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CIVIL ENGINEERING APPLICATIONS OF ACOUSTIC EMISSION

by

Theodore Hopwood II
Chief Research Engineer

Transportation Research Program
College of Engineering
University of Kentucky
Lexington, Kentucky

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HISTORICAL BACKGROUND

In 1939, a suspension bridge at Portsmouth, Ohio, experienced stress-corrosion cracking of the main-cable wires at anchorage points located at each end of the bridge. Watchmen were placed in the anchor chambers where the fractures had been detected. Subsequently, they reported hearing the sounds of further wire breakage on quiet nights. When this was reported, a decision was made to recable the bridge (1). That was one of the earliest documented instances of the use of the acoustic emission phenomena in a structural application.

Also, in the late 1930′s, L. Obert and W. I. Duval at the U. S. Bureau of Mines were performing sonic tests on rock mines. They were surprised to find that stressed rock pillars emitted micro-level sounds (2). Those noises were later termed "rock-talk."

Unlike the early acoustic emission structural monitoring at Portsmouth, the "rock-talk" phenomena has been the subject of continuous ongoing geotechnical research since the late 1930′s.

Over the years, much progress has been made in civil engineering applications using acoustic-emission (AE) testing. However, most of those applications are still in developmental stages. Also, some of the past research is contradictory. Therefore, the potential AE user should perform preliminary tests to ascertain the viability of the intended AE procedure. Both laboratory and field tests should be performed under controlled conditions to ensure the applicability and usefulness of that test method before it is employed in service. While this approach is expensive, subsequent cost savings from AE in-service testing, compared to other nondestructive methods, usually justifies those expenditures.

The following three sections discuss the primary applications of acoustic emission in civil engineering. Those are 1) geotechnical, 2) structures, and 3) special component testing. Due to the vast scope of AE research, these reviews are certainly not complete. There are several state-of-the-art AE reviews that provide reference to specific applications (3, 4).

GEOTECHNICAL APPLICATIONS OF ACOUSTIC EMISSION

The AE phenomena may be applied to a variety number of geotechnical materials. Those materials include (but are not limited to) soils (sandy and clayey), rocks (igneous and metamorphic), fossilized deposits (coal), and ice. AE monitoring may be conducted on foundations, mines, tunnels, excavations, embankments and fills, tied-back and retaining walls, and dams. AE monitoring may be useful in nearly every geotechnical application where subsurface deformation can be anticipated.

In the application of the AE test method, instability must exist in the material before meaningful results can be obtained. Instability creates a change in the disposition of the material that may be detected by the AE sensors. The instability may be caused by the removal of material (as encountered in tunnels, mines, or cuts), by the addition of material (as encountered in a fill, retaining wall, or earthen dam), by the imposition of a load (as in a foundation), or by the interaction of the material with water or chemicals (as in ground-water seepage).

fracture, or particle flow in a liquid medium. Acoustic emissions are detected as either stress-wave packets traveling through the material or as moving particles contacting a sensor or wave guide.

Diverse AE source mechanisms operate in geotechnical testing and the resulting stress waves often are transmitted through heterogeneous mediums. This has led to a variety of test methods and systems. For AE geotechnical studies as shown in Figure 1, frequencies range from the low audible (25 Hz) to the ultrasonic (50 kHz).

AE signals have three important characteristics that must be taken into consideration (5) -- signal strength, frequency, and attenuation. An approximate relationship for maximum acceleration of the signal at its source (for soils) is given by the following (6):

$$a_{max} = (\pi f^2 e^2 VRc)^{1/2}/(2\Delta tr) \qquad (1)$$

where a = acceleration of the elastic wave at "r",

f = frequency of the elastic wave at "r",

e = elastic strain released,

V = volume of soil involved,

R = radiation coefficient (i.e., efficiency of radiating elastic waves),

c = wave velocity,

Δt = time increment for release of elastic strain "e", and

r = distance from source.

AE events contain a spectrum of different frequencies. The AE spectrum usually contains higher frequencies at the emitting source than at some distance from the source. That is due to the greater attenuation or a weakening of high frequency portions of AE events as

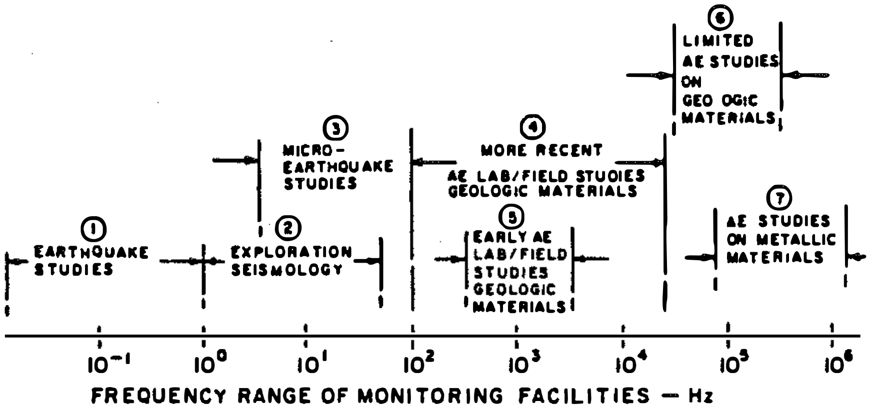


Figure 1. Frequency Range over which AE and Other Associated Studies Have Been Conducted.

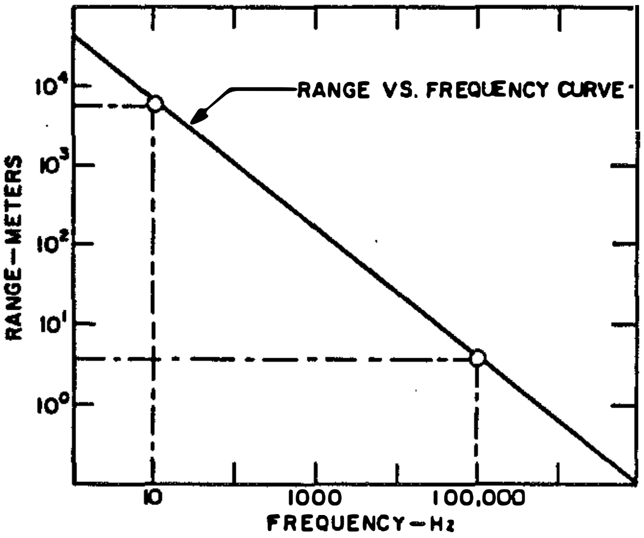


Figure 2. Typical Range versus Frequency Data for AE Signals.

they propagate as stress waves (AE waves) through the material. This is shown in Figure 2. In that example, an AE sensor is sensitive only to stress waves with frequencies greater than 100 kHz, then the maximum range of AE detection is 5 meters. Frequencies measured during AE events are affected by the source of the AE activity, the acoustic properties of the transmitting material, and the frequency response characteristics of the sensor and AE system.

The third factor that may affect AE response is the loss of AE energy as waves travel through a material. Loss of energy is called attenuation. Attenuation may be measured by placing several transducers at different distances from an AE source. Attenuation can be calculated as

$$\gamma = (20/x) \log (A_1/A_2)$$

where γ = attenuation coefficient in dB/unit distance,

x = distance between pickup points,

A_1 = amplitude of signal at Point 1, and

A_2 = amplitude of signal at Point 2.

Attenuation is a function of the frequency content of the AE waves and the medium through which they travel. As shown in Figure 3, soils have higher attenuation responses than rocks or coal.

LABORATORY AE BEHAVIOR OF GEOTECHNICAL MATERIALS

A good understanding of the AE response of geotechnical materials is necessary to design field AE tests. Field situations may not always mirror laboratory results, especially if circumstances require simplified laboratory designs. However, laboratory tests will provide

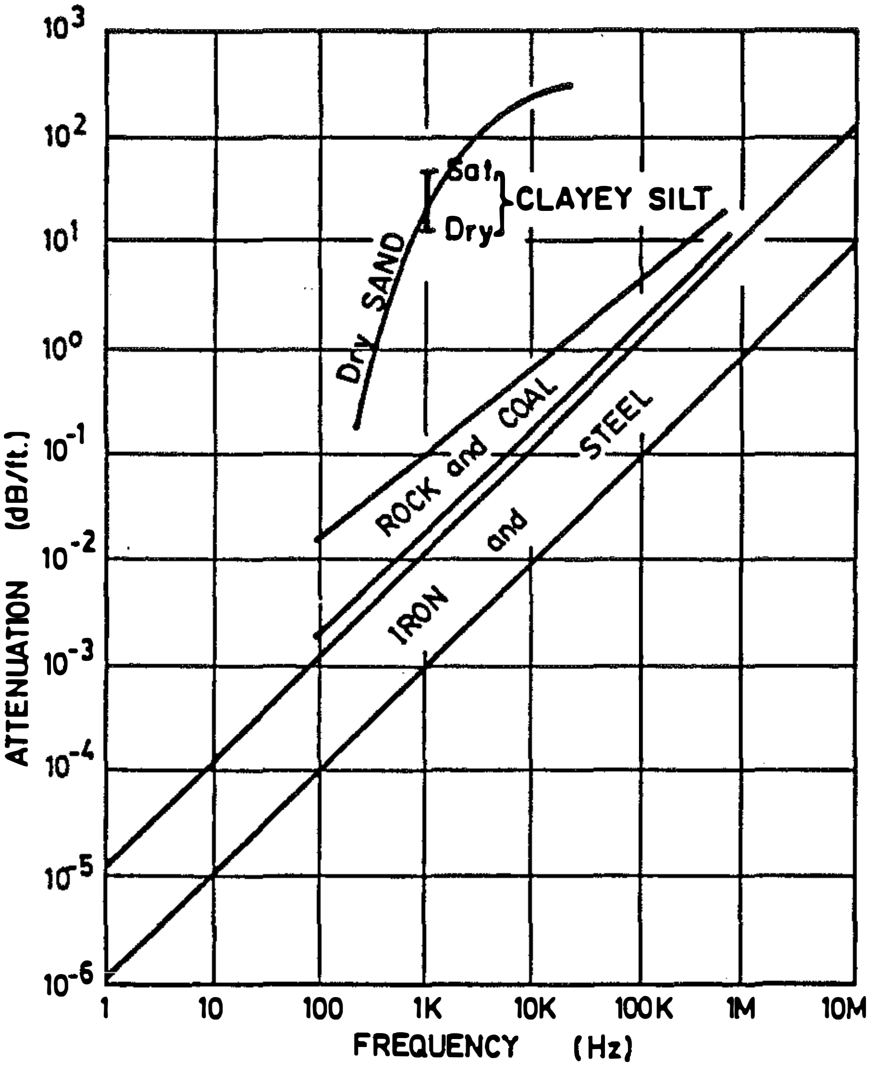


Figure 3. Attenuation Response of Different Soil Types Contrasted to Rock/Coal and Iron/Steel.

valuable insights into the responses of geotechnical materials and may be useful in preparing feasibility studies before expensive field testing is performed.

Earlier studies (7) of AE laboratory compressive tests on rock indicated that, as the applied stress in a material approached failure, the AE rate increased (Figure 4). In another study (8), the AE activity rate decreased after structural failure occurred in a rock mine. Such observations indicated that AE rate is a function of the degree of rock stability.

Early research was conducted on the repeated compressive loading and unloading of rock samples (9). Above a certain high stress level, the AE event rate increased significantly. If the rock was subjected to stress cycling below that level, the material became less emittive with each succeeding stress cycle. When the rock was subjected to stress cycling above that level, it became noisier with the application of successive stress cycles. Rock also was emittive during the unloading portion of each stress cycle.

The basic AE behavior of rock subjected to compressive stress is shown in Figure 5. The Type I curve was determined by Mogi (10). Cumulative AE count is plotted as a function of compressive stress. Four different zones of AE behavior may be identified. They are related to crack closure (Zone AB), linear elastic deformation (Zone BC), stable fracture propagation (Zone CD), and unstable fracture (Zone DF). Experimental work has revealed other types of AE signatures. Those were discerned from tests of ten different types of rocks including dolomite (Type I), shale (Type III), micaschist -- Philadelphia, PA (Type III), horneblende (Type II), marble (Type II), dolomitic marble (Type I),

granite (Type I), shale (Type II), micaschist -- Germantown, PA (Type III), and limestone (Type IV). Type II rocks lacked stable fracture behavior, Type III rocks lacked the crack closure region, and Type IV rocks lacked both crack closure and stable fracture regions. Differences in AE response with stress indicate the need to have a good understanding of the type of material existing in the field prior to monitoring.

The state of stress also affects the AE response of rock. Split tensile tests of the same rocks produced only Type III and Type IV behavior. In tension, Type I and Type II signatures would not be expected.

Direct shear tests of rock performed by Koerner and Lord (11) produced either quick or slow failure. Slow failure was characterized by initial slow shear movement of mating rock faces followed by sudden failure. Both failure modes produced high-amplitude AE activity.

Direct shear/AE monitoring tests of soils were performed on three types of soils: beach sand, clayey silt, and kaolinite clay (12). The resulting shear stress and accumulated AE counts-strain curves indicate that the soil producing the most total AE activity during loading (sand) showed the least strain and that the soil producing the least total AE activity during loading (kaolinite clay) showed the most strain (Figure 6). Other laboratory tests (13) indicate that increased amounts of water in soils will result in less AE activity when strained. Laboratory tests also showed that soils produce relatively large amounts of AE activity when they fail. A series of triaxial compression tests was conducted on clayey and silty soils using confining pressures of 5, 10, and 15 psi to simulate soils at depths of 8, 16, and 24 feet,

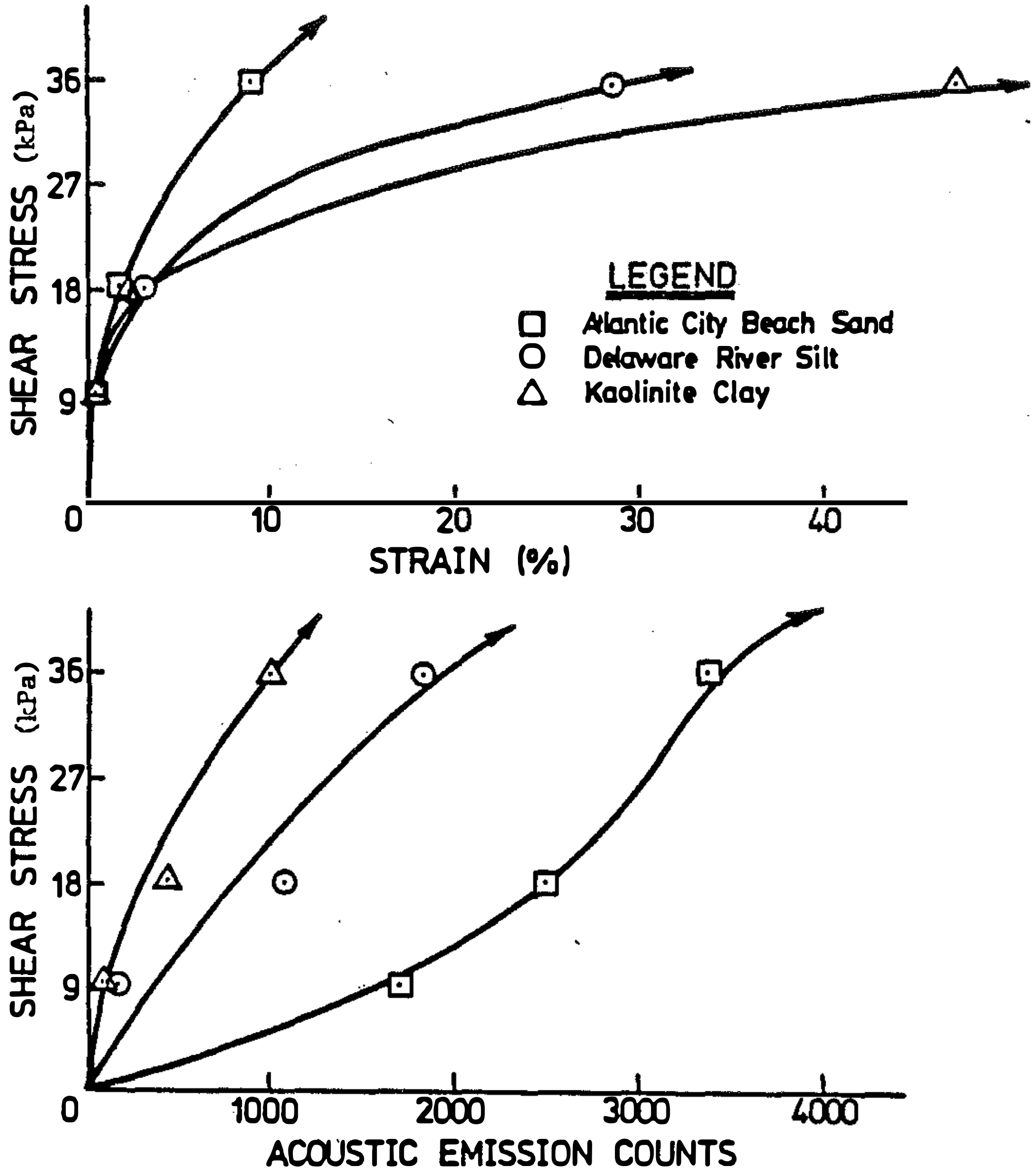


Figure 6. Stress versus Strain and Stress versus Acoustic Emission Behavior of a Sand, Silt, and Clay.

respectively (14). The test results in Figure 7 show a good correlation between total AE activity and strain. Based on those results, both AE and strain may be used to evaluate soil stresses and therefore failure. This type of correlation exists for many soils.

The frequency contents of soil AE activity depends on many variables such as the distance between the source and AE sensor, the nature of the AE sensor, and the type of sensor pickup used to monitor AE activity. Figure 8 shows the frequencies obtained from clay, silt, and sand tested under identical conditions. While such conditions may be monitored in the laboratory, difficulties may be encountered when attempts are made to perform frequency spectral analysis in the field without consideration of the aforementioned variables.

The amplitude curve shown in Figure 9 reflects the relatively weak AE emissivity of cohesive (clayey) soils compared to granular soils (sands). Increasing AE amplitudes are produced by both types of soils with increasing stresses. As expected from Figure 9, granular soils produce higher amplitude AE activity than cohesive soils. Also, there are differences in AE amplitude behaviors of cohesive and granular soils as the failure stresses of these two different materials are approached. Cohesive soils show a decrease in AE amplitudes above 70 percent of the failure stress whereas AE amplitudes in granular soils increase until failure. Such behavior indicates that AE amplitude analysis may be better suited for granular soils than for cohesive soils.

Laboratory AE tests have been conducted to determine if water seepage could be detected (15). A hydrophone was embedded in a column of gravel and both clear and turbid water were passed across the hydrophone. The turbid water could be detected at a lower flow rate

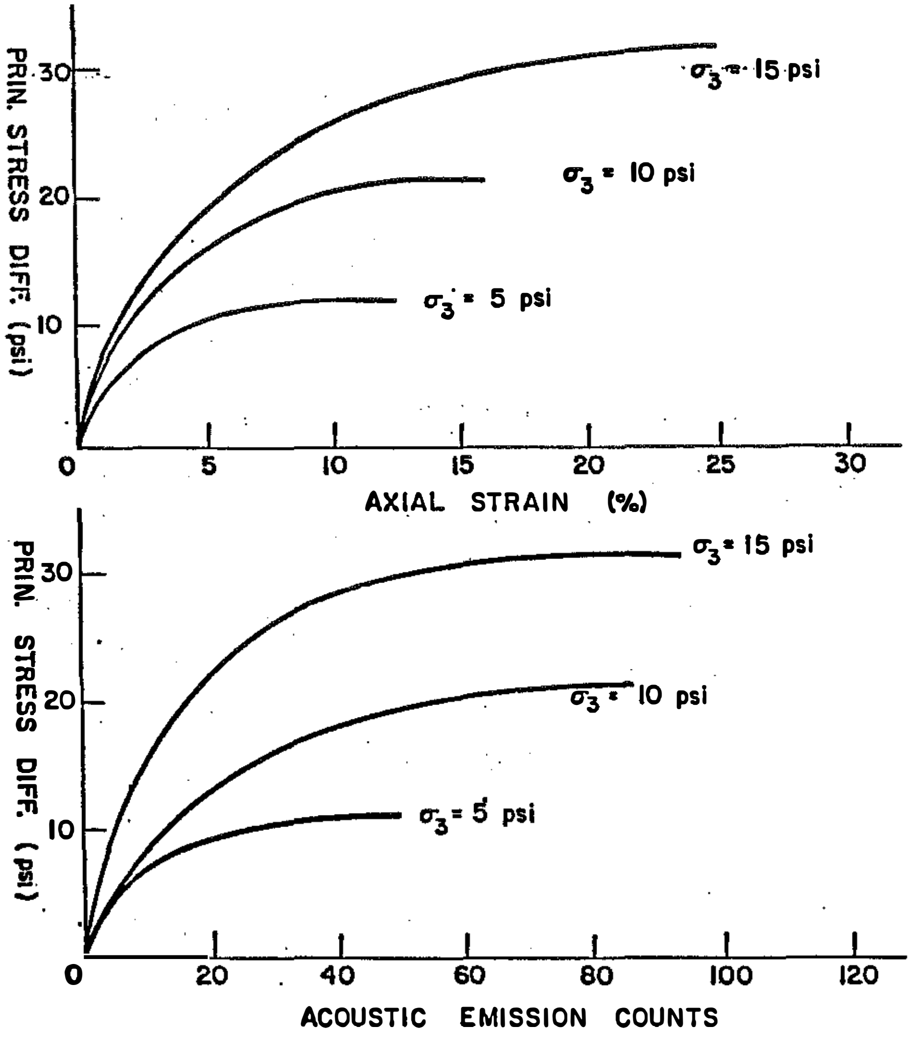


Figure 7. Stress/Strain and Stress/Acoustic Emission Response of a Clayey Silt Soil at 15 Percent Water Content Tested in Triaxial Shear with Confining Pressures of 15, 10, and 5 psi with Accelerometer Embedded in Sample.

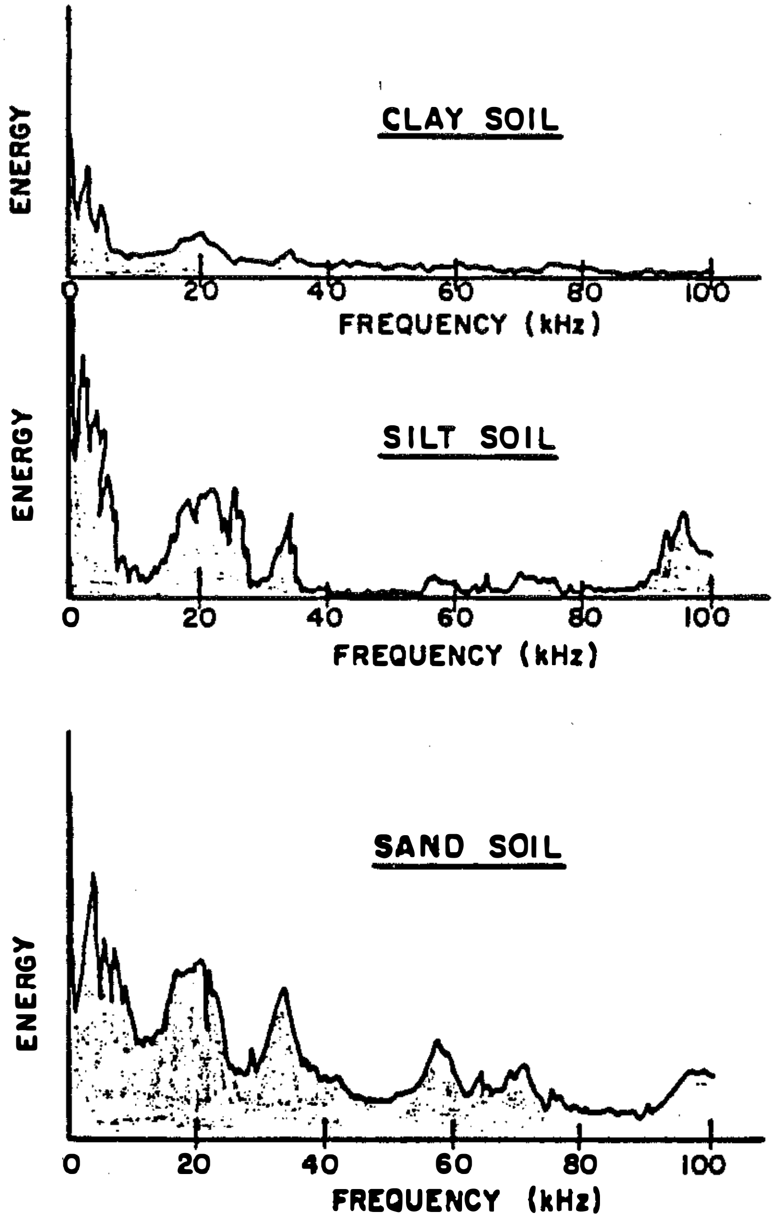


Figure 8. Frequency Spectra of Sand, Silt, and Clay (near Failure) Tested under Identical Conditions

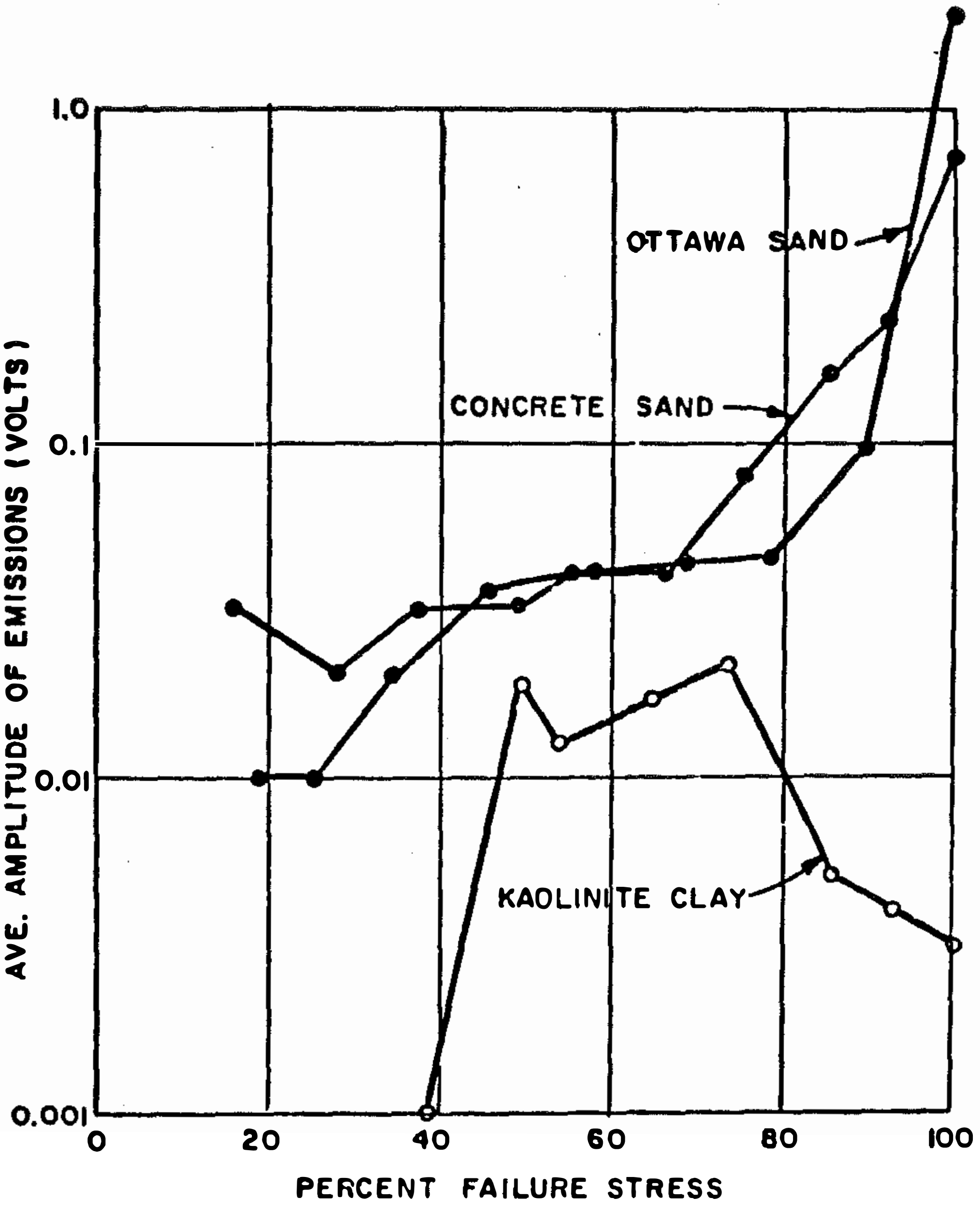


Figure 9. Amplitude of AE´s in Various Soils.

than the clear water (10 ml/sec versus 45 ml/sec). The AE rate for both specimens increased exponentially with flow rates (Figure 10).

Past laboratory tests of rocks and soils have shown that AE activity is an indicator of material instability. Unstable conditions may be associated with a number of failure mechanisms encountered in geotechnical structures. Based on initial laboratory tests, the only geotechnical materials that appear to present a problem in AE testing are clayey (cohesive) soils. High monitoring sensitivities are necessary to detect failure of clayey soils.

GEOTECHNICAL AE EQUIPMENT

A schematic of a simple single-channel AE monitoring system is shown in Figure 11. The system consists of 1) a wave guide (optional), 2) a sensor (or transducer), 3) a pre-amplifier, 4) signal cable, 5) filters, 6) an amplifier, 7) a counter, and 8) a output recording device(s) (typically an oscilloscope, tape recorder, or X/Y or chart recorder). Geotechnical AE equipment is typical of instruments used in other AE applications except that it usually monitors lower frequencies and in some cases employs volumetric AE source location.

A wide variety of sensors employed in geotechnical work include 1) accelerometers, 2) piezoelectric transducers, 3) geophones, and 4) hydrophones (Figure 12). The wide range of geotechnical AE test frequencies shown in Figure 1 represents resonant frequency responses of those sensors. Geophones and hydrophones are used in tests involving frequencies between 1 and 2000 Hz. At frequencies greater than 2000 Hz, accelerometers and piezoelectric transducers are employed.

As geophones and hydrophones monitor lower frequency AE activity, they are capable of detecting high-amplitude AE events that typically

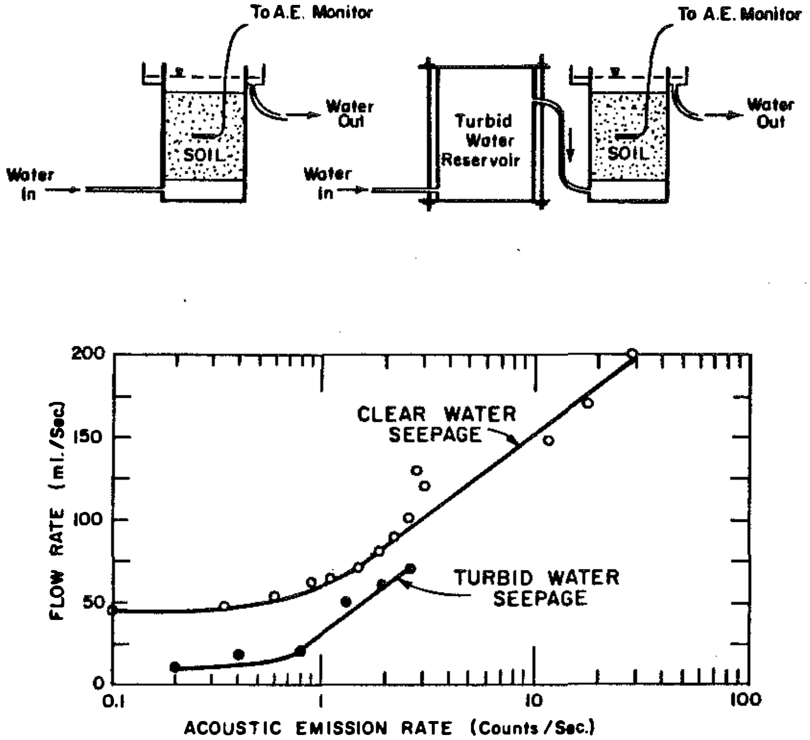


Figure 10. Schematic Diagram of Clear-Water and Turbid-Water Seepage Tests Using Small Gravel Soil and Resulting Flow versus AE Rate Response.

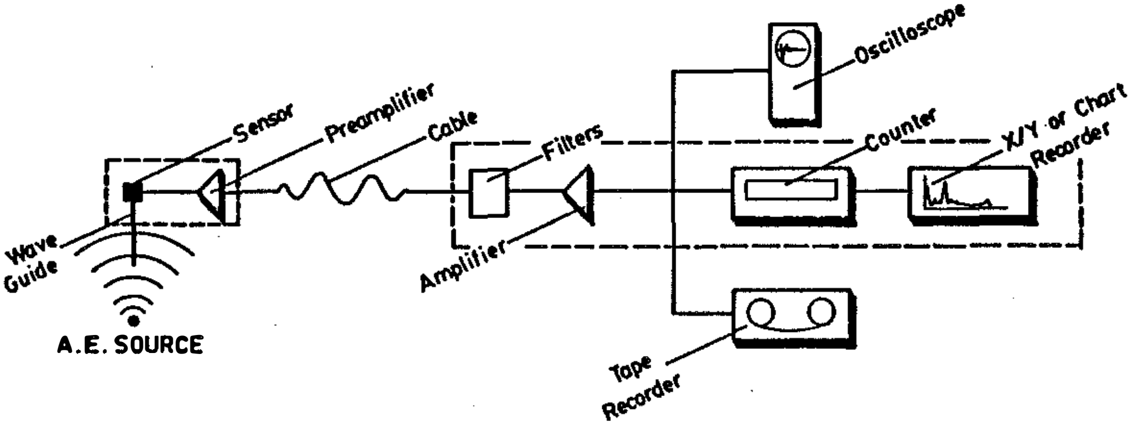


Figure 11. Schematic Drawing of Basic Single-Channel Acoustic-Emission Monitoring System for Recording Total Counts or Count Rate Response.

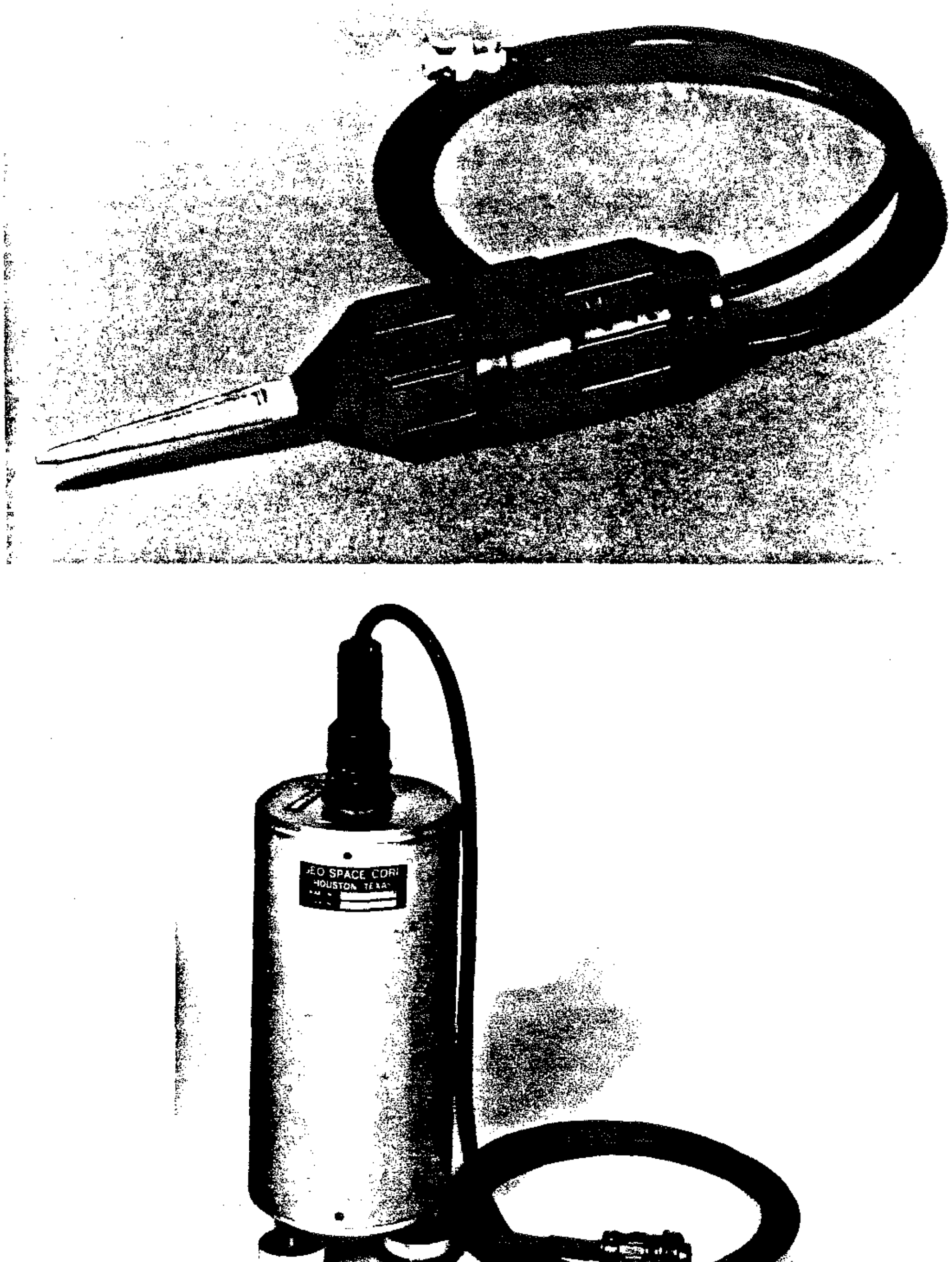


Figure 12. Typical Geophones Used as AE Sensors.

occur at those frequencies. As noted in Figure 3, those AE events are less subject to attenuation as they travel through a material than is higher frequency activity such as ultrasound. Attenuation problems encountered in high-frequency AE monitoring may be offset by mounting accelerometers or piezoelectric transducers near the source of material instability or by using wave guides that penetrate through the unstable material. Higher frequency transducers offer the advantage of being more resistant to ambient noise sources around the test site.

As shown by Hardy in Figure 13, geotechnical AE monitoring may be conducted at a number of locations. For an underground geological structure (ST), the transducers may be located on the surface of the structure or at holes drilled outward from it (B). If access is not convenient, the substructure may be monitored from transducers installed from the ground surface (C1-C4).

A number of localized mounting techniques have been used (Figure 14) for underground mines and tunnels. Where installation from the ground surface is desirable, a number of installation techniques has been implemented (Figure 15), including the borehole technique (Figure 15d). In this method, the borehole is filled with water to a given level and a hydrophone is placed in the water, which acts as a coupling medium. In monitoring deeply buried structures or structures with deep overburdens, Hardy (16) has used special deep burial techniques (Figure 16). The indirect mounting technique uses metal wave guides placed in the earth or sidewall of a mine (Figure 17). A transducer or accelerometer is bonded to the exposed end of the waveguide. Koerner and Lord used 1/2-inch diameter steel rods with threaded ends for wave guides. A section of the rod is driven into the ground until only the threaded end

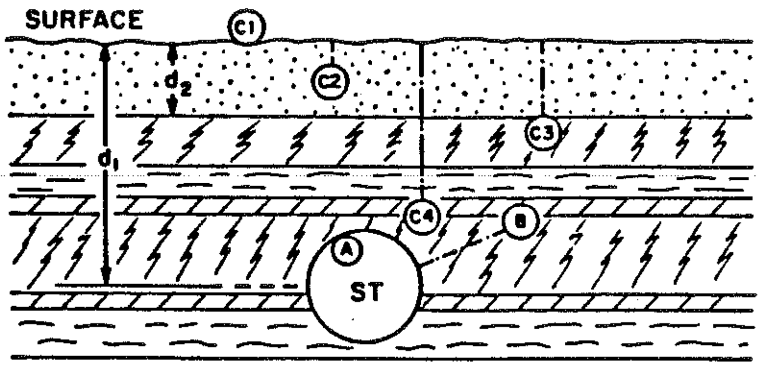


Figure 13. Simplified Field Situation Illustrating Possible Locations for AE Transducers.

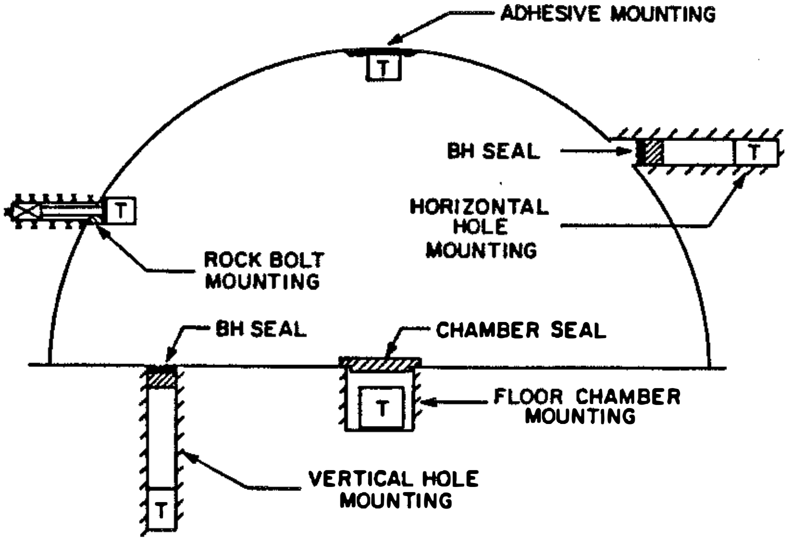


Figure 14. Various Methods Employed for Underground Mounting of AE Transducers.

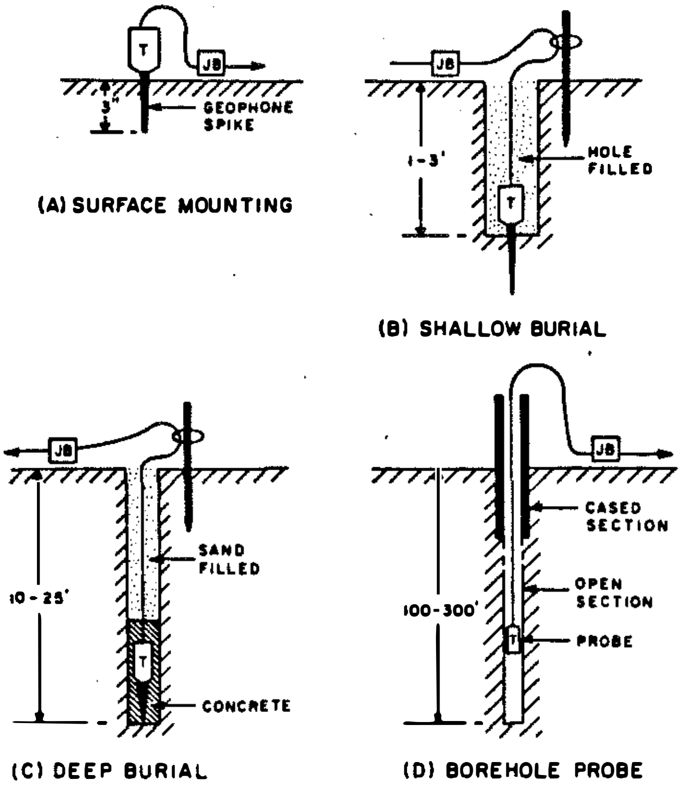


Figure 15. Transducer Installation Techniques for Depths less than 100 m (T = transducer, JB = junction box).

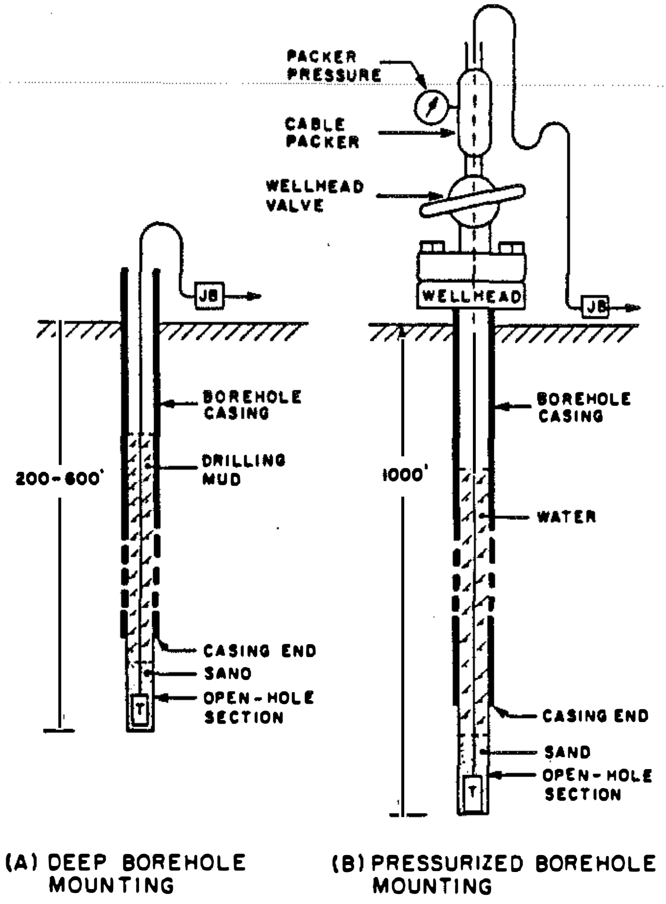
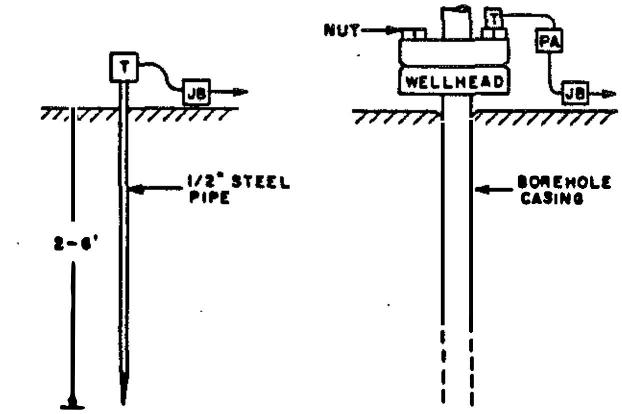
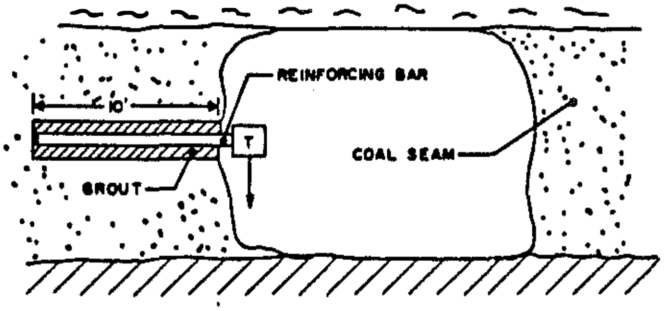


Figure 16. Very Deep Transducer Installation Techniques (T = transducer, JB = junction box).



(A) WAVEGUIDE MOUNTING (B) WELLHEAD MOUNTING



(C) MODIFIED WAVEGUIDE MOUNTING

Figure 17. Indirect Methods for Transducer Installation (T = transducer, JB = junction box).

is exposed. Another section of rod is coupled to the buried rod, and they are driven further into the ground. Once the desired depth is reached, the transducer is bonded to the end of the exposed rod (Figure 18). Another technique makes use of well casing as the wave guide. The transducer is mounted to the well head (Figure 17). Any material instability or AE wave activity in the soil will excite the waveguide. AE waves then travel along the waveguide and trigger signals by the AE transducer.

There are several advantages and disadvantages of the direct and indirect (waveguide) transducer mounting techniques. Below about ten feet, the direct surface mounting techniques are usually more difficult and expensive to install. Also, the mounting depth of the AE sensor must be sufficiently close to the material instability to allow the transducer to detect the resulting AE activity.

Waveguides are easier to install than the direct mounting methods. Also, since the entire length of the waveguide can be a receptor of AE activity, it can be placed sufficiently deep in the ground to ensure that it will be near a location of material instability, such as a plane of shear failure. However, Hardy (17) noted that the depth of AE activity cannot be determined using waveguides and that the possibility exists for waveguides to interact with the surroundings and create AE activity. Therefore, caution should be exercised when using waveguides.

Geotechnical AE monitors are usually either simple single-channel AE devices or complex multichannel units capable of volumetric instability location.

The simple single-channel AE monitoring devices are usually portable and mounted in shock-resistant, weatherproof cases (Figure 19). Often,

Figure 18. Accelerometer Attached to Threaded Steel Rod (Waveguide).

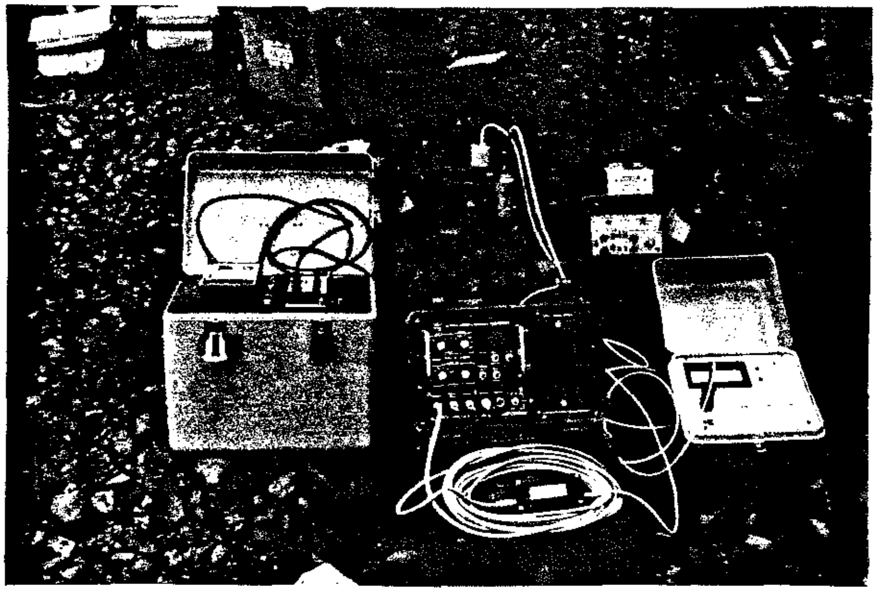


Figure 19. Typical Simple Portable AE Monitor Used in Geotechnical Applications.

those units are battery-powered and may be left in the field for remote monitoring for periods up to 48 hours. Those devices are suitable for general condition monitoring. Usually, this means that one single-channel AE monitor is dedicated to one AE transducer or, in effect, one test location. Many test locations require concurrent AE monitoring at several detection sites. Due to their relative low cost, those multiple sites may be economically monitored using a number of single-channel AE systems. Proper placement of AE sensors (and possibly waveguides) and the high attenuation encountered in many geotechnical applications should provide AE isolation between the different test sites. In employing such AE systems, the user must locate the sensors properly to ensure detection of any AE activity.

For more complex monitoring tasks, multichannel AE systems capable of AE source location are employed. For source location along a horizontal plane, a four-channel system is required. For volumetric (three-dimensional) location, a minimum of five channels is required. A five-channel system is shown in Figure 20, with a source located at point P_o. Computerized methods for determining source locations normally utilize a least-squares iteration technique that searches for the best average solution for a set of equations that contain the transducer coordinates, X_i, Y_i, and Z_i (i = 1, 2, 3 ... n), and the corresponding AE arrival times and velocities t_i and V_i. The method involves the solution of the following set of i equations:

$$(X_i - X_o)^2 + (Y_i - Y_o)^2 + (Z_i - Z_o)^2 = V_i^2(t_i - T_o)^2 \qquad (3)$$

where X_o, Y_o, and Z_o are the true coordinates of the source and T_o is the true origin time.

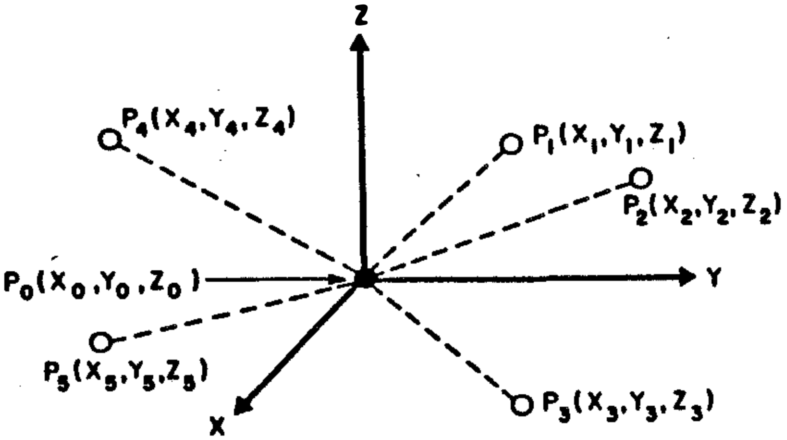


Figure 20. Geometry of a Typical AE Transducer Array (Transducers Are Located at Points P_1, ..., P_5 with the AE Source at Point P_0.

Such analyses require interfacing the AE system with a computer, though a number of the newer commercial AE systems contain microprocessor circuitry for source location. A number of computer programs have been prepared for source location. The Pennsylvania State University program (IBMSL) assumes the AE source and monitoring transducers are located in a homogeneous medium with provision for anisotropic velocity characteristics. The U.S. Geological Survey has prepared a program (HYPO71) for source location in bedded strata.

Data output from the single-channel and multichannel AE systems may include total AE counts, AE event rate, AE amplitude, signal rise time, signal-to-background noise ratio, AE energy, AE energy rate, and AE event duration. Multichannel systems also furnish coordinates of the AE sources.

GEOTECHNICAL FIELD APPLICATIONS

The potential for application of the AE method to foundation monitoring, especially for shallow foundations such as spread footings, appears good. Laboratory bearing capacity testing has been conducted on a footing (Figure 21) (18). The transition between linear deflection and failure is clearly indicated as a function of load by both the footing deflection and total AE activity diagrams.

The two types of shallow foundation failures, punching shear and tilting shear, should be relatively easy to monitor. Transducers or guide rods should usually be placed close to or beneath the foundation footing and should be located close to the anticipated failure planes. The shear planes in punching failures should occur symmetrically in the soil around the footing. In the case of bearing-capacity tilting failures, some shear activity is located on the side of the substructure

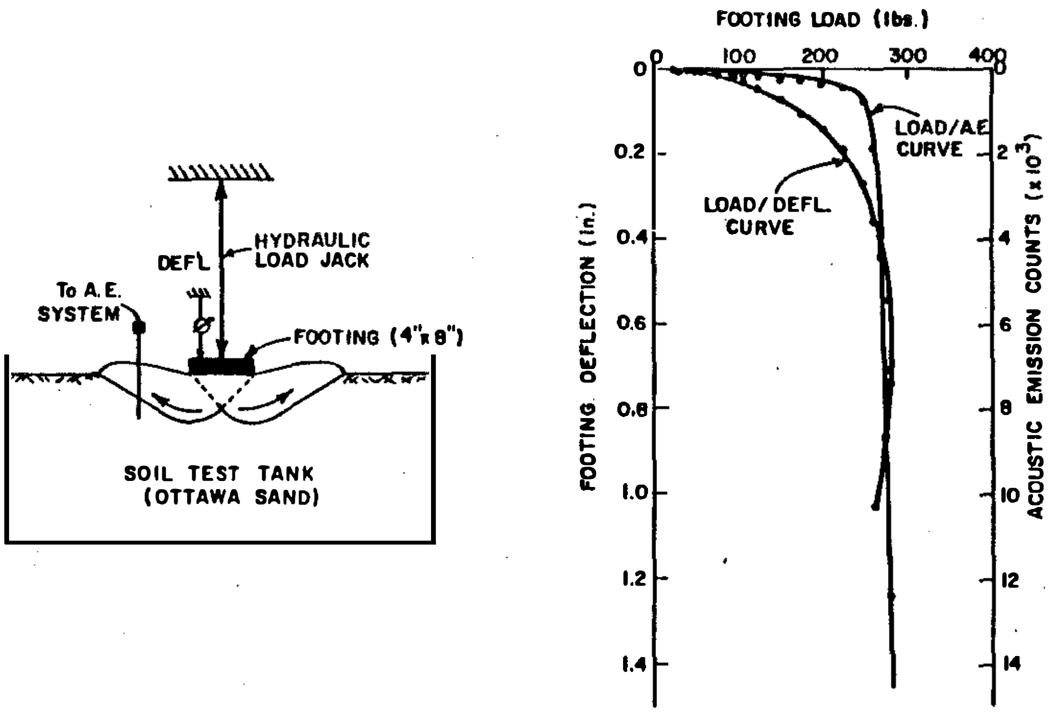


Figure 21. Schematic Diagram of Bearing Capacity Failure of a Shallow Foundation and Resulting Load versus Deflection and Load versus AE Response.

that is opposite to the direction of tilt.

In the case of settlement, the largest portion usually occurs during construction. Generally, after the structure is completed, foundation settlement (secondary compression) is relatively small, or in certain cases may be inconsequential. This settlement is very dependent on time. Therefore, it is desirable to perform AE monitoring on foundations or footings during construction. Monitoring of several, similar foundation structures simultaneously to determine the comparative AE activity among those sites is also useful. AE activity could be correlated with the amount of settlement observed at the various sites. AE acitivity during a given time period could also be compared with the amount of settlement that has occurred at the foundation over that time interval.

If the foundation settlement or tilt stabilized with time, then periodic AE testing could be used to determine the onset of additional movement. If nearby excavation or tunnelling work was being performed, AE testing would be useful to detect any unfavorable subsurface interaction between that work and the foundation that would result further foundation movement.

Application of AE monitoring to detect instability of tunnels appears promising. Koerner and Lord have monitored tunnels embedded in grouted soil, plain soil, and rock (19). Sensors used to monitor AE activity included hydrophones and accelerometers. The hydrophones were used in downhole installations partially filled with water for the tunnel-through-soil tests. In those tests, holes were placed adjacent to tunnel shafts. The tunnel-through-rock tests were conducted from within the tunnel. Accelerometers were attached on threaded studs epoxied to the rock wall, clamped on a spiling bar, and threaded on a piton driven into a tight joint. Noise due to construction activity interfered and meaningful AE data could not be obtained during construction hours. However, one AE test conducted during off-hours gave good indication of material instability, which was manifested as a minor roof fall. Further tunnel monitoring experience is required to correlate AE activity with incipient failures.

AE monitoring of soil and rock embankments and cut sections may provide warnings of slope failures. Numerous experiments have been conducted to detect slope instability in rocks and soils (20). Previous tests indicated that AE activity may provide warning of slope instability prior to visible signs of movement and subsequent failure. To detect those failures, AE sensors should be placed on top of a slope (to detect tension cracks) or at the toe (to detect shear movement). If failure or severe shear is possible, waveguides should be used to safeguard the sensor. Also, waveguides should probably be used in soft soils. Due to the low-amplitude AE emissions from soft soils, it may be necessary to have waveguides penetrating directly through areas of possible shear movement.

A large portion of past work has been conducted on mines (21). That work has included studies of rock bursts, column failures, roof falls, and outbursts in coal. As in other applications of AE monitoring, collapse or material instability is usually preceded or accompanied by large increases in AE activity. One interesting analytic technique consists of monitoring daily AE activity at various locations in mines. Cumulative plots of AE activity are compiled as a function of time at various locations. Areas with persistent and increasing levels of AE activity are candidates for potential failures.

Most AE tests in mines require long-term monitoring. In many cases, sensors have been located inside the mine shafts and signal wires are routed up the shaft to the AE monitoring system. Another method used by researchers at Pennsylvania State University involves surface monitoring (22). In one case, geophones were placed in bore holes at various depths over and in advance of a long wall coal mine. The tests were band-pass filtered between 0 and 1000 Hz using a system gain of 70-90 dB. High-amplitude AE events were subjected to source-location analysis. Viable results were obtained.

Earthen dams are also a good prospect for AE monitoring to detect soil movement or water seepage. Waveguides may be mounted either vertically or horizontally in areas where soil shear is likely to occur (Figure 22). Also, AE sensors and possibly waveguides could be placed at the toe of a dam to monitor water seepage. AE activity in this area of an earthen dam is often a precursor to subsequent failure.

Much AE testing has been conducted on subterranean storage areas. Those areas are usually old caverns or mines converted to storage of materials such as oil, natural gas, and nuclear waste. Monitoring techniques are similar to those employed for mines. AE methodology has been used to monitor the structural integrity of caverns and mines. In the case of pressurized natural-gas storage, AE leak detection methodology is possible. Hardy has investigated AE activity of salt dissolution by water that is applicable to some salt-mine storage problems (23).

Some research indicates that AE may be used to determine prestress in soils and rock (24). In general, the technique consists of coring a

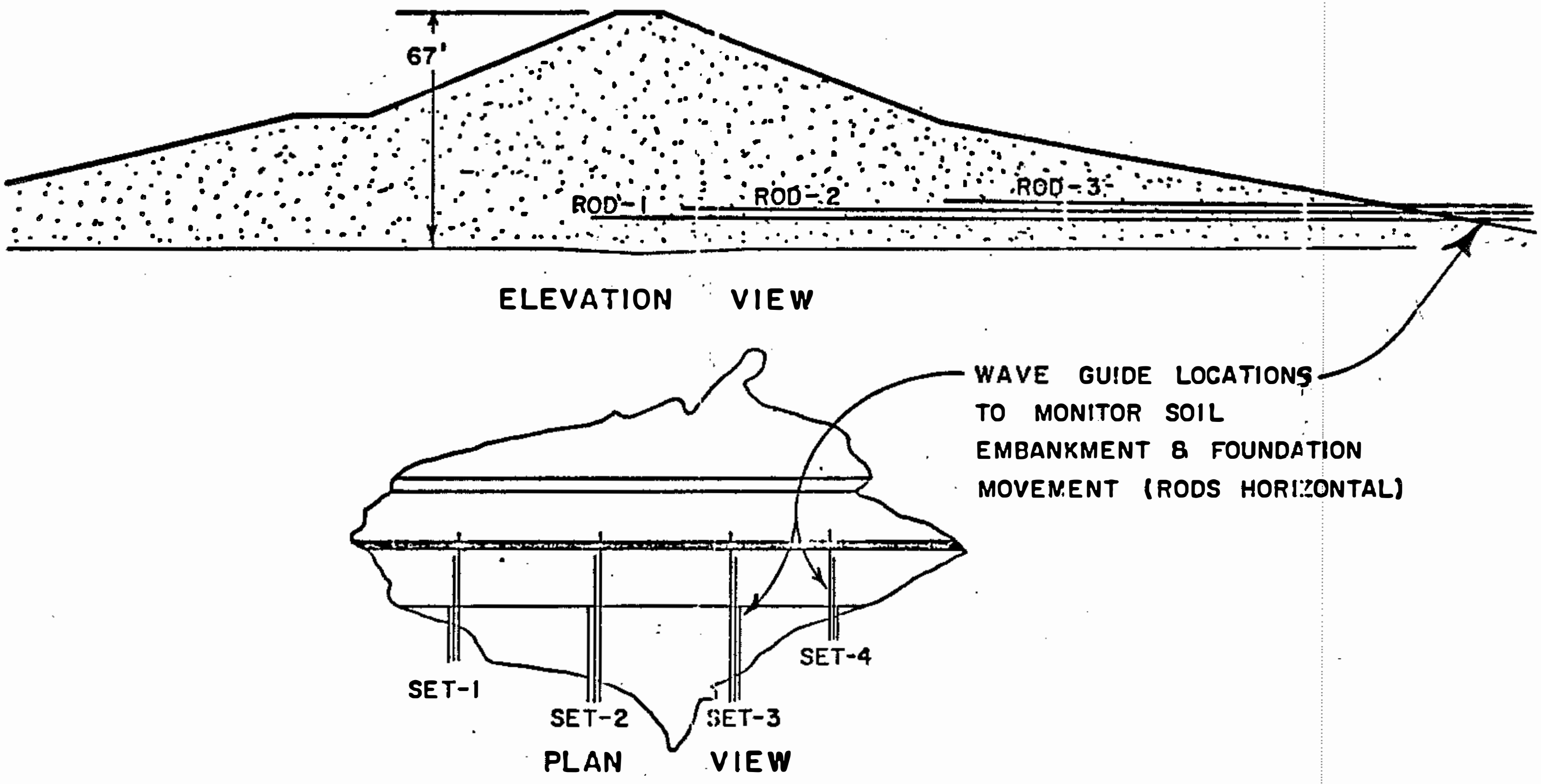


Figure 22. Elevation View and Plan View of NEB - 200 Earth Dam Showing Waveguide Locations.

hole in the soil or rock mass and placing a pressurizing device and an AE sensor into the hole. The AE sensor must be in contact with the material as the pressurizing device is actuated. The soil or rock will apparently produce AE activity after its previous high stress is exceeded (the Kaiser effect). This technique promises to provide rapid on-site determinations of prestress. However, further tests should be conducted before its adoption as the method is still in the developmental stage.

AE MONITORING OF STRUCTURES

AE monitoring appears to be most useful for the nondestructive inspection of structures made from steel (plates or rolled shapes) or prestressed concrete. Structures made of other materials such as conventional reinforced concrete, masonry, wood, or aluminum also may be inspected by AE testing. However, there has been little AE work performed on such structures.

Prestressed and post-tensioned concrete structures have proven especially difficult to inspect by conventional NDT methods (25). The primary area of concern on those structures are steel-wire strands used as the tension ligaments. The strands are made from high-strength steel wires that are susceptible to corrosion cracking in some environments. Cracking of the strand wires may be associated with live loading (fatigue or corrosion fatigue) or in a static environment due to stress corrosion. The utility of AE testing on prestressed concrete structures has yet to be demonstrated. Some review of AE experiments related to corrosion of reinforced concrete is contained in the final portion of this paper.

A major potential civil-engineering application of AE monitoring is to inspect large steel structures such as bridges, dams, penstocks, towers, buildings, cranes, and oil platforms. Those structures are usually subjected to some cyclic loads that may promote fatigue cracking. The potential for fracture and the severity of such events have increased over the past forty years due to widespread use of welding as a fabrication method.

Welded structures are often monolithic. When fractures occur in welded structural members, the potential exists for their complete fracture. If the structure is nonredundant, it may catastrophically collapse. Even if the structure is redundant, it may be severely disabled by loss of a structural element.

Structural failure of steel members usually occurs at connections such as welded splices and bolted or riveted joints (Figure 23). Welds are often locations of stress concentrations and of defects. They are initiation sites for fatigue cracks in the presence of cyclic stresses. Less frequently, fatigue cracks may nucleate from bolt- or rivet-hole areas into structural members. Occasionally, some structural steels will exhibit brittle behavior at low temperatures. Structural elements made from such steel may fail at very low stresses.

The potential structure service problems offer good opportunities for AE monitoring. Any AE testing plans should be formulated by a multidisciplinary team consisting of structural engineers, metallurgists, and nondestructive testing engineers to obtain the best results. AE testing may involve the application of service loads (dead loads and live loads) or proof loads. The magnitudes of those loads

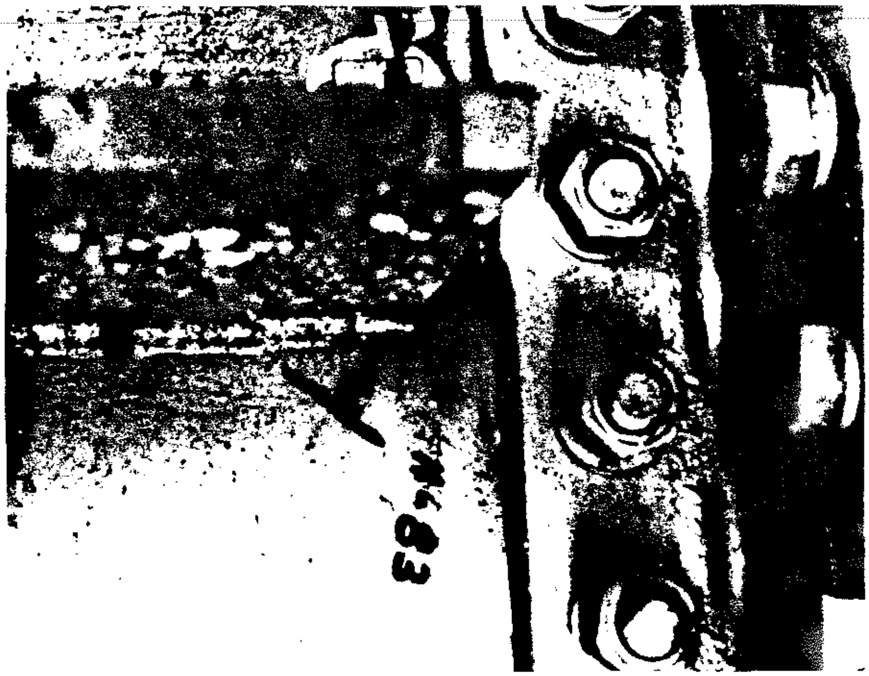


Figure 23. AE Transducer (Partially Visible above Stiffener). Note the Crack at the End of the Welded Stiffener.

should be anticipated and, at least in initial AE tests, those loads should be measured.

AE ACTIVITY IN STRUCTURAL STEEL MEMBERS

According to Wadley and others (26), three possible AE sources have been proposed for steel. Those are Luders-band propagation, carbide fracture, and decohesion/fracture of inclusions. Those are believed to be responsible for the copious AE activity that usually accompanies the stressing of steel. Much of that activity occurs over short time intervals (bursts). AE activity is produced by both gross deformation and by fracture processes of a wide variety of ductile and brittle structural materials (27-31) (Table 1).

When cracks propagate across a steel member, a plastic zone is generated at the tip of the crack. It is probable that the major source of AE activity is the plastic work done in generating the crack. For metals, the plastic work in propagating a crack is usually 50 to 1,000 times greater than the work expended to create a new crack surface area. In two-dimensional perspective, the plastic zone may be assumed to be circular. The radius of the plastic zone at yield, r_y, has been related to fracture toughness by

$$r_{y(max)} = (1/A)(K_c/\sigma_{ys})^2, \qquad (4)$$

where A = 2a for plane stress and 6a for plain strain,

a = crack length for a penny-shaped crack,

K_c = critical stress intensity of a crack, and

σ_{ys} = yield stress.

As the applied stress intensity increases, i.e. $K \rightarrow K_c$, the size of the

TABLE 1. FACTORS THAT INFLUENCE ACOUSTIC EMISSION DETECTABILITY

FACTORS RESULTING IN HIGHER AMPLITUDE SIGNALS	FACTORS RESULTING IN LOWER AMPLITUDE SIGNALS
High strength	Low strength
High strain rate	Low strain rate
Anisotropy	Isotropy
Nonhomogeneity	Homogeneity
Thick section	Thin section
Twinning materials	Nontwinning materials
Cleavage fracture	Shear deformation
Low temperatures	High temperatures
Flawed material	Unflawed material
Martinisitic phase transformations	Diffusion controlled
Crack propagation	Plastic deformation
Cast structure	Wrought structure
Large grain size	Small grain size

plastic zone increases. One relation derived by Harris, Dunegan, and Tetelman (32) related the amount of AE activity, N, on a count basis with stress intensity, K, by the relation

$$N = (Da/16\sigma_{ys}^{4})/K^{4}, \qquad (5)$$

where a = crack length for a penny-shaped crack,

D = proportionality constant between plastic volume and AE counts, and

K = stress intensity of a crack

The growth of the plastic zone, and subsequent AE activity of a crack, is in some ways reflective of the AE response of tensile specimens. This is because some of the same AE source events may be active during the crack-growth process. However, the magnitude of AE activity and the general stress level in the reminder of a flawed structure may differ markedly.

The AE wave packet released from slowly growing crack propagates through the material as an expanding sphere (Figure 24). When the wave contacts a bounded surface, the wave mode changes from a body wave to a Raleigh wave or a plate wave. Those waves expand on the bounded surface as concentric circles radiating from the epicenter of AE source event. While body waves may propagate through the material at higher velocity than surface waves, they are more readily attenuated than surface waves. The velocity of plate waves in steel is approximately that of shear waves (1.3×10^{5} inches/second).

Acoustic emissions are transient elastic waves generated by the rapid release of strain energy in a material. The energy may be furnished from a number of possible sources in metals, including dislocation motion and crack propagation. Only a small portion of the

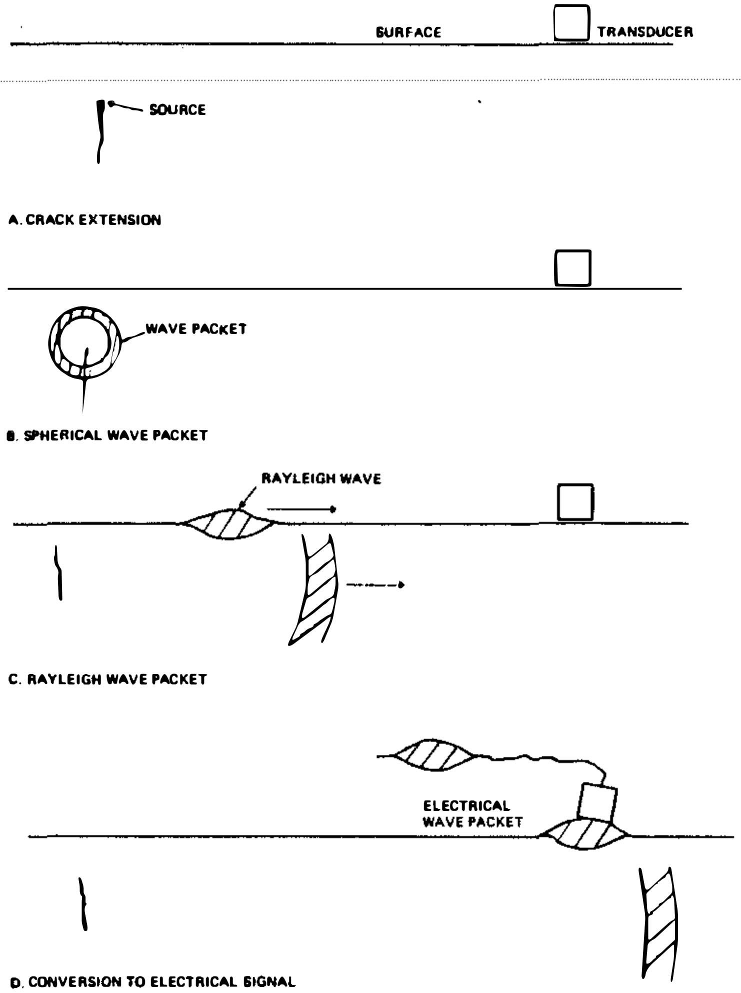


Figure 24. Simple Illustration of an AE Event.

actual energy released (≈ 5 percent) is available for acoustic emissions.

While measurement of this AE energy might provide insights about the initial process, the AE signal is affected by rate of energy release at the source, by the properties of the material adjacent to the source, by the distance of the source from the transducer, and by the shape of the structural member. The resulting wave also must undergo other changes when being converted from a mechanical wave to an electrical signal at the transducer.

One approach is to consider the dynamic effect of the AE event in terms of rise time of waves detected at the surface of a body, produced by the rapid release of strain energy inside the material. However, much theoretical work needs to be done to relate rapid transient events, e.g., force step functions, to specific sources.

Considering the source of acoustic emissions as a point, the newly generated waves propagate through a infinite body as a series of expanding spherical surface waves. There are several factors -- scattering, true absorption, true attenuation, and retransmission through a different material -- that weaken the sound pressure from an AE source as it propagates through the material to the AE sensor.

Scattering occurs because transmission through a body is affected by inhomogeneities. These include (in steel) cementite, inclusions, pores, and grain boundaries. True absorption is loss of sonic pressure due to the conversion of mechanical energy (wave oscillations) to heat. This process is called damping. True attenuation is caused by spreading of the spherical wave as it travels away from the AE source. Higher frequencies are subject to greater amplitude attentuation than lower frequencies. When a sound wave hits a boundary, if the surface is smooth, the wave will be reflected. If the surface is rough, the wave is partially reflected and partially scattered. Transmission of AE waves through a couplant from the source material to the AE sensor also offers distortion of the AE source event. If a solid couplant, such as a paste or glue, is employed, both shear and transverse waves may be detected. If fluid couplants are used, the transmission of shear waves will be dampened.

The distance of the transducer from the epicenter of the event affects the type of wave measured. In a semi-infinite source, waves arriving at the AE sensors usually bear good resemblance to the source event. When the distance between the AE source and the transducer is large, the plate-wave form dominates and it becomes difficult to use dynamic modeling to predict AE sources using plate waves. However, in a bounded material such as a structural steel plate, AE waves reaching the sensors may have undergone multiple reflections, interferences, and mode conversions so that the plate waves bear less resemblance to the wave form generated by the source than possibly to the effects of specimen geometry.

There have been a number of attempts to relate AE source properties to AE wave forms in bounded specimens. However, there is some doubt about the practical application of those methods. All of the aforementioned problems reflect the difficulties in relating available information from small finite tensile type or compact fracture specimens to the semi-infinite situations encountered in the field.

AE transducers detect surface displacement waves and convert the mechanical vibrations of the structure to electrical signals, which are then processed to provide information about the AE source. The ideal transducer would measure both horizontal and vertical displacement (or velocity) and convert these linearly into electrical signals over a bandwidth up to 100 MHz. AE signals can be expected to be generated in steel in frequencies up to and exceeding 10 MHz. Unfortunately, most existing wide-band transducers do not have the sensitivity to measure small amplitude displacements below 10^{-10}m. Some capacitive transducers exist that are displacement sensitive over a frequency range from 0 to 50 MHz. However, these are less sensitive to surface displacements than the narrow-band piezoelectric transducers widely used in AE tests.

Piezoelectric transducers are able to measure displacements down to 10^{-14} meter. However, the respond is over a narrow band about the resonant frequency, which usually gives a response range of 50 to 1,000 kHz. This type of transducer cannot cover the full spectrum of monitorable AE waves, but is good for detecting and locating the position of weak emission sources. Piezoelectric transducers have been employed in amplitude and energy distribution analyses. However, the transducers may sample only emissions from a small spectrum of frequencies.

The most common means of processing AE signals are 1) ringdown counting, 2) energy analysis, 3) amplitude analysis, and 4) frequency analysis.

Counting is a technique whereby the number of times a signal amplitude (the cumulative ringdown count), or its time derivative (the ringdown-count rate), exceeds a threshold during an experiment is recorded. This method has been the most common means of displaying AE results. A less common type of counting is the recording of the number of acoustic emission events by eliminating successive ringdown waves with a time delay before following threshold-exceeding signals can be counted. This method provides the least information about an AE event. But, it is the easiest method to record, especially when limited data storage capacity is available. Standard ringdown count data are strongly influenced by test variables including the test specimen, detection threshold, and equipment variables. It is also difficult to relate these data to an AE source function, especially when measuring only total counts.

Acoustic emission energy is assumed to be proportional to the integral of the square of the transducer voltage. The commonly measured root mean square (RMS) voltage is closely related to energy rate or acoustic emission ´power´. Energy analysis is usually measured after amplification of 80-100 dB and a band width of about 1 MHz. It is difficult to relate measured energy to acoustic wave energy for several reasons. One is the uncertainty of the mode of transducer operation and the partial coverage of the source bandwidth by the detection system. The advantage of RMS voltage counting is that it gives continuous measurement of a parameter that may be standardized and used for comparative experiments.

In amplitude analysis, amplitudes of voltage signals from a piezoelectric transducer are plotted as a distribution and compared. Signals exceeding a specified level may be expressed as a power law cumulative distribution function (33):

$$\Phi(v) = (v/v_t)^{-b} \qquad (6)$$

where v = amplitude of the transducer voltage,

v_t = lowest detectable amplitude, and

b = distribution characteristic.

With this representation, b is independent of system gain; hence, attenuation in the structure, when the AE source is remotely located, has no effect.

Frequency analysis has the potential to yield information on the source rise time and fracture type. However, signal processing is extremely complex. This usually is accomplished by passing the amplified wave through a transient recorder to digitize the wave and process the wave using fourier transform routines in a small digital computer. This limits the upper bounds of frequencies analyzed to 50 MHz. Most experimental frequency analyses have been done with an upper limit of about 5 MHz. Characteristics of the AE signal are then analyzed in terms of power spectra, frequency bandwidth, and phase data. Graham and Alers (34) have done frequency analyses on emissions produced during the deformation and fracture of a pressure-vessel steel.

Not only is AE testing capable of detecting flaws in structures, but also it is able to locate or isolate them. When attempting to monitor acoustic emissions from a known source, several techniques apply. One technique employs one channel of a multichannel system to only monitor emissions from the flaw. The active channel AE transducer is located adjacent to the flaw. Several other channels of the system would be to serve as "guards." AE transducers for those channels would be placed on the structure more distant from the flaw. Flaw-generated acoustic emissions would be expected to strike the "active" transducer first. If one of the "guard" transducers were activated first, that would indicate that the AE events detected by the active transducer in the time interval required for a sound wave to travel from the "guard" to the "active" transducer would probably be extraneous noise. This is often prevented by the AE system circuitry designed to ignore any AE signals from the active transducer for that time period. A second method is related to planar flaw location and will be discussed shortly.

Another type of AE monitoring occurs when an AE source is at some unknown location between two AE transducers a fixed distance apart. This is termed linear flaw location. When one transducer is struck by an AE burst, a clock in the AE system is started. When the second AE transducer is struck by that burst, the clock is stopped. The difference in the time-of-arrivals of the AE wave at the two transducers may be used to locate the defect between the two transducers. If the two AE transducers lie in a plane (steel plate surface), the loci along which all possible sources lie, which have the same time of arrival difference, would be a pair of hyperbolas symmetrical to the bisector of the line drawn between the two transducers (Figure 25). The hyperbola containing the AE source would be the one closest to the transducer that first received the AE event. To eliminate AE sources that are not on the line between the two active transducers, two or more guard transducers may be employed. If the guard is struck first by waves from AE sources transverse to the active array, subsequent signals from the active transducers are not processed by the AE system.

If the boundaries of the active AE region are narrow, such as in a weld or a row of fasteners, and the two transducers lie close to that boundary, the source may be accurately located with only the two transducers. If emission sources lie in an extended area, then it is necessary to have at least one additional transducer to determine a second hyperbola (Figure 26). The line between the second array is

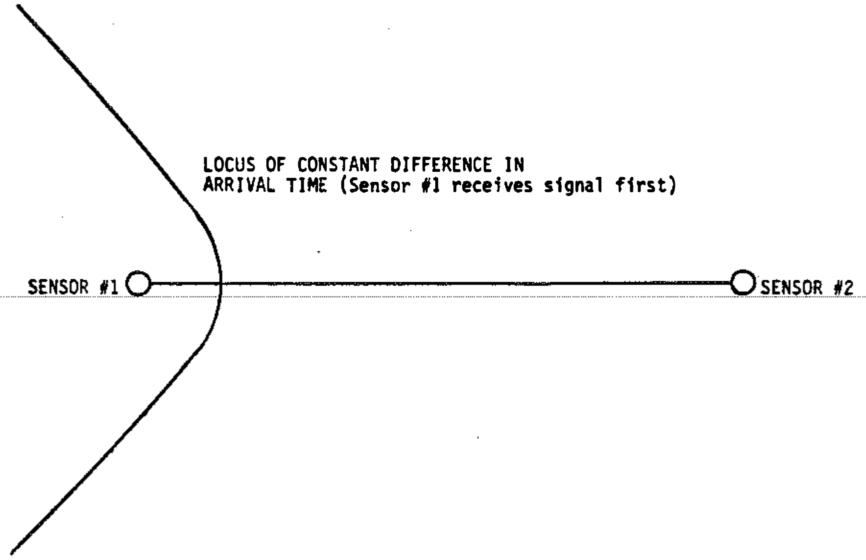


Figure 25. Linear Source Location Using Two Transducers (Sensors).

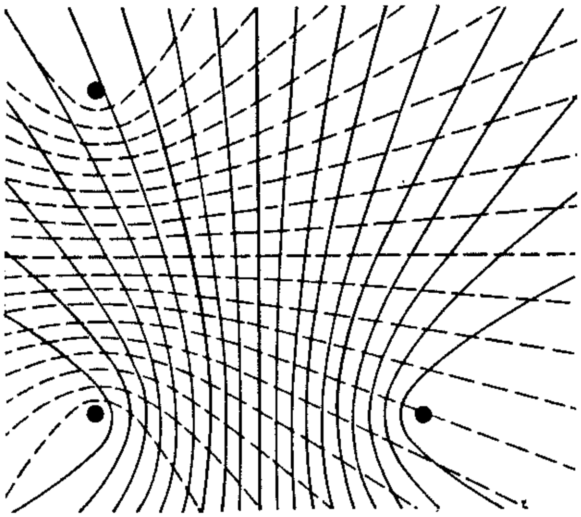


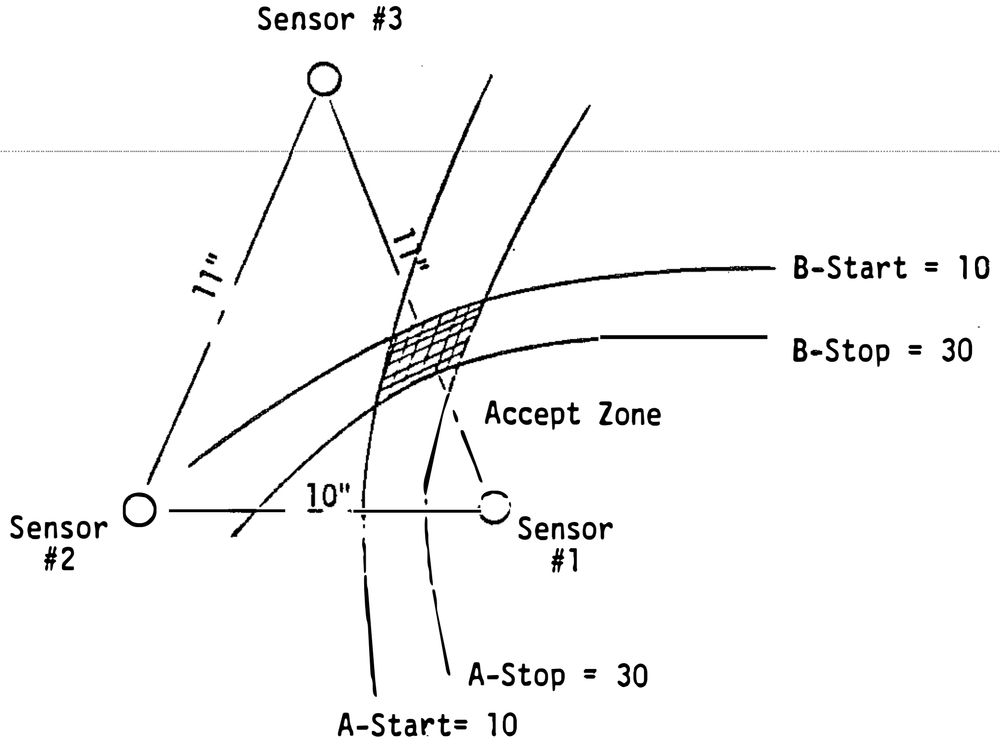
Figure 26. Three-Transducer Arrangement Showing Solutions for Planar Flaw Location (Intersections of Hyperbolae).

usually normal to that of the first array. The source will then lie at the intersection of the two appropriate hyperbolas.

A second planar method termed planar source isolation was employed in the Digital Memory Acoustic Emission Monitor (DAEM) developed by Battelle Northwest, of Richland, Washington, for the Federal Highway Administration. In that system, planar source isolation was achieved using two transducer pairs. The transducer pairs shown in Figure 27 were No´s. 1 and 2 and No´s. 1 and 3. Data-accept windows were preset in the device to allow only AE events with predetermined times of arrival to be accepted. The overlap of the two hyperbola-accept intervals creates an acceptance zone of fixed size and location relative to the transducer arrays. Only AE events emitted from that zone are expected to be accepted by the AE system.

The performance of successful field AE monitoring tests of structures depends upon being able to activate deleterious AE sources, detect and define AE events, and locate AE sources. Flaw location and/or noise rejection capabilities are basic requirements for field AE tests. There are two principal types of AE field tests -- proof testing and service monitoring. Both methods have certain operational advantages and disadvantages.

Proof testing requires a structure or structural element to be deliberately stressed to a level above the maximum anticipated service stress, but usually below the yield stress of the structure (or element). The proof test has several advantages over service monitoring. The application of a high stress increases the chances of AE source activation. Weak sources of emission may be more readily detectable when proof stressed. Critical flaws not subject to



Sensor Pair 1 and 2 are Set A

Sensor Pair 1 and 3 are Set B

Physical Requirements:

- Flaw Nearer Sensor 1 than 2
- Flaw Nearer Sensor 1 than 3
- Flaw inside AE Triangle

Figure 27. AE Source Isolation Array.

subcritical crack growth also may be detected. AE monitoring with this method may be performed in real time, eliminating some cause-effect questions. The tests may be completed in a shorter time than required for service monitoring.

Proof testing also has some disadvantages, compared to service monitoring. Proof tests require multiple personnel. Special techniques and equipment must be developed to proof test large structures. To test complex structures, multiple-channel/multiple AE-detection devices must be employed. Proof testing will activate more AE sources, making data analysis more difficult. Those tests must be performed at relatively warm ambient temperatures to ensure maximum material toughness. Also, some structures may not be adaptable to the proof-testing techniques due to design limitations.

Service monitoring has several advantages over proof testing. The test may be performed with relatively simple AE monitoring devices. The tests may be set up and left, requiring less field personnel. Tests may be conducted over a period of time, giving some idea of the activity of subcritical crack mechanisms. Few coincidental AE source mechanisms will be activated, simplifying data analysis. Due to their design, some structures are stressed to significant levels in service. Those structures may not require proof testing. Older structures will be more prone to subcritical crack growth than to catastrophic failure by large or severe flaws. Service monitoring may be performed over a wide range of temperatures. Service monitoring also may be safely performed on all members of a structure.

Service monitoring has several limitations. There may be times in the growth of a subcritical flaw when no AE sources are active; or if they are active, the sources are very weak. Also, the structural loads are generally not measured in relation to AE activity. Service monitoring tests may need to be run over long periods of time. That ties up equipment and makes it difficult to relate AE activity to events on the structure. Also, due to the duration of these tests, equipment may need to be left unattended, exposing it to vandalism. If the equipment is to be fully portable, data-handling capabilities will be limited, especially if battery power is required.

Proof testing may be a more desirable method for testing newer structures and those of limited size that may be monitored with a reasonable number of AE sensors. Service monitoring may be appropriate on older structures and on larger, more-complex structures. In either case, the number of structural members to be monitored may be limited by several practical considerations. Members to be monitored should be critical to the integrity of the structure. The members also should have tensile loading components. The most critical areas of a structural member are points of geometric discontinuity or of fabrication (welding).

The plausible sources of detectable AE activity on steel structures include crack initiation, crack growth, crack closure, plastic deformation, elastic deformation, paint decohesion and oxide fracture, rubbing noises, hydraulic noises, and electrical noises.

It is highly unlikely that any AE monitoring would detect the initiation of fatigue cracks. Stage I fatigue crack growth in steel involves surface shear that may be two weak of an energy process to be detected by a field-type AE system. However, it is highly likely that Stage II fatigue cracks could be detected by AE monitoring.

Fortunately, most fatigue cracks of concern are those that grow from large pre-existent flaws that arise from material, fabrication, and erection problems.

Crack closure is a valid AE location mechanism. Stress reversal or complete tensile stress relief are not required. Cracks usually corrode. The corrosion product expands, filling the crack opening. Forces acting on the crack displace and impact the corroded crack faces, creating detectable noise.

Plastic deformation processes detected in the field may be considered to be anelastic events. Unless high stresses are imposed during the AE tests, it will be difficult to explain these emissions. AE events also may be expected from elastic strains. However, as with most plastic-strain emissions, these may occur randomly along the stressed structural member. But, if many emissions of high energy content are addressable to one location, in the absence of a detectable geometric defect, care should be taken to ascertain if the circumstances are likely for a catastrophic crack pop-in.

Paint decohesion and surface-oxide fractures are possible sources of acoustic activity especially when high stresses are imposed on structural members. These activities are also likely when AE monitoring is conducted at temperature extremes. Most of this activity may be anticipated on older structures with built-up paint, cracked or spalled paint, and general corrosion.

Rubbing or fretting noises present the greatest problems in performing AE monitoring. This is a drawback because one of the areas of highest concern is the joints of structural members. Joints are usually the noisiest areas on a member. It is extremely difficult to use either wide-band spectrum analysis or flaw-location methods at joints. Lowpass filtering and transducer characteristics may eliminate low-frequency (audible) noise. Higher frequency noise must be eliminated by signal-processing techniques.

Air flow is not a problem, as the acoustic spectrum falls off rapidly with increasing frequency. Hydraulic noise may be a problem if it cannot be isolated from the test area. Tests of off-shore platforms have shown that wave noise is not a serious impediment to AE monitoring.

Electrical noise problems may severely affect the performance of an AE detection system. Electric noise may be dealt with several ways. Differential (anticoincident) transducers can eliminate some electric noise. Electrical isolation of the transducer and signal cable from the structure is also necessary. High-pass filtration, eliminating signals with frequencies greater than 1 MHz in the main AE system is effective. Electrical noise tends to exist in the form of voltage spikes of short duration. Introducing an instrumentation acceptance window requiring "valid" AE signals to have a predetermined duration will eliminate consideration of voltage spikes (hi-pass filtering). In the field, most AE detection systems require 110-volt power. A transient voltage suppressor should be placed on-line between the power cable and the AE device to avoid problems with voltage spikes.

Properly shielded connectors and signal cables also will help preclude electrical noise problems. The placement of transducers and signal cables away from the traffic also may ease the situation. Use of flaw-location and noise-rejection techniques will lessen any anticipated problems from electrical noise.

AE INSTRUMENTATION

AE instruments used for structural monitoring are commonly multichannel systems capable of linear and/or planar flaw location, source isolation, or noise rejection. AE instrumentation ranges from simple battery-powered units to complex multichannel systems capable of monitoring many locations simultaneously. Some complex AE systems are mounted in vans.

Many AE structural monitoring systems are capable of detecting AE activity in the 100-500 kHz range. They usually store analog or digitized test data for record keeping or post-test processing. Some AE systems are capable of real-time defect detection and location.

Some newer AE systems are capable of pattern-recognition data processing to distinguish between defect-related AE activity and noise. Parameters analyzed include AE ringdown counts, AE amplitude, AE signal rise time, AE event rates, AE location data, AE event rates, AE frequency content, and external load or strain data. Usually, relevant parameters are front-end filtered or extracted in digital form and stored on floppy discs. This greatly reduces data storage requirements compared to storing recordings of raw AE data. Most new AE systems may be used to post-process digitized data. This allows selection of AE defect-activity patterns and scanning of the stored digitized data to see if AE defect activity meeting the pre-selected pattern(s) is present.

INSTRUMENTING A STRUCTURE

Wiring a large structure may be a difficult task. This is especially true if long-term monitoring is to be performed. Wires must be protected from wind vibration, abrasion, snagging, and excessive heat. Wires used to connect the transducer (and pre-amplifiers) to the

AE monitoring system should be shielded. For wire runs exceeding 100 feet, RG58 co-axial cable is recommended. This is especially true if power-transmission towers are in the vicinity. For shorter wire runs, RG174 cable is suitable. That cable is smaller than RG58 and may be obtained in multiple-wire cable assemblies. Those are convenient when using multiple transducer arrays to monitor specific locations. BNC or TNC connectors are commonly used for electrical field connections. Lighter-duty electrical connections such as the Micro-Dot type are usually too frail for field applications.

In most field tests, pre-amplifiers are required to transmit a sufficiently strong signal from the transducers to the AE system. Care should be taken to electrically isolate pre-amplifiers and transducers from the structure being monitored. Usually, magnets or tape are used to mount transducers on the structures. As the lead wires from the transducers to the pre-amplifiers are usually less than 10 feet long, the pre-amplifiers also must be mounted to the structure. A recent innovation has been the integral pre-amplifier/transducer that eliminate the need for unnecessary mounting work. Also, lead wires are not required and extra wire connections are eliminated.

Transducers should be firmly coupled to the structure. Most standard transducers have flat wear-plate faces. Care should be taken to ensure that the face is mounted to a relatively flat, clean surface on the structure. If the structure´s surface is not flat, the transducer wear plate may be machined or sanded to conform to the structure contour. Long-term coupling may be achieved by gluing the transducer to the structure. If the transducer mounting is exposed to the elements, the bonded area should be protected with a caulk. Shortterm coupling may be achieved with a silicon grease or thick resin. Care should be taken to prevent grit from contaminating the coupled area as it may interfere with sonic coupling. Poor coupling also may be caused by loose paint or rust on the structure.

Once transducers are mounted, it is desirable to check for sonic coupling. This may be done using an ultrasonic or spark-type pulser or by breaking pencil leads or glass capillaries (Figure 28). This will serve to 1) determine the AE system function, 2) check coupling between the transducer and the structure, and 3) calibrate or check the AE system flaw-location (or noise rejection).

PAST AE MONITORING OF STRUCTURES

The first mention of the use of AE testing of civil engineering structures was by R. A. Muenow of Law Engineering Testing Company in 1971 (35). AE testing was conducted on buildings that were water loaded. The technique was said to have successfully located weld problems, defective concrete, and soft wood. Large cranes also were monitored.

Also, in 1971, AE tests were conducted on a portable military bridge being proof-tested by the British Army (36). During the proof-test, one bridge girder was instrumented with seven transducers, including several pairs used for linear flaw location. Analysis of AE ringdown counts was conducted on-line during load periods, hold periods, and repeat tests. Post-test analysis yielded further information on AE amplitude distributions and source locations. The AE sources were attributed to locations where plastic deformation had occurred.

In 1972, Dunegan/Enderco Corp. performed AE tests on eight cables of the Dunbarton Life Bridge in San Francisco Bay, California. That work

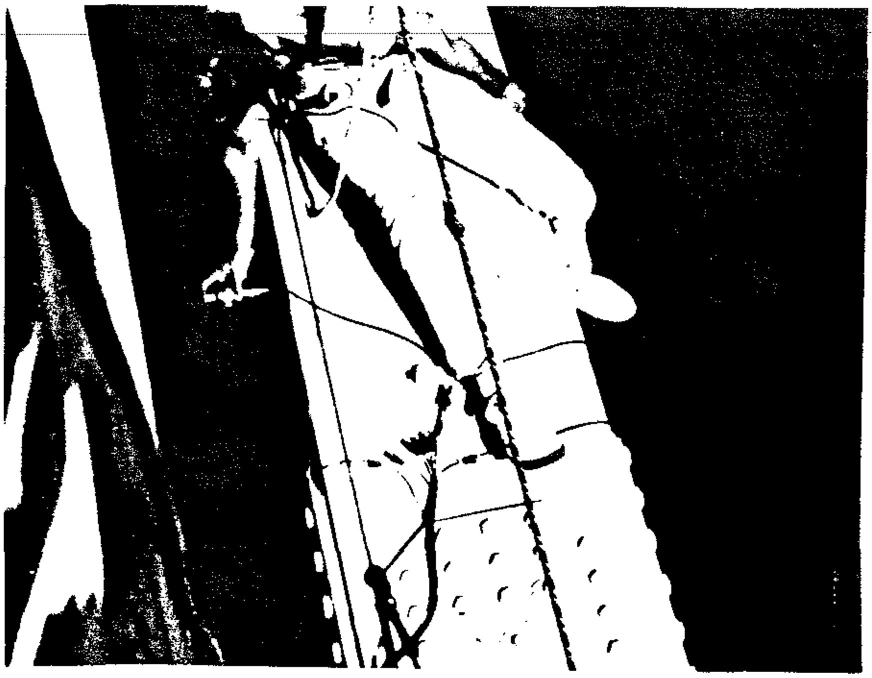


Figure 28. Calibrating a Transducer Array on a Bridge Member Using a Small Hand-Held Spark-Bar Calibration Device.

will be discussed in the next section of this paper. Also, in 1972, AE sound measurements were made by the Argonne National Laboratory on a steel bridge located on I 80 in Illinois (37).

The Kentucky Transportation Research Program performed an AE monitoring test on a continuous eyebar truss bridge in 1973 (38). A single-channel AE device was used for that study. The test was run using a 140-kHz resonant transducer with a system gain of 80 dB. The test revealed that mechanical noise was a serious problem for AE testing of bridges. Also, it was found that good sound transmission existed between the pinned eyebars.

The next notable AE testing on steel bridges was performed by Battelle Northwest for the Federal Highway Administration. That project consisted of developing and demonstrating an AE system for inspecting in-service bridges (39, 40). Initially, work was aimed at determining the acoustic spectrum of bridges and developing an AE system for centralized AE signature analysis.

The first Battelle field tests were conducted on the I-5 (tied-arch) bridge over the Toutle River in Washington state. Cracks had been detected on the floor beams of that bridge. Single transducers were attached to different floor beams that exhibited varying degrees of cracking. Pre-amplifiers with different resonant frequencies were employed in the range from 5 kHz to 1 MHz. The bridge was subject to normal vehicular traffic during the monitoring period. Amplified AE activity was stored on a video recorder. Later, the recorded tape was replayed through a spectrum analyzer.

The tests revealed that responses to traffic did not seem to be present above 250 kHz. Attempts to detect a crack signature based on frequency content, as determined from a single transducer, proved futile.

A second test was performed on girders of a prestressed concrete bridge, the Colorado Street overpass on Route 12 near Richland, Washington. There were some broken strands in a tendon where the bridge was damaged by impact with an oversized vehicle. A single transducer was attached to both good girders and the damaged girder. A data analysis method was similar to that used on the Toutle River Bridge. Both piezoelectric transducers and accelerometers were used as sensors. The traffic excitation was centered about frequencies in the 15-40 kHz range. It was felt that the concrete attenuated the higher frequencies. Spectral analyses did not distinguish the damaged girder from those that were in good condition. On this structure, traffic noise disappeared below 100 kHz.

Battelle personnel then monitored the Route-224 bridge over the Yakima River near West Richland, Washington. That work was limited to attenuation measurements. Those tests indicated that frequencies above about 500 kHz were almost completely attenuated by the joints in the structure.

Initial Battelle work indicated that the development of a central monitoring system performing AE signature analysis on AE data from transducers located about the bridge might be feasible. It was believed that such work would need to be conducted with monitoring frequencies below 50 kHz. However, that work was not pursued. Instead, Battelle concentrated on developing a small self-contained AE-flaw monitor.

The original system used a 1 MHz hi-pass filter for noise rejection. The system was battery operated and was capable of unattended AE monitoring for a period. Thereafter, the device was to be taken to a laboratory. It contained an erasable programmable read-only memory (EPROM) chip on which the AE field data was recorded. The chip would be read and subsequently erased for future reuse. The system was tested in conjunction with an AE system that recorded three channels of concurrent AE data on a magnetic tape recorder. Data for that system came from a triangular three-transducer array enclosing the single transducer of the self-contained AE unit.

The self-contained system was used on the I-80 Charquinez Bridge near Vallejo, California. Eyebars on the upper chord of the truss bridge were to be removed. Several parallel eyebars were monitored prior to removal of that eyebar. The eyebars monitored by the AE system during this operation assumed the load of the damaged eyebar that was expanded by heating. The AE-system monitoring frequency was restricted to 400 kHz and above. Single transducers were epoxy bonded to two eyebars adjacent to the eyebar pin.

AE data was very low, indicating the absence of flaws in the eyebars. Low AE data peaks that were present generally corresponded to load transfer as the eyebars were removed.

The unit was subsequently placed on a cracked floorbeam of the Toutle River Bridge. The three-transducer system was placed near an extending crack and the single transducer of the self-contained system was located inside that array some 3 inches from the crack tip. The system monitored the bridge for several extended periods of about 15 days each.

Taped data from the three-transducer system was replayed through a commercial AE flaw-location system. Results indicated that the possible

AE sources could be along the bridge deck/floorbeam interface, the riveted connection between the floorbeam and the tie girder, and the crack. The majority of the AE sources were from locations other than the crack.

Results indicated that the self-contained AE system did not have sufficient flaw discrimination capabilities. Battelle personnel felt that flaw-location/source-isolation capabilities would be required. The portable, self-contained AE system was upgraded with a three-transducer, two-linear array system. That system used adjustable time-accept limits for each linear array to define a set of hyperbolas. The AE data falling outside the set of hyperbolas were rejected. Only data that met the time of arrival of the two hyperbola sets were accepted. That created an accept zone defined by the area bounded by the overlapping hyperbola boundaries.

The revised Digital Memory Acoustic Emission Monitor was tested on the floor beams of the Toutle River Bridge and suspect areas of a girder weld on the Airport Overpass Bridge at Walla Walla, Washington. Also, the system was used to monitor edge fillet welds on box girders at the Allied Structural Steel plant at Clinton, Tennessee.

The system was used to monitor a floorbeam crack on the Toutle River Bridge for a period of 10 1/2 days in 1976. The three-transducer array was placed and the time-of-arrival accept limits were set to provide a valid zone that was located at the crack tip. The zone was defined by breaking pencil leads and defining the valid zone on the surface of the floorbeam web about the crack. The unit employed two EPROM memories. One recorded all AE event count data from the No. 3 Sensor. The other EPROM only counted AE events from the valid zone.

The EPROM data showed that the total AE counts varied between 300 to 3,000 counts (data from the No. 3 Sensor). Valid AE data ranged from 0.5 to 3 percent of the total AE. As part of a second one-day test, a crack-free zone in the web was monitored to determine the effectiveness of the source-isolation system. The noise level at that location was less than 0.5 percent. Some crack growth was believed to have occurred during the 10 1/2 day monitoring period.

A third 22-day unattended test of the Toutle River Bridge floorbeams was conducted in 1977. The 1976 test was conducted using a detection frequency of 600 kHz. The 1977 test used a detection frequency of 400 kHz.

Resulting data indicated that the frequency change increased the amounts of both the valid and total AE data. It was difficult to correlate the valid AE data to crack growth during that monitoring period. The data showed the bridge loading was irregular during the test, weekdays being more active than weekends. During the testing period, valid AE data were much less than the total AE, only reading 10 percent for six, 4-hour monitoring periods.

A weld on the Airport Overpass Bridge revealed high AE activity when tested earlier by another AE monitoring system. The DAEM was placed on the bridge with the transducer array and accept-limit sets to form an AE accept or valid zone. The weld was monitored for a 16-day period using 1-hour updates.

Subsequent data analysis indicated a period of high total AE activity. During several periods, valid AE data equalled the total AE data (from the single transducer). However, the event counts during those periods less than 50 counts per hour.

From August 1980 to July 1982, the Kentucky Transportation Research Program conducted tests on the I-471 bridge over the Ohio River at Newport, Kentucky. The DAEM system was used to monitor a tie-chord butt weld that contained ultrasonic-detected discontinuities (Figure 29). The DAEM was stored in the tie-chord box and the EPROM's were replaced on regular intervals over a 1 1/2-year period.

Those tests showed that high AE event activity count be detected during peak traffic hours over the bridge. Rainfall also produced high AE rates. However, comparative AE tests between the weld area and a similar weld containing no ultrasonic flaw indications proved inconclusive.

From March 1982 to January 1983, the West Virginia Department of Highways (WVDOH) monitored AE activity on the I-64 Dunbar Bridge over the Kanahwa River near Charleston, West Virginia. The Dunegan Corporation had mounted an AE monitor on a pier of the bridge (41). Eight weld locations that contained subsurface AE indications were instrumented. Resulting AE data were transmitted to WVDOH offices over telephone lines and placed on a digital tape. Planar source location was subsequently performed by Dunegan using a copy of the data tape supplied by WVDOH.

Of interest were the transducer arrays. Special angle-beam 500-kHz transducers developed by Dunegan were placed along the weld lines. Those transducers were 20 dB more sensitive to signals from AE activity travelling along the angle beam (weld line) than from sources approaching from the sides. Additionally, conventional guard transducers were placed offset of the midpoints of the weld lines. The guards acted to lock-out the angle-beam transducers when first struck by

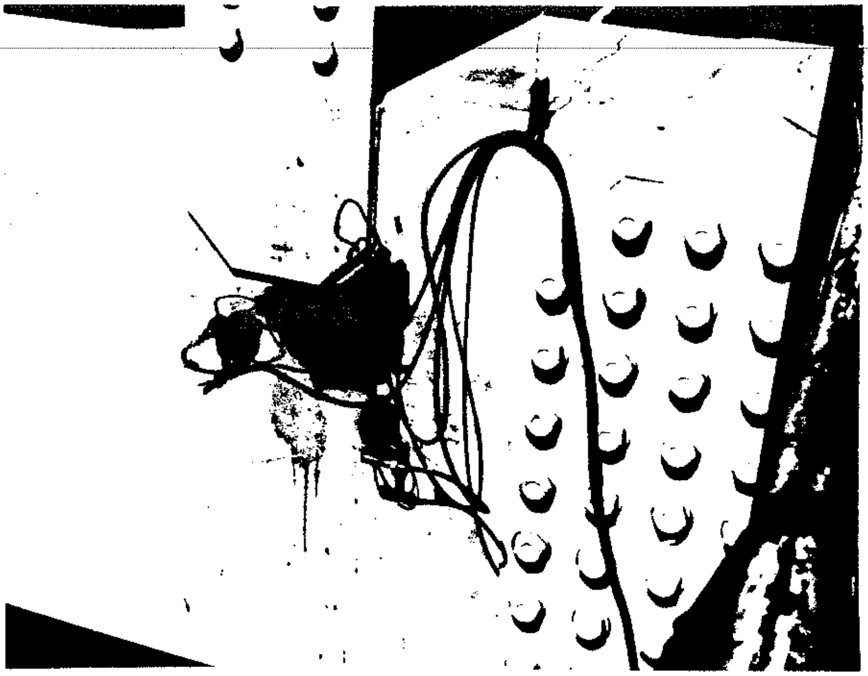


Figure 29. Three-Transducer AE-Source Isolation Array of DAEM Monitoring a Welded Joint.

AE activity. The transducers were cemented to the steel girders.

The planar flaw location system required at least three of the transducers to be struck for an AE event to be considered "valid." One array produced 12,560 such events. This was almost 1,000 times greater than the least active array (14 planar-valid events) and about 10 times more active than the second most active location (1,461 planar-valid events).

In the period 1982-1984, United Technologies Corporation developed a broad-banded piezoelectric transducer for the Federal Highway Administration (42). The transducer was of the point-contact type with a conical piezoelectric element. Laboratory tests showed the transducer had flat, continuous wave response between 100 kHz and 1 MHz. The transducer was intended for use with broad-band instrumentation and signal processing to provide signal characterization as a means of differentiating between noise and AE activity from cracks in steel bridges. The transducer offered the possibility of an advanced approach to flaw evaluation.

From 1982 to the present, the GARD Division of Chamberlain Mfg. and the Kentucky Transportation Research Program (KTRP) have used the GARD-developed Acoustic Emission Weld Monitor (AEWM) to detect crack activity on steel bridges (43, 44). The AEWM was originally designed to monitor in-process welding operations (as will be discussed in the next section).

The AEWM uses analog electronics to acquire and preprocess AE activity. This includes the use of analog signal amplification and band-pass filtering from signals produced by standard resonant transducers. Also, the conventional time of arrival (Δt) technique is employed for linear flaw location using two active transducers. The AEWM possesses a microprocessor-based multiparametric filtering program, which analyzes the AE data, rejects noise-related activity, and locates and characterizes flaws in real-time.

Consecutive AE events are subjected to a three-step sequential test or AE pattern-recognition filtering program (Figure 30). First, the analog preprocessing circuitry computes the ringdown count (RDC) and time of arrival. Then, the microprocessor portion of the system tests the collected analog information for each event. As the first step in the filtering program, the ringdown count must lie within fixed limits. If this is satisfied, the second filtering step is imposed wherein the AE event must occur within a predetermined minimum event rate with other AE events preceding or following it (which also have passed the ringdown test). The third step determines whether all events passing the first two filtering tests were located by time of arrival within a specified locational tolerance. All AE event data that fail to pass any one of the tests are discarded. Additionally, the frequency content of each AE event is analyzed using a comb filter. Valid AE events having high-frequency biases are classified as cracks. Other data that satisfy the model are characterized by the AEWM as unclassified defects.

The AEWM can continuously process large numbers of AE events occurring at rates too fast for an operator to analyze. The microprocessor circuitry also determines when valid flaw activity occurs. The operator is informed of flaw-related events by an indicating lamp on the AEWM and by a LED panel that displays the relative location of the flaw between the two active transducers. The unit also is capable of storing data on floppy discs and direct hardcopy

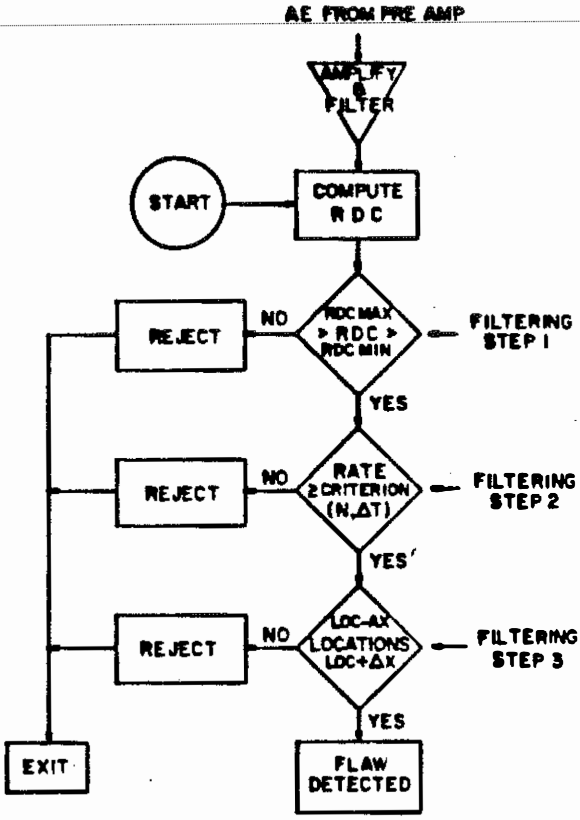


Figure 30. AEWM Processing Flow Chart for Flaw Detection.

output subsequent to a test.

Over the last four years, GARD and KTRP have conducted thirteen field tests on nine different bridges in four states. The bridges inspected included the I-24 bridge over the Ohio River at Metropolis, Illinois (Illinois Department of Transportation); the I-24 bridge over the Tennessee River in Kentucky; the I-471 bridge over the Ohio River at Newport, Kentucky; the I-75 bridge over the Ohio River at Cincinnati, Ohio; the I-64 bridge over the Ohio River at Louisville, Kentucky; the US-25 bridge over the Rockcastle River in Kentucky; the US-18 bridge over the Mississippi River at Praire Du Chien, Wisconsin; the I-94 Oklahoma Avenue overpass in Milwaukee, Wisconsin (Wisconsin Department of Transportation); and the I-310 bridge over the Mississippi River at Luling, Louisiana (Louisiana Department of Transportation and Development).

During that time, the AEWM has been used to monitor visible cracks, ultrasonic subsurface defect indications, stress-intensifying weld details, and elements containing riveted or bolted connections. During that work, the AEWM has detected AE flaw activity emitted from visible cracks on three occasions. Once, it detected AE flaw activity from a subsurface ultrasonic indication. On those occasions, the AEWM interpreted flaw activity eminating from the crack.

In every instance except for the I-310 bridge at Luling, Louisiana, the bridges were subject to normal traffic. The I-310 structure was subjected to heavy proof-type loads. Typically, the tests have used gains of 70-80 dB and linear-array spacings of 20-80 inches. Standard 175-kHz resonant transducers were employed.

Work to date indicates a correlation between fatigue crack activity, structural vehicular loading, and AE flaw activity. The most active flaw monitored was a 6-inch long crack in the floorbeam of an interstate bridge. The bridge was subjected to frequent truck loads. Monitoring of that crack produced AE flaw activity (as determined by the AEWM) about every 15 minutes. The AE flaw activity corresponded to the passage of one or more heavy vehicles over the bridge. Some bridges have been monitored for extended periods up to 128 hours without undetected AE flaw activity. In those cases, even with large surface cracks, long-term visual inspection has revealed no fatigue growth (indicating those cracks are benign).

Recent strain-gage work done in conjunction with the AEWM on a bridge with visible large cracks has helped explain some previous test results. On one bridge, even heavy truck loading did not produce high stress fields about the cracks. Therefore, even though cracks monitored were large, the vehicular loads were insufficient to cause fatigue-crack growth. Existing cracks had been created prior to erection, and at the time of AE testing, they were inactive. In some cases, fatigue cracks will be created and propagate to low-stress areas and become benign. At least two such instances were monitored using the AEWM. The ability to determine if a flaw is harmful is one advantage of the AE test method. AE monitoring of bridges that are heavily travelled by trucks may only have to be performed for short time periods (one or two days) to detect fatigue cracks.

Tests with the AEWM have been successful in rejecting large amounts of mechanical noise emissions from bridges. The noise-rejection model in the AEWM will possibly exclude some valid AE flaw data. However, past testing indicates that those exclusions are not significant.

Typically, on a bridge member with an active fatigue crack, the AEWM will detect 1,000-3,000 discrete AE events per hour. The device may consider only 3 or 4 of those to flaw related. This indicates that attempts to use long-term AE monitoring of structures to integrate AE flaw activity from background noise are futile. Similar locations on bridges produce widely varying amounts of background noise.

The amount of AE noise is dependent on the type of structural detail near the AE transducer array and the amount and characteristics of vehicular loading on the bridge. Members that are primarily in tension (Figure 31) are very quiet. A good example would be the tie chords of a tied-arch bridges. Bridge members directly abutting a concrete deck or near some types of bolted connections tend to be very noisy. Typical examples are floorbeams, stringers, and floor beam-to-girder bolted connections (Figure 32). AE noise not only depends on the volume of traffic on the bridge, but also on the vehicle weight and speed. Heavy vehicles traveling at high speeds created large background noises, but they also are best at triggering AE flaw activity.

Testing of the AEWM has indicated the occasional need to use guard transducers to prevent "false hits" on the linear array. A typical example of such situations is encountered in monitoring welded cover plates on steel-beam bridges. Cover plates are located on the lower flange of the beam. To monitor such areas, it is best to mount the transducer array on the lower flange. However, fretting noise from the interface between the concrete deck and the upper flange may create signals that can trigger false indications that appear to come from the center of the array. One solution would be to shift the array along the lower flange in relation to the cover plate and ignore any flaw

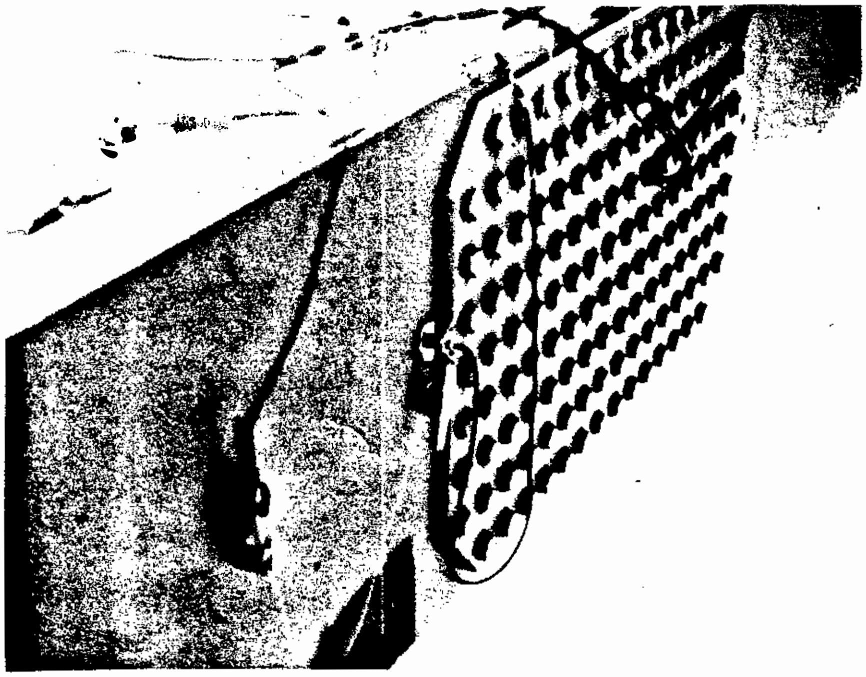


Figure 31. AEWM Transducer Array on the Tie-Chord of an Arch Bridge.

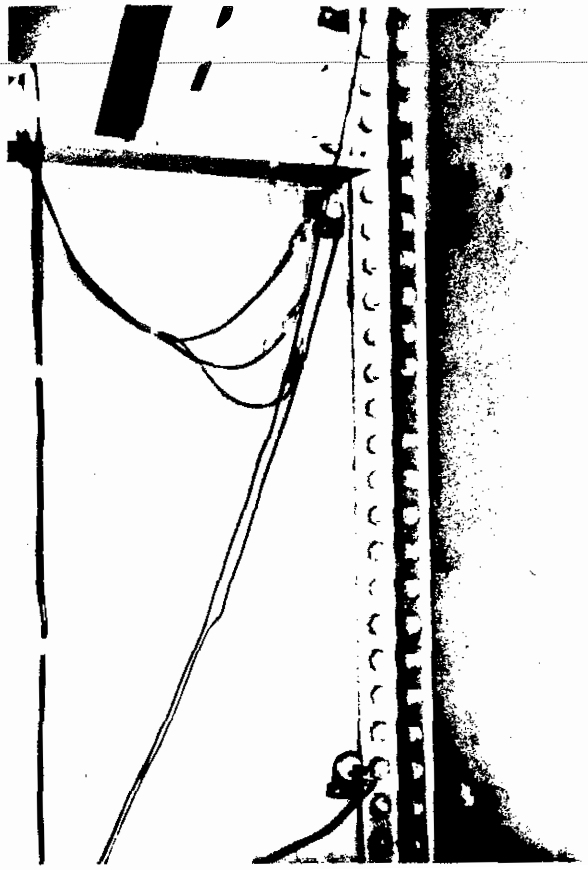


Figure 32. Linear Transducer Array Adjacent to a Bolted Angle Splice on a Bridge.

indications from the center of the array.

The second and better choice is to employ a guard system that will preclude the analysis of AE events that first strike a guard transducer (Figure 33). In this case, the guard transducer is placed on the upper flange and is located approximately halfway between the two active transducers when viewed from the ground. Care must be taken to locate the guard so it is at least twice as far from the array as the array spacing itself. Otherwise, it will prevent the reception of any AE signals from sources along the line between the two active transducers.

The Federal Highway Administration is presently contracting with GARD to produce an updated AEWM designed specifically for bridge inspection. That work will involve laboratory fatigue tests to ascertain the AE response of structural steels under typical field testing conditions.

AE testing of large structures is not restricted to bridges. Recent AE tests were performed on a semi-submersible offshore platform (45). The rig contained a 4 1/2-inch long through-wall crack in a column leg. The crack was surrounded by four resonant transducers in a rectangular array. The array spacing was varied from a position near the crack to a maximum transducer-to-crack distance of 1.5 meters.

The crack was loaded by sea waves. When the nearest array was used, the wave loading was about one-half of that at the time of maximum transducer spacing. At the closest transducer spacing, wave stressing produced 5 to 10 AE events per minute that were addressable to the crack tips. At an intermediate transducer array spacing, the wave loading increased with a resulting increase of crack-related AE events to 99 per minute. At the greatest transducer array spacing and highest wave

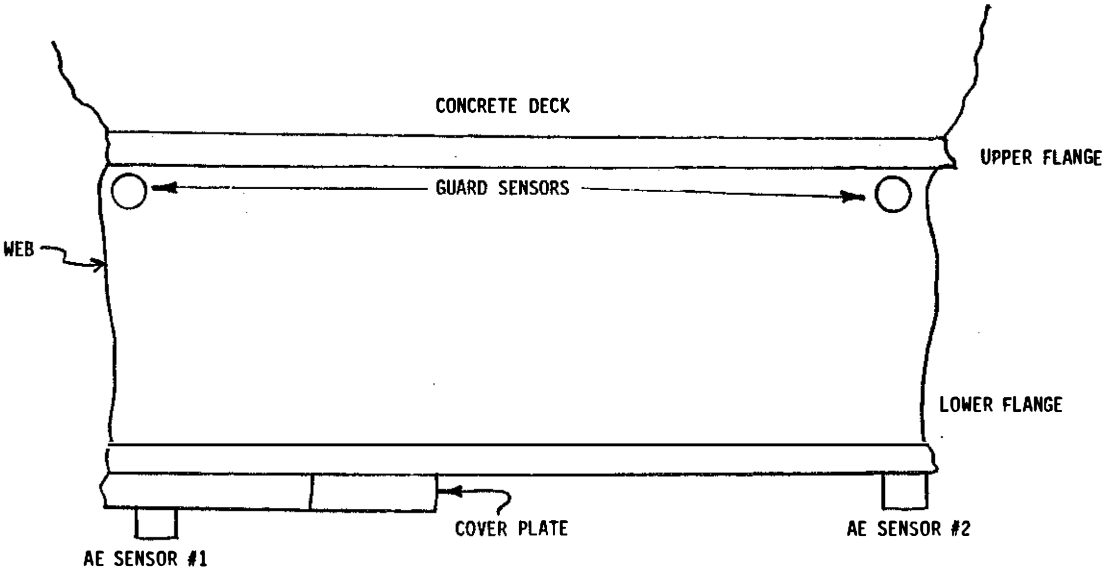


Figure 33. Use of Guard Sensors on a Steel Girder Bridge.

loading, the AE rate was still high (about 95 AE events per minute). Most events occurred during the rising load. However, some occurred at the peak load.

Those results indicate that offshore platforms may be appropriate for AE inspection while subject to in-service wave loading.

COMPONENT TESTING

Much civil engineering design of structures makes use of welding to fabricate structural components. Also, new structures are being designed to take advantage of the high tensile strength of steel wires. Unfortunately, both welded and steel-wire structural components pose unique problems.

Welding may induce flaws into a structural component that lead to eventual failure of the completed structure or at best an expensive repair of a completed weld. Structural components containing steel wire are more subject to corrosion damage than normal steel beams or girders. The increased use of prestressed concrete beams containing wire reinforcement presents many future inspection problems.

The earliest use of AE monitoring of welds was for post-weld monitoring of high-strength (D6ac) steel (46). Later AE tests of in-process slagless welding showed promise (47, 48). However, most welding of steel structures required the use of slag-type welding methods. That limited most early AE efforts to post-weld monitoring (49, 50).

One slag-type method, electroslag welding, is relatively quiet and several successful AE tests have been employed on in-process welding operations and in post-weld monitoring (51, 52). In both cases, the researchers were able to determine if the flux-pool was satisfactory. Also, during post-weld monitoring, using linear flaw location, they were able to detect typical electroslag defects, including cracking.

GARD conducted early tests of AE monitoring of slag-type welding operations (53). That work led to the development of the AEWM system described earlier. The Federal Highway Administration contracted with GARD to test the AEWM on typical submerged-arc butt-welding operations (54). Much of the laboratory tests were performed on grooved plates of typical highway bridges steels. Defects including cracks, porosity, slag inclusions, and lack of fusion were deliberately embedded in the welds as they were deposited. The AEWM successfully detected all 24 of the planar defects (cracks and lack of fusion), all six of the slag inclusions, and seven out of eight of the porosity defects. Following those tests, GARD conducted field tests at three fabrication shops (Figures 34-36). During those tests, the AEWM monitored 700 linear feet of in-process welds. Six minor flaws were detected by the AEWM. All of those were visually confirmed. No other defects were detected by the AEWM or by others who inspected the welds with radiography. In 1985, the AEWM was demonstrated to highway personnel from 21 states. Presently, the Federal Highway Administration is having extended field tests of the device performed by the Kentucky Transportation Research Program.

Early laboratory tests of wire rope showed that wire fracture was readily detectable (55). Continuous AE monitoring of cyclic tests provided warning of fatigue failure as early as half the lifetime. Proof testing/AE monitoring of cyclically loaded wire rope also provided warning of impending fatigue failure.

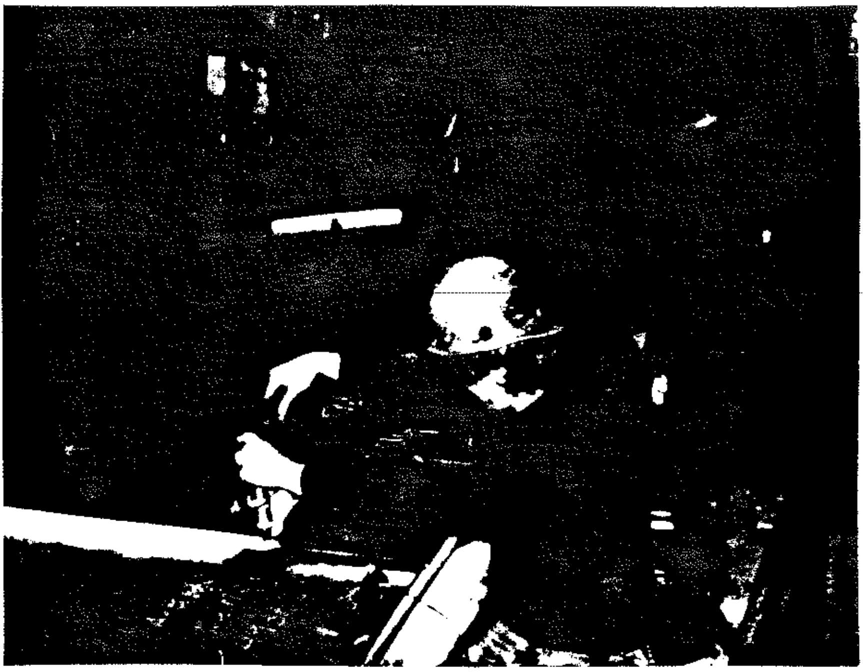


Figure 34. AE Monitoring of Semi-Automatic Submerged-Arc Butt Welds (Note Magnetic Transducer Hold-down under the Welding Operator's Elbow).

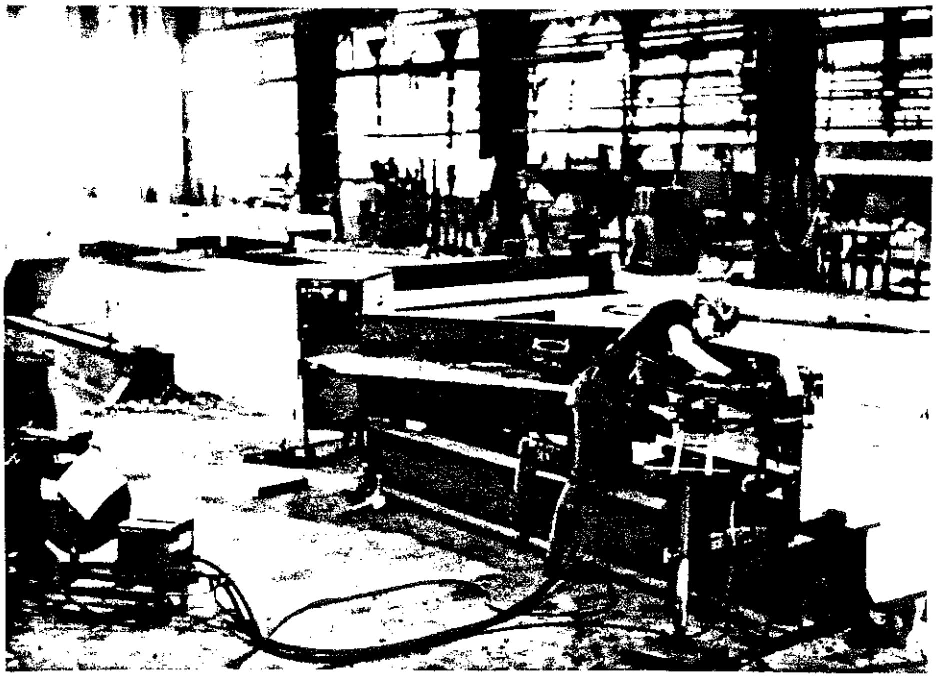


Figure 35. AE Monitoring of a Large Complex Weldment Using Automatic Submerged-Arc Welding. Transducers Are Attached to the Backside of the Flange. The AEWM Is to the Left of the Weldment.

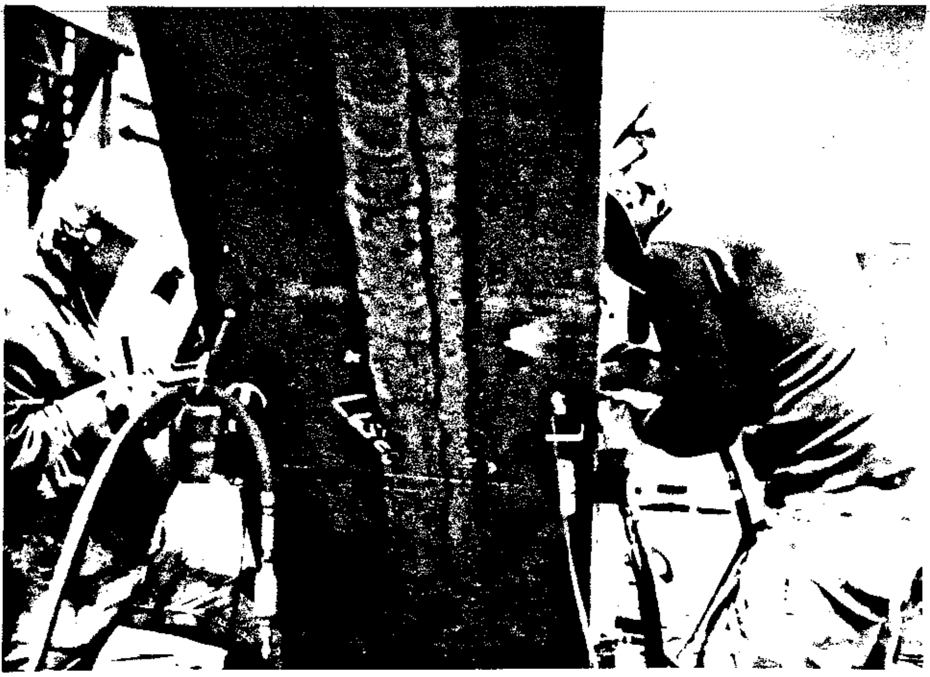


Figure 36. AE Monitoring of Concurrent Welding Operations. Note Transducers Attached to the Plate on the Backside of the Welding

In 1972, the Dunegan/Enderco Corporation conducted AE tests on cables of Dunbarton lift bridge over the San Francisco Bay California (56). The old bridge showed wear on the cables and connectors. To prevent high sound attenuation, radiator hose clamps were placed around the wire-rope strands and tightened to consolidate the strands. The 150-kHz transducers used in the tests were coupled the radiator clamps. The cables were proof-loaded by providing a transverse load with a "come-along." The load was applied and held for 10 minutes. Transducers also were placed on the wire-rope connectors for continuous AE monitoring for a 24-hour period.

Several cables showed more continuous AE activity than others. However, the AE proof-load tests showed no sign of serious deterioration. As the bridge was to be demolished in a few years, it was recommended that no additional cable repairs were necessary.

Green performed early AE tests on a model prestressed concrete reactor vessel (57). Those tests showed that AE testing could detect the onset of failure and progression of failure processes, previous loading levels, and locations of failure.

Muneow utilized AE techniques for in-service monitoring of concrete bridges, of precast reinforced roofing panels, of mixing concrete, and of grading aggregate. AE was used only as an indicator and warning for the use of more comprehensive inspection techniques (58).

Researchers at Florida Atlantic University conducted a series of laboratory experiments on corroding of steel reinforcement embedded in concrete (59-61). Some of those tests were conducted at a natural corrosion rate and others were accelerated by impressing an anodic DC current on the reinforcing steel (usually in the presence of a saline solution or sea water). Those tests revealed that AE activity from those corroding specimens is much greater than from specimens in a noncorrosive environment.

AE activity was associated with the creation of a corrosion product, an expansive ferrous oxide on the surface of the reinforcing steel. That induces internal hoop-type stresses in the concrete, which leads progressively to concrete fracture.

Cumulative distributions of peak amplitudes have been employed based on the simple power law model:

$$I(v) = (v/v_t)^{-b}, \tag{7}$$

where v = voltage of the signal and

vt = threshold voltage of the detection system

I(v) is the normalized amplitude distribution function for the signal. The b-value serves to characterize the cumulative distribution slope. Figure 37 shows the AE and b-slope behaviors for a reinforced concrete specimen corroded to produce surface cracking of the concrete. During days when the number of AE counts increased, the b values were closer to 1.0. The concrete was highly attenuative of AE signals in 100- to 300-kHz range. The maximum useful detection distance was 50 cm.

Field tests were conducted on a concrete cap and walk at Delray Beach, Florida. The site was near the sea and several locations along the walkway exhibited surface cracking of the concrete with rust stains seeping from the steel reinforcement. A commercial AE system with source isolation was used to monitor three locations. Two of those possessed cracks and the third was crack-free. The sites were monitored for several months. The reference area with no visible distress emitted

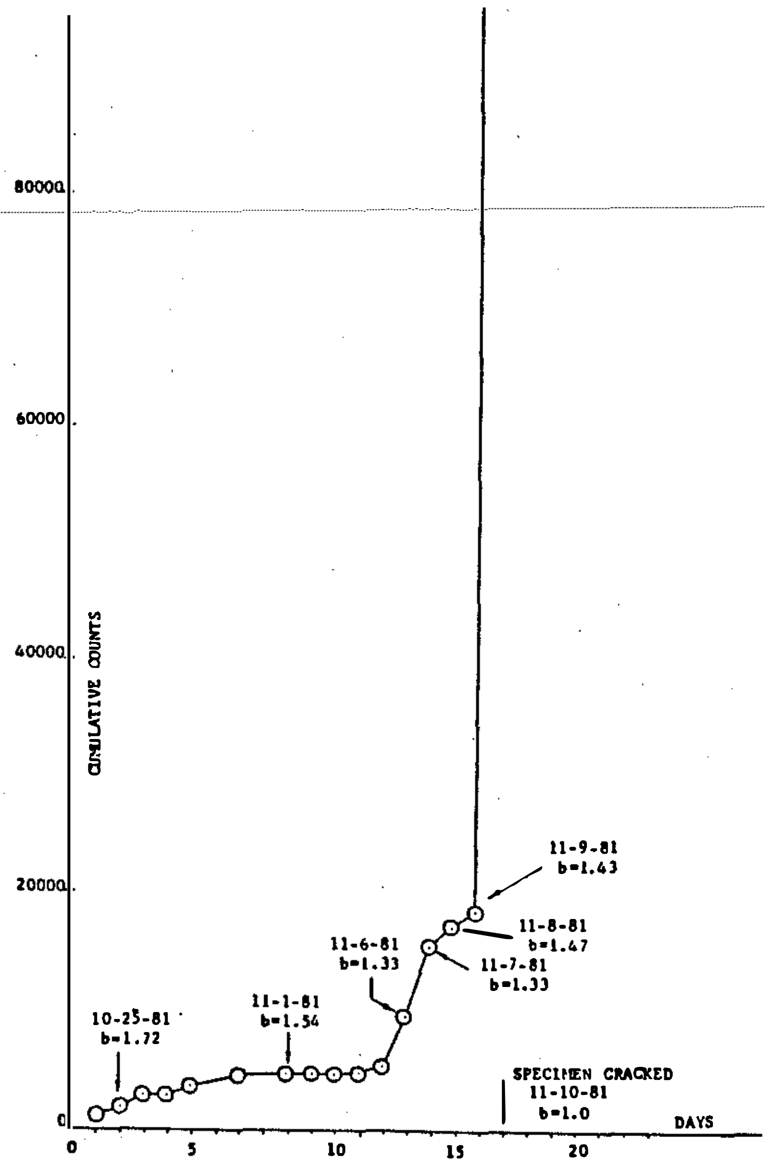


Figure 37. Specimen (Loaded) Cumulative Counts History.

only low-level emissions One of the active sites with a surface crack produced numerous AE events of moderate amplitude. The second active site, which exhibited only a small amount of surface cracking, produced many high-amplitude AE events. Some weather problems that interfered with the monitoring process were encountered. However, the tests demonstrated that the AE pattern varied with the corrosion process. The area with the larger crack probably produced lower AE activity as the crack acted as a vent for the corrosion product formed on the reinforcing steel. At the second active site, the expanding corrosion product was probably developing its cracking process.

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