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INTRODUCTION AND BACKGROUND

Acoustic emissions (AE) are transient elastic waves generated by the rapid release of energy within a material which deforms under stress. Sometimes these sounds are audible (wood cracking, tin "crying", ice expanding, soil and rock particles abrading against one another, etc.), but more often they are not, due to either their low amplitude or their high frequency. Normally a piezoelectric sensor (some form of transducer) is used as a "pick-up" to detect the emissions. These sensors produce an electrical signal when mechanically stimulated. The signal is then amplified, filtered, counted, displayed and recorded or otherwise processed. Some aspect of the signal is then related to the basic material characteristics of the specimen or material being tested to determine its relative stability. If no signals are present, the material is in equilibrium and thus stable. However, if signals are detected, some instability exists which could ultimately lead to excessive deformation or failure.

Historically, AE work began in the mining industry to detect instability in mine roof, face, or pillar rock, and predict when failure might occur. This work was initiated by Obert [1], and Obert and Duvall [2] in the United States, and Hodgson [3,4] in Canada. Although these early workers were hampered by a lack of sophisticated and reliable equipment, their ideas and goals were certainly in the right direction and set the tone for many modern projects. Their monitoring of rock emissions, which they called microseisms, began in the early 1930's and is being continued today by the Bureau of Mines [5] and others [6,7].

Beginning in the 1950's AE research was initiated in the metals area. Kaiser [8,9] worked with steel, copper, aluminum, lead and zinc, and discovered many fundamental properties relating AE activity to the state of stress. Tatro and Liptai [10,11] in the 1960's used the technique to detect yielding in metals, and also did pioneering work in analyzing the fundamental characteristics of AE in metals. Recently, the most active AE work has been in the area of pressure vessel proof-testing [12,13]. A large number of transducers are placed on the vessel, which is pressurized. Any flaws that may be present are detected and evaluated by their acoustic emission response. These flaws can be source located to within inches of their actual locations. Civil Engineering structures should also be capable of being monitored using the acoustic emission method as suggested in the review article of Galambos and McGogney[14].

While the previously mentioned materials (rock and metals) have been the major subjects of AE research, other materials have also been evaluated. These include composites, concrete, ceramics, ice and wood, and the results have been summarized in a number of review articles written by Liptai, et al. [15], Dunegan and Tatro [16], Knill, Franklin and Malone [17]. Lord [18] and Lord and Koerner [19]. Additionally, a recent bibliography on the subject has been compiled by Drouillard [20].

Information regarding AE response in soils is noticeably lacking in the literature. The original soil reference, stemming from a rock monitoring program [21], appears to have been by Cadman and Goodman [22] who addressed soils per se, in a relatively preliminary manner. Subsequent work has been done at Drexel University over the past 12 years, and is summarized in reference 23.

Stemming from this work at Drexel has been the recognition that AE is generated by water flowing through soils as reported in reference 23 (for field work) and reference 24 (for laboratory work). Related to the evaluation of seepage via AE, is the fact that low pressure grouting (cement and chemical) and high pressure grouting (hydrofracturing) are also emittive phenomena[25].

These latter studies, which certainly show technical feasibility of the monitoring of subsurface flow phenomena, were performed in a relatively simplistic manner. AE counts (actually the cumulative threshold crossing or ringdowns of the signals) were monitored and related to flow and/or pressure, with little regard to location. This monitoring was all performed using single channel AE monitoring systems which necessitate one to geometrically source locate using various pickups at different locations and depths. Far better would be a methodology for source location of AE events using a multi-channel system which has real time processing capabilities of source location. This concept is the focal point of this project. The initial laboratory and field trials will be described in this paper.

INSTRUMENTATION DETAILS AND SYSTEM METHODOLOGY

A basic AE system consists of three essential components. The first, and most important, component is the sensor to detect the AE stress wave. The second component is a preamplifier to amplify the sensor output for transmission to the processor. The main function of the third component, the processor, is to detect and quantify the acoustic emission signal.

As shown schematically in Figure 1, the sensors must detect the transient stress wave as it is generated. Instantaneously, the sensor transduces the short duration elastic displacement into an electric signal. The sensors chosen for this project were piezoceramic (lead zirconate titanate, PZT-5A) sensors resonant at 30 kHz (AET Model AC30L). They are calibrated as having a sensitivity of approximately -70 dB referred to 1 volt per microbar. The preamplifiers used were AET Model 160B which provide 60 dB (X 10^3) of gain. They also bandpass filter the signals from the sensors. The bandpass filter used was the Model FL1-100 with a bandpass of 1 kHz to 100 kHz.

The system used to provide the signal processing was the multi-channel (up to eight) computer-based AET 5000. This system quantifies the amplified sensors output. Additional gain was applied to each signal so there was a total system gain of 90 dB for each sensor. The threshold setting for the system was 0.5V fixed. This threshold and amplification made the system sensitive to very low (12 dB) amplitude signals. Figure 2 shows an AE event and defines each of the signal characteristics.

Besides measuring each of the AE signal parameters, the system also determines the time of signal arrival on each of the channels. When the first sensor is 'hit' (disturbed from a state of rest with enough energy to generate a signal above threshold -- see later discussion) all the timing circuits are activated and the first channel is flagged with a Δt of 0. With each succeeding sensor that is hit, a Δt is generated (clock pulses times clock rate) and that sensor is also flagged. With this Δt information, the computer sorts the channels and performs a source location analysis using a stored program.

SOURCE LOCATION DETAILS

Software currently available allows for the determination of a zone source location. Essentially, this is an adaptive learning network that allows the system to generate a look-up table consisting of sensor order of hit and Δt data. All that is necessary is to simulate AE sources at known points of interest. In the case of a mine or tunnel where there is access, this technique would work fine. In most other geologic cases, the requirement of AE simulation would be difficult to implement. The software program will allow one to input manually through the keyboard the look-up table data, but this implies that a good velocity profile exists. This aspect of the program is in progress. The program will have four alternate options. The simplest is a table of typical velocity data for various types of soils and rocks. More accurate, however, are site specific and field determined values of velocity. Options here will include a linear velocity test (thereby assuming isotropy), a three dimensional test (thereby obtaining velocities in x, y, and z directions) and an averaging test done from the ground surface to a point within the soil or rock mass.

The next step of the program which is also currently underway, is to install a real-time analytical source location program. Several investigators, Leighton and Blake[26], Leighton and Duvall [27], Beattie[28], and Hardy, Mowery and Kimble[29] have programs from which we will draw parts. Briefly the analytical solution may be written:

$$d_i = [(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2]^{1/2} \quad (1)$$

where

a_i, b_i, c_i = co-ordinates of i^{th} sensor

d_i = distance from source to i^{th} sensor

x, y, z = coordinates of source

furthermore d_i, the distance the P-wave travels is

$$d_i = V_i\ (t_i - t_o) \quad (2)$$

where

V_i = velocity of sound in the direction from the source to the i^{th} sensor

t_i = time at the i^{th} sensor

t_o = time at the source,

therefore

$$V_i(t_i - t_o) = [(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2]^{1/2} \quad (3)$$

Equation 3, when reduced to a series of at least four equations and appropriate measured times and known a, b, c values at four sensors, can be solved simultaneously for the location of the AE source.

A final consideration as to the characteristics of an event that will trigger the location system is in order. Figure 2 shows the various AE signal characteristics. Note that these are characteristics of the signal out of the transducer and not of the transient elastic stress wave. The primary requisites to trigger the system are signal amplitude and system threshold. Signal amplitude is a combination of the energy in the stress wave and the system gain (or amplification). Assume, the system amplification is known (e.g., 60 dB preamplification + 19 dB post amplification) as is the reference voltage (e.g., 1.00 volts fixed); therefore with the equation:

$$\text{gain} = 20 \log \frac{V_{out}}{V_{in}} \quad (4)$$

$$79 \text{ dB} = 20 \log \frac{1 \text{ Volt}}{V_{in}} \quad (5)$$

$$V_{in} = \frac{1 \text{ Volt}}{10^{79/20}} = 112 \text{ microvolts} \qquad (6)$$

Thus, a transducer output of 112 microvolts will trigger the system. Now equation (4) must be again considered to determine the pressure that is exerted on the transducer to generate this output. Consider the case of a transducer that is calibrated at -65 dB referenced to 1 volt/microbar (assume excited and measured at resonance frequency):

$$65 \text{ dB} = 20 \log \frac{V_{out}}{V_{in}} \qquad (7)$$

$$\frac{V_{out}}{V_{in}} = 10^{65/20} = 1778 \qquad (8)$$

then referred to 1 V/microbar

$$\frac{1V}{1778} = 562 \text{ microvolts} \qquad (9)$$

therefore

$$\frac{112 \text{ microvolts}}{562 \text{ microvolts}} = 0.2 \text{ microbars} \qquad (10)$$

since 1 microbar = 1.45×10^{-5} psi

$$(0.2 \text{ microbars})\ (1.45 \times 10^{-5} \text{psi})\ \frac{1}{\text{microbar}} = 2.9 \times 10^{-6} \text{psi} \qquad (11)$$

With a 30 kHz transducer of surface area 1.56×10^{-1} sq. in. the pressure on the crystal would be:

$$(2.9 \times 10^{-6} \text{ psi})(1.56 \times 10^{-1} \text{ in}^2) \simeq 5 \times 10^{-7} \text{ pounds}$$

This is, of course, an oversimplification of the determination of the actual pressure necessary to generate a signal at a 1 volt threshold but illustrates some of the concepts involved. Items such as coupling efficiency of the transducer have been ignored as well as assuming that the pressure front acts simultaneously (and in a normal orientation) over the whole surface of the transducer and that all of the energy goes into generating a voltage (ignoring heating for instance). Be that as it may, the value 5×10^{-7} pounds appears to be a reasonable order of magnitude estimate of the minimum stress wave pressure necessary to generate a signal at the transducer with the amplification, threshold, and transducer sensitivity as stated.

RESULTS OF INVESTIGATIONS TO DATE

Both laboratory and field investigations have been performed to date on this project aimed at source location of seepage, grouting or hydrofracturing using the AE method just described.

Laboratory investigations consisting of pumping water and chemical grout into a sand filled box 4' wide by 4' high by 6' long. This box was filled with a well graded sand placed in a uniformly compacted manner. The sensors were attached to 0.5" diameter steel rod metal wave guides measuring 3' long. The exposed ends of the rods were drilled and tapped to receive a threaded shoe with a 1.0" diameter plate for holding the sensor.

These wave guides were driven into the sand in two arrangements. One had the wave guides in line to measure attenuation effects. The second arragement of wave guides was a rectangular array for performing source location studies.

Figures 3(a) to (d) are plots of total events versus time for the first attenuation study. Figure 3(a) for sensor 1, shows a steady increase of events with time. This is attributable to several modes of AE generation, the most significant of which are probably compaction, flow, and fracture. Figure 3(b), for sensor 2, shows discontinuous events that start late in the test and a very low event rate. This is probably due to isolation of the wave guide (it was very loose when the test was dismantled) from the compaction and fracture events. Eventually events are received when the sand is saturated with water. Figure 3(c), for sensor 3, indicates the second highest data total and a curve that matches sensor 1. This wave guide was tight (good contact with sand) and was receiving most of the high energy events sensor 1 received. Figure 3(d), for sensor 4, is similar to sensor 3 except it is further from the source.

Figures 4(a) through 4(d) are a second linear study. The major difference in this case from the previous one is that the sand was essentially saturated to begin with. Figure 4(a) and 4(b), for sensors 1 and 2, indicate a discontinuous event rate with slightly more events on sensor 2. Sensor 1 recorded high event rates at the end of the test when the injection rod suddenly decended into the soil due to the instability created by the moving water. Figure 4(b) shows lesser activity but at the same time. Figures 4(c) and 4(d), for sensors 3 and 4, indicate a steady event rate. It is probable that a tunnel developed at the bottom of the sand. The water flowed through this tunnel and generated moving sand grain events (piping effects) at both sensors 3 and 4. Note that neither of these sensors recorded the falling injection rod activity shown in Figures 4(a) and 4(b). This means that event amplitudes generated by the falling rod were attenuated below threshold level between rods holding sensors 2 and 3.

The third test in this series used a rectangular array of transducers and was conducted in the nearly saturated sand previously described. Injection of a sodium silicate based chemical grout was in the approximate center of the array. Figures 5(a) through 5(d) indicate various events on the individual channels. Although sensors 3 and 4 had the first hits, the inflection parts of all four sensors are seen to be nearly the same and AE events are active throughout the test.

Field investigations were performed at a chemical grouting site in Pittsburgh, Pennsylvania during an early stage of construction on an underground transit system and at a cement grouting site in Ridgeway, Colorado for blanket grouting of a rock foundation for an earth dam.

For the Pittsburg chemical grouting test site, Table 1 presents the calculated difference in distance between the first sensor hit and succeeding sensor data. This data is calculated from the following equation.

$$\overline{\Delta t} \times \text{Clock Rate} \times \text{Velocity AE wave} = \text{Distance} \quad (12)$$

where

$\overline{\Delta t}$ = average Δt value

Clock rate = 4000 nanoseconds

Velocity = 2000 feet/second

therefore:

$$\overline{\Delta t} \times 4 \times 10^{-6} \text{ (seconds)} \times 2000 \text{ (feet/second)} = 0.008\ \overline{\Delta t} \text{ (feet)} \quad (13)$$

The above relationship, i.e. 0.008 $\overline{\Delta t}$ gives the distance difference between the first sensor hit and the second, third, or fourth sensor hits in feet. For example, if Δt, was zero then the source would be on a plane equidistance between the first sensor and second sensor responding, if the medium is isotropic. Figure 6 shows an attempt to locate the first source (listed) graphically. The results seem reasonable in light of the field situation. The continuation of such calculations would show the propagation of the AE sources with time as grouting continues. This type of graphical portrayal is the ultimate goal of the project.

For the Ridgeway cement grouting test site, field monitoring has just been completed as of this writing. AE's were monitored at distances of up to 50' from the location of grout injection. This is reasonable since the cement grout being injected was an 8:1 mix (water to cement ratio) and thus very fluid in its consistency. Multiple sensor hits on up to five channels were recorded at various times during the injection process. All data was recorded on floppy discs for subsequent data processing on the computer program described previously.

SUMMARY AND CONCLUSIONS

The detection and monitoring of seepage, grouting and hydrofracturing using a nondestructive testing method promises to give great insight into the actual behavior of these subsurface phenomena. Indeed, if the activity can be located in three dimensional space, and in real time, the entire grouting industry could utilize the technology, turning what is often called an art into a science. A candidate technique for this accomplishment is acoustic emission (AE) monitoring. This paper represents the initial tests in evaluating equipment hardware and software and in determining technical feasibility.

Using a multi-channel (up to five channels were used) AE system (AET Pioneer 5000) and 30 kHz resonant sensors (AET AC30L) with bandpass filters of 1 kHz to 100 kHz and a total system gain of 90 dB, a set of laboratory and field tests were conducted.

In the laboratory, a large sand filled box was used where both water and chemical grouts were injected. Two tests on attenuation evaluation, with a linear array of wave guides, were performed, see Figures 3 and 4. Both showed that events were recorded on each wave guide with some physical phenomenon being simultaneously recorded, see Figures 4(a) and 4(b) for movement of the wave guide at sensors 1 and 2. A rectangular zone array was also evaluated where multiple event hits were recorded (compare Figures 5(a) through (d)) indicating proper equipment selection, system tuning and system functioning. Zone locations studies were then conducted using a computer program for calculating time difference values (Δt's) between sensor hits. Numerous multi-channel hits were recorded during these tests.

The system was then used in two field projects. During chemical pressure grouting, activity was seen on all four channels and in several cases actual pressure pulses were observed. The field data from the system was summarized (Δt values), distance differences were manually calculated and a source location was estimated, see Figure 6. Although not "ground truth" verified, it is reasonable in its location and represents the first known attempt at performing this type of prediction. Cement grouting tests were also conducted, which produced numerous multiple channel hits, but data reduction is not yet complete.

Obviously, more remains to be done. Future work will be entirely field oriented using system computer subroutines to calculate distances from the Δt values, then calculate the AE sources in x-y-z coordinates, and eventually displaying these AE source locations on a CRT screen. This should enable the owner or engineer to trace the subsurface seepage, and the grouting contractor to knowledgeably locate where the injected grout is flowing. Additionally, the injection pressure should be capable of being controlled so as to know if, when and how severe is high pressure (hydrofracture) grouting.

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REFERENCES

1. Obert L., "Use of Subaudible Noises for Prediction of Rock-burst," Report Invest. 2555, United States Bureau of Mines, 1941.

2. Obert, L. and Duvall, W. I., "Microseismic Method of Predicting Rock Failure in Underground Mining: Part I and Part II," Report Invest. 3897 and 3803, United States Bureau of Mines, 1946.

3. Hodgson, E. A., Bulletin of the Seimological Society of America, Vol. 32, 1972, p. 249.

4. Hodgson, E. A., Trans. of the Canadian Institute of Mining and Metallurgy, Toronto, Ontario, Canada, Vol. 46, 1943, pp. 313.

5. Blake, W., Leighton, F., and Duvall, W. I., "Microseismic Techniques for Monitoring the Behavior of Rock Structures," Bulletin 665, United States Department of the Interior, Bureau of Mines, 1974.

6. Hardy, H. R., Jr., "Evaluating the Stability of Geologic Structures Using Acoustic Emission, " ASTM-STP-571, American Society for Testing and Materials, 1975.

7. Mearns, R., and Hoover, T., "Subaudible Rock Noise (SARN) as a Measure for Slope Stability," Final Report CA-DOT-TI-2537-1-73-24, United States Department of Transportation, Federal Highway Administration, Aug. 1973.

8. Kaiser, J., "Untersuchungen uber das auftreten Gerauschen Beim Zugversuch," thesis presented to Technische Hochschule at Munich, Germany, in 1950, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

9. Kaiser, J., "Erkenntnisse und Folgerungen aus der Messung von Gerauschen bei zugbeansprunchung von Metallischen Werkstoffen," Arkiv fur das Eisenhuttenwesen, Vol. 25, 43, 1953.

10. Tatro, C. A., and Liptai, R. C., "Acoustic Emission from Crystalline Substances," Proceedings of the Symposium on the Physics of Nondestructive Testing, Southwest Research Institute, San Antonio, Texas, 1962, pp. 145-174.

11. Tatro, C. A., and Liptai, R. G., Proceedings of the 4th Symposium on Nondestructive Testing of Aircraft and Missile Components, Southwest Research Institute, San Antonio, Texas, 1963, pp. 287-346.

12. Green, A. T., "Detection of Incipient Failure in Pressure Vessels by Stress-Wave Emissions," Nuclear Safety, Vol. 10, 1969, pp. 4-18.

13. Nakamura, Y., "Acoustic Emission Monitoring System for the Detection of Cracks in a Complex Structure," Materials Evaluation, ASTM, Jan., 1971, pp. 8-12.

14. Galambos, C. F. and McGogney, C. A. "Opportunities for NDT of Highway Structures," Materials Evaluation, ASTM, July, 1975, pp. 168-175.

15. Liptai, R. G., et al., "Acoustic Emission Techniques in Materials Research," Inter. Jour. of Nondestructive Testing, Vol. 3, 1971, p. 215.

16. Dunegan, H. L. and Tatro, C. A., "Acoustic Emission Effects During Mechanical Deformation, " Techniques of Metal Research, Vol. 5, R. F. Bunshah, ed., Interscience Publication, New York, NY, 1971.

17. Knill, J. L., Franklin, J. A., and Malone, A. E., "A Study of Acoustic Emission from Stressed Rock," Inter. Jour. of Rock Mechanics and Mining Sciences, Vol. 5, 87, 1968.

18. Lord, A. E., Jr., "Acoustic Emission - A Review," Physical Acoustics, Vol. 11, W. P. Mason and R. N. Thurston, eds., Academic Press, New York, NY, 1975, pp. 289-353.

19. Lord, A. E., Jr., and Koerner, R. M., "Acoustic Emission in Geologic Materials," Invited Paper to appear in Proceedings of the Joint Meeting of the Acoustical Societies of America and Japan, Hawaii, Dec. 2-5, 1978.

20. Drouillard, T. F., "Acoustic Emission: A Bibliography with Abstracts," Plenum Press, New York, 1979.

21. Goodman, R. W., and Blake, W., "Rock Noise in Landslides and Slope Failures," Highway Research Record, Vol. 119,