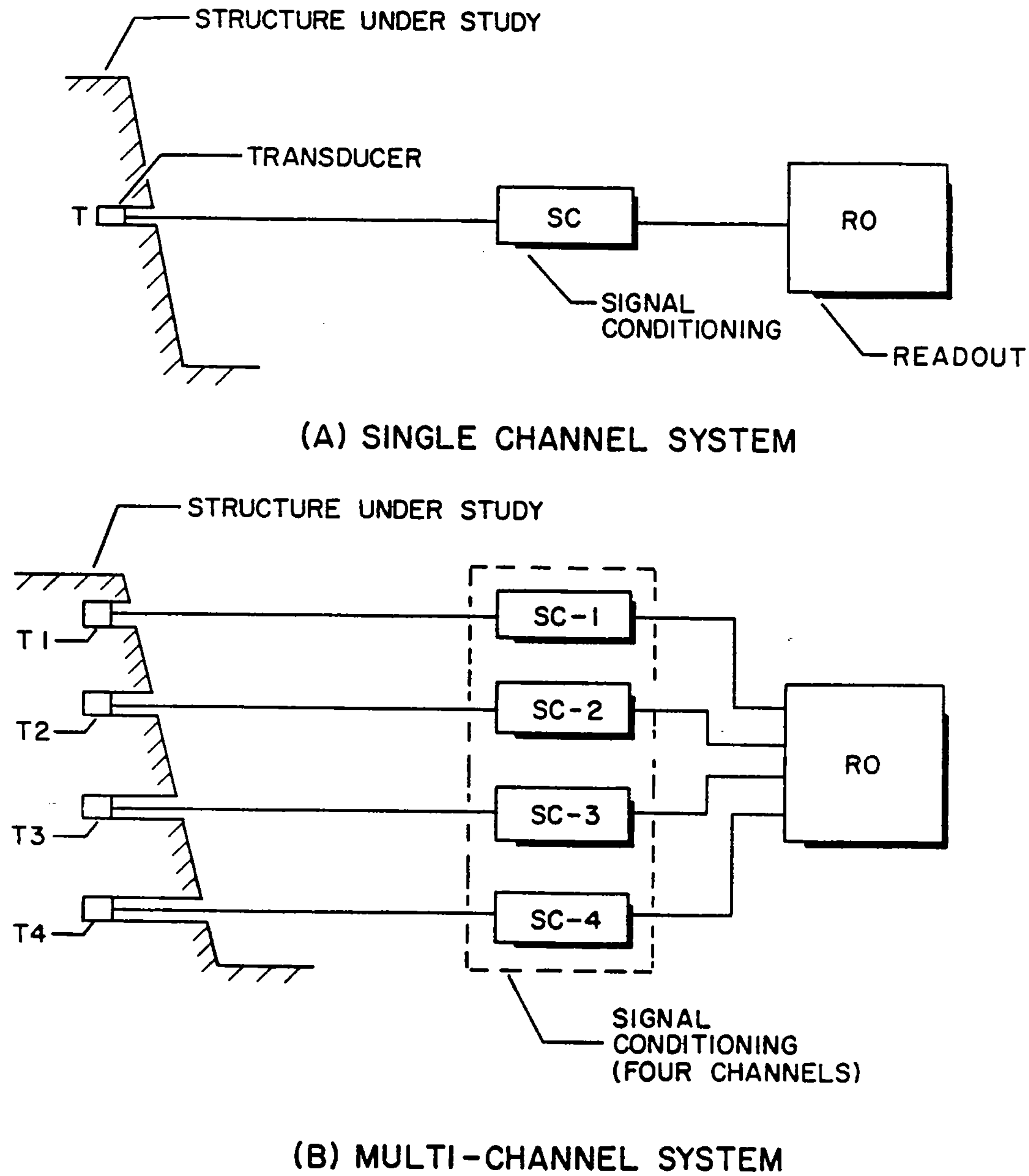
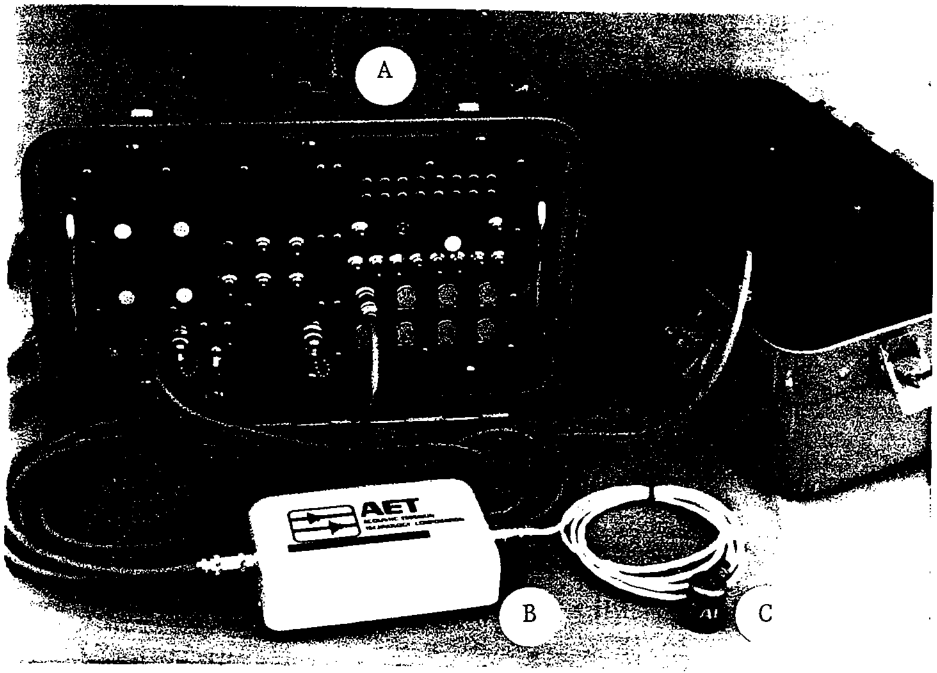


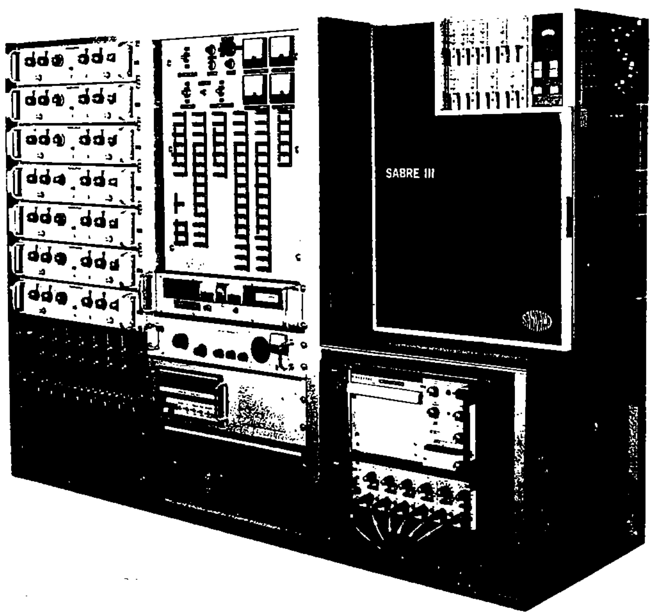
Figure 12. Simplified block diagrams of a single- and a multi-channel AE monitoring system.

is detected by the transducer, the resulting electrical signals are suitably modified by the signal conditioning section (i.e. amplified, filtered, etc.), and finally displayed and/or recorded in the readout section. In general, two totally different types of signal conditioning are in common use, "basic" and "parametric." Multi-channel systems are often required to obtain meaningful field data and a simplified four-channel system is illustrated in Figure 12. In most cases such a system merely involves additional transducers and signal conditioning units, with the total data from all channels being recorded on a single multi-channel readout system. Regardless of the number of monitoring channels involved, the various components of the system must be selected to provide the frequency response, signal-to-noise ratio (SNR), amplification, parametric processing, and data recording capacity necessary for the specific study. A limited number of complete single channel monitoring systems are commercially available for geotechnical field use. In most cases, however, the required system is assembled for the specific field application from commercially available components. Figure 13 illustrates typical examples of a single- and a multi-channel monitoring system.

4.5 Data Analysis - With the exception of the commercially available single-channel monitoring systems and a number of the more sophisticated multi-channel systems, which provide on-line analysis of AE data, recorded field data is normally analyzed at a later time. In the past, analysis of AE field data in the geotechnical area has been for the most part based on manual and/or "hardwired" techniques. In recent years, with the increasing availability of compact and relatively inexpensive computers, the use of computer-based data analysis systems have become more common. Manual analysis is still very common today, and although time consuming and often rather subjective, it is relatively inexpensive in terms of equipment and offers the advantage of allowing the operator to interface directly with the field data. In this type of analysis, the previously recorded field data is replayed into a suitable multi-channel hardcopy recorder and examined manually. Hardwired techniques, using electronic counters and ratemeters, are also utilized to determine such AE parameters as accumulated activity and event rate. In those field situations where the character of the associated AE data is well defined, or has been investigated in some detail earlier in the study, it may well be possible to utilize some form of computer assisted on-line analysis [13].



(A) Portable, commercially available single-channel system. (A-monitoring system, B-preamplifier, C-transducer.)



(B) Custom-built multi-channel system.

Figure 13. Examples of a typical single- and multi-channel AE monitoring system.

5. Rock Mechanics Field Applications

5.1 In recent years, AE field-oriented studies have been actively underway in a number of areas [3], including: rock burst and roof fall prediction; stability evaluation of mines and underground storage facilities, rock and soil slopes, and a variety of civil engineering structures; and basic studies relative to surface subsidence, rock anchor stability, and evaluation of in-situ stress. Details of a number of these studies are included in this section. Although many of these studies have been associated with surface and underground mining operations, the techniques utilized are directly applicable to a variety of other geotechnical applications.

5.2 Rock Bursts - During the last 15 years extensive AE research associated with coal and hardrock mines have been carried out in the USA. Similar studies have also been underway in South Africa and, to a limited extent, in Canada, Europe, Australia, and Japan. To date, probably the most outstanding endorsement of the usefulness of AE techniques in the geotechnical area is its successful application by the USBM in rock burst studies in the hardrock mines of Idaho [14-18]. Installations of AE monitoring facilities in these mines have made it possible to accurately locate potential rock burst areas and to monitor the controlled distressing of such areas.

5.3 Roof Falls - In recent years a limited number of AE studies have been underway by the USBM and others in an attempt to detect zones of unstable roof rock in coal and hard rock mines. Rock falls from such areas, although often small in volume, are responsible for many serious injuries and other fatalities. Since these unstable zones are limited in areal extent, it is important to be able to locate them precisely and to predict within a reasonable period of time when the roof fall will occur. Results of preliminary roof stability measurements in coal mines using relatively simple commercially available monitoring facilities, sensitive in the range 36-44 kHz, have been reported [19]. The effective range of the equipment was found to be approximately 25 m. Based on these preliminary studies more refined AE monitoring equipment was developed and is now commercially available [20]. Using these AE monitoring facilities, further roof fall studies were undertaken in a variety of coal mining situations with encouraging results [21]. A preliminary evaluation indicates that AE roof fall monitoring will be applicable to hard rock mines and in other similar geotechnical applications.

5.4 Tunnel Stability - A number of the early AE studies in the civil engineering field were carried out in relation to tunnel development projects. For example, Crandell [22] employed these techniques for monitoring tunnel safety. A later paper by Beard [23] lists a number of tunneling operations where simple AE monitoring devices were used with great success. In all but a few tunnel studies, measurements were made with a single transducer inserted in boreholes drilled into the rock surrounding the tunnel. An observed low degree of AE was interpreted as indicating a stable condition. Unfortunately, further development of AE techniques for tunnel stability monitoring have been relatively limited.

5.5 Underground Storage - In recent years considerable use has been made of underground space for the storage of solids, liquids, and gases. At present commercial and government owned facilities for underground storage of such products as natural gas, LNG, crude oil, compressed air, and radioactive wastes are in use, or are under development, in many countries. Due to their size and often inaccessible nature, the AE technique appears to offer one of the more suitable methods for stability monitoring of such structures [24]. For example, AE studies have recently been carried out to evaluate the stability of salt caverns used for the storage of crude oil [25] and a prototype radioactive waste repository located in granite [26].

5.6 Slope Stability - Although slope stability studies associated with both open pit mining and various civil engineering projects, has been relatively limited in the past, activity in this area has increased in recent years. The recent publication by Voight [27] entitled, "Rock Slides and Avalanches" includes an excellent review of the associated theory as well as an extensive series of case histories associated with various engineering projects. AE techniques have been investigated by a number of workers as a tool for monitoring rock slope stability, and during the late 1960s and early 1970s the USBM carried out a number of such studies [28]. Projects of particular interest include a number of open-pit mines in California [29], Nevada [30], and Chili [31], and the Libby dam in Montana [32]. These studies indicate that, in spite of a number of inherent difficulties, AE techniques do provide an important method of monitoring rock slopes and of assessing their stability.

5.7 Seepage - Reservoir water seeping through, around and/or under earth and earth- and rock-fill dams has always been a major concern to dam builders.

Seepage can result in a phenomenon commonly referred to as "piping" in which seepage water creates internal erosion by removing embankment fines. If left undetected and untreated, piping will lead to failure. In many cases, the time from detection to failure is quite short; thus leaving little time for remedial corrections. Excessive seepage can also cause excessive pore pressures along the downstream embankment face or in the foundation material thereby reducing the effective shear strength. Such conditions may lead to sliding failures. Recent studies [33, 34] indicate that AE techniques appear applicable to the problem of seepage detection and location in earth and rock filled dams. Similar techniques may also be applicable to concrete dams and associated structures.

5.8 Rock Reinforcement - Recent studies [35] indicate that the stability of rock anchors, and structures reinforced by such devices, may be effectively monitored using AE techniques. Studies by Koerner [36] have also demonstrated that such techniques may provide a viable method for monitoring rock grouting operations. Both studies suggest that AE techniques may be useful to monitor the stability of a wide variety of rock and concrete structures during rehabilitory activities.

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