United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

Technology Transfer

EPA

Capsule Report

Acoustic Monitoring To Determine the Integrity of Hazardous Waste Dams

Technology Transfer EPA 625/2-79-024

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This report was developed by the
Industrial Environmental Research Laboratory
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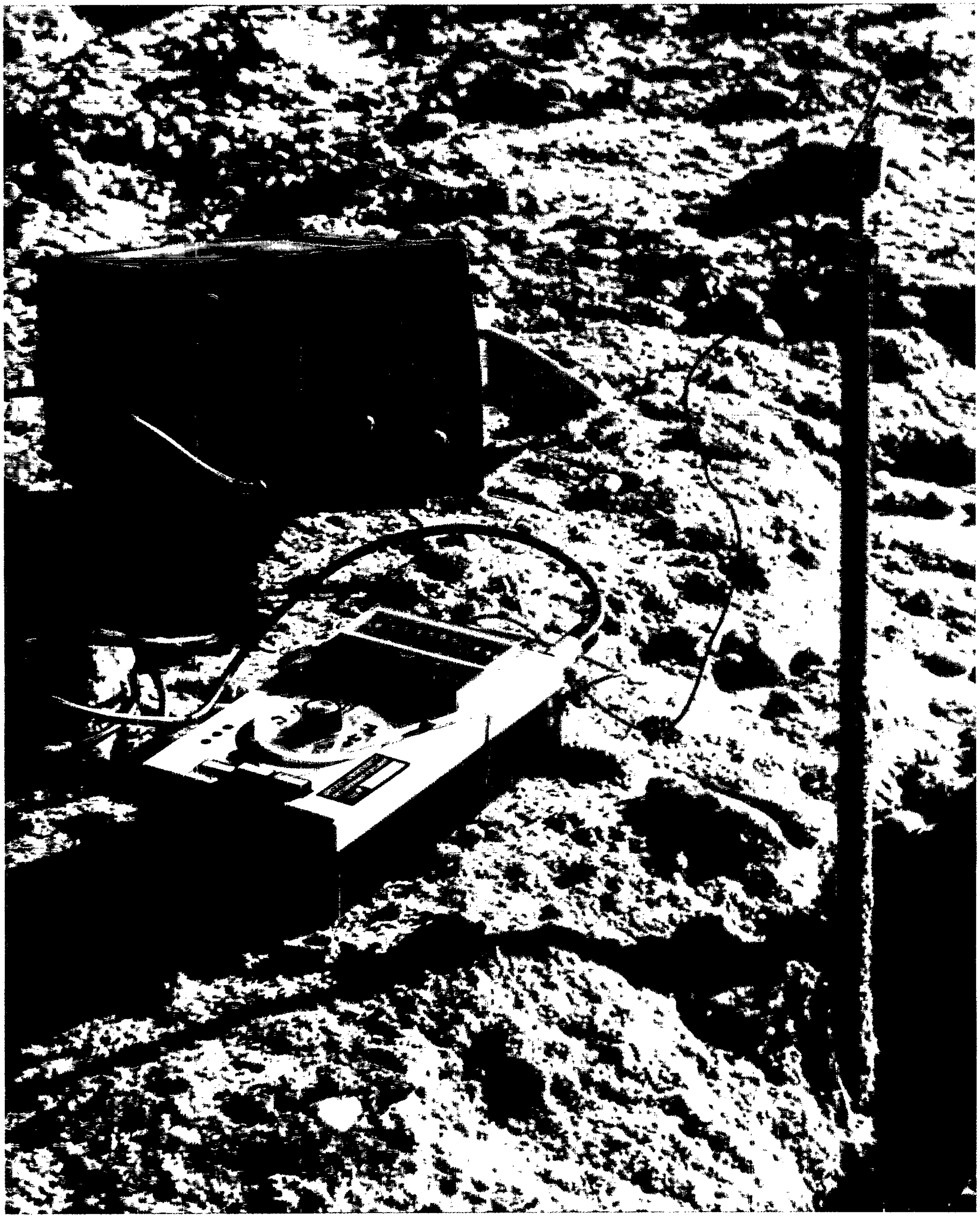


Acoustic monitoring system: waveguide, accelerometer, amplifier, and counter

1. Significance

There are as many as 500,000 diked areas in the United States containing potentially hazardous wastes. This total includes small waste ponds at minor chemical manufacturing plants as well as mile-square tailings lagoons at mines, smelters, and phosphoric acid plants.

The U.S. Environmental Protection Agency's (EPA's) Office of Research and Development has long been aware of the large number of marginally safe impoundments. A seemingly secure dam may suddenly fail with provocation as slight as a heavy rain. The full extent of leaks and spills from small, earthen-dam waste ponds is not known, because many such spills go unreported or may be known only locally. The overall damage to the environment, however, is probably great.

Those spills resulting from earth dam failure that have been reported often have had serious environmental impact, for example:

- In 1967, an alkaline waste lagoon failed, sending 400 acre-feet (493,000 m^3) of fly ash into the Clinch River in Virginia. These wastes traveled downstream to Norris Lake, Tennessee, where it has been estimated that 216,000 fish were killed.
- A few years later, another lagoon was responsible for seriously contaminating the James River with kepone when the restraining dam gave way.
- In 1976, in Oswego, New York, the failure of a lagoon 100 feet × 130 feet × 15 feet (30 meters × 40 meters × 5 meters) holding chemical manufacturing wastes resulted in the material ending up in Lake Ontario.

Many similar spills have been reported in recent years. Releases of contaminants such as the foregoing pollute waterways, kill aquatic species, adversely impact drinking water systems, and despoil scenic areas. Even small spills from dikes that hold hazardous wastes can have long-lasting environmental impact.

It is also necessary to consider the danger to human life posed by marginally stable tailings dams that hold back large quantities of liquid refuse. Failure of such dams is much less frequent, but the consequences are far more immediate. When danger of failure is increasing, some means of providing warning is badly needed.

Because the problem is extensive, involving thousands of small facilities, an inexpensive and simple technique for monitoring the stability of earthen dams was desired. It seemed unlikely that conventional methods of inspection, which require expensive instrumentation and trained geotechnical engineers, could meet the need.

Under this impetus, a system—acoustic emission monitoring—was developed based on the phenomenon that soils emit sounds under stress.

The EPA's Oil and Hazardous Materials Spills Branch, in Edison, New Jersey, awarded a grant to Drexel University to develop an acoustic emission monitoring system to determine the stability of dams. The Drexel investigators found that the resulting signals, when properly amplified and quantified, can be a valuable guide in evaluating the stability of earthen dams.

2. Theory

Small waste dams are constructed of a variety of soils, as a rule using the materials at hand. The resulting structure may be susceptible to failure by one or more mechanisms. The high cost of conventional methods of monitoring dam stability usually rules them out as candidates for evaluating failure potential of small waste dams.

Shear Strength of Soil

The acoustic emission mechanisms within soil are related closely to the mechanisms of shear strength. The shear strength of soil is the resistance to deformation when a tangential (shear) stress is experienced. This shear strength is made up of:

- The structural resistance provided by interlocking of the soil particles (Figure 1)
- The frictional resistance (rolling and sliding) at the contact points of the soil particles (Figure 1)
- True cohesion between the surfaces of the particles resulting from intermolecular attraction (important in clays)
- Apparent cohesion caused by capillary forces at suitable water content

The frictional resistance to failure increases with an increase in the normal force on the shearing plane (Figure 1). Only the normal force supported by the solid soil skeleton, however, results in frictional resistance. The part of the normal force that is supported by the pore water pressure reduces the friction component of the soil strength.

Failure Mechanisms in Dams

Earthen dams consist of an embankment (with an upstream and downstream slope) and a base foundation. The point at which the downstream slope meets the base is termed the toe of the dam. If the dam is built across an existing valley, the intersection of the dam and the valley slope (abutment) is termed the groin of the dam. The stability of a slope is somewhat indeterminable, inasmuch as the integrity of a slope made of soil can never be guaranteed because of changing climatic conditions, varying loads, and the activity of man in the area. In particular, the possibility of the soil becoming saturated over time must be considered, because pore water (water filling the voids of the soil skeleton) can have an important deleterious effect on the strength of soils.

Dams that fail usually do so by one or more of the following mechanisms:

- Groin failure (Figure 2a)
- Downstream slope failure above or through the toe (Figure 2b, 2c)
- Base failure, if the rupture surface is deep seated and passes through the supporting soil below the toe (Figure 2d)
- Seepage of such a nature that soil particles are carried away with the flow, and piping (erosion by percolating water resulting in conduits) develops
- Overtopping (impounded wastes overflowing the embankment) and subsequent erosion caused by the fluid flow
- Upstream failure during drawdown

Even if piping does not occur, seepage may reduce slope strength and contribute to failure, because it brings fluid to the downstream slope and thereby adds weight, increases the load, and decreases apparent cohesiveness and effective normal force. Failure through the base must be considered, particularly when the soil beneath the dam is softer than the slope-forming soil. In addition, unless adequate freeboard (embankment height above the maximum expected water level) is provided, failure can occur through overtopping.

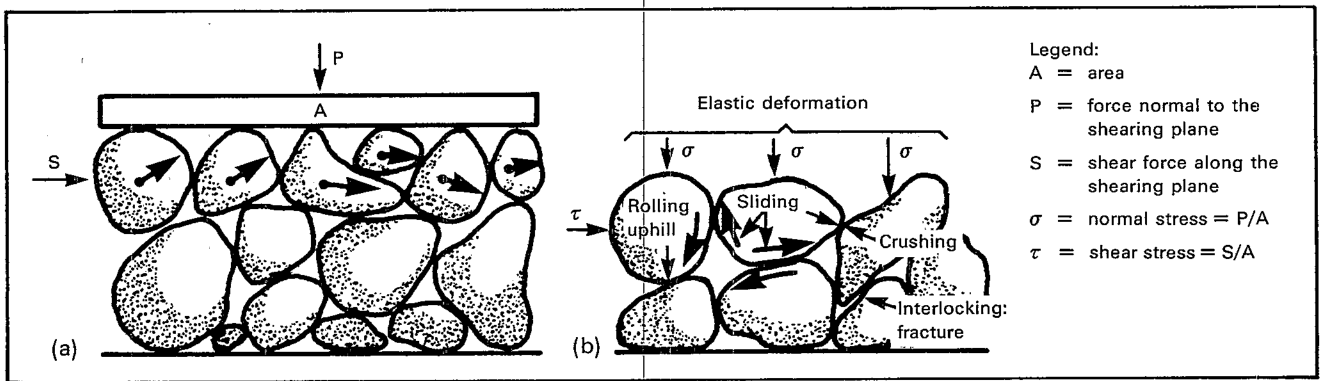


Figure 1.

Soil Shear Strength Components of Friction and Interlocking: (a) Shear in Granular Mass Showing Potential Particle Movements and (b) Mechanisms of Resistance, Deformation, and Movement in Grains

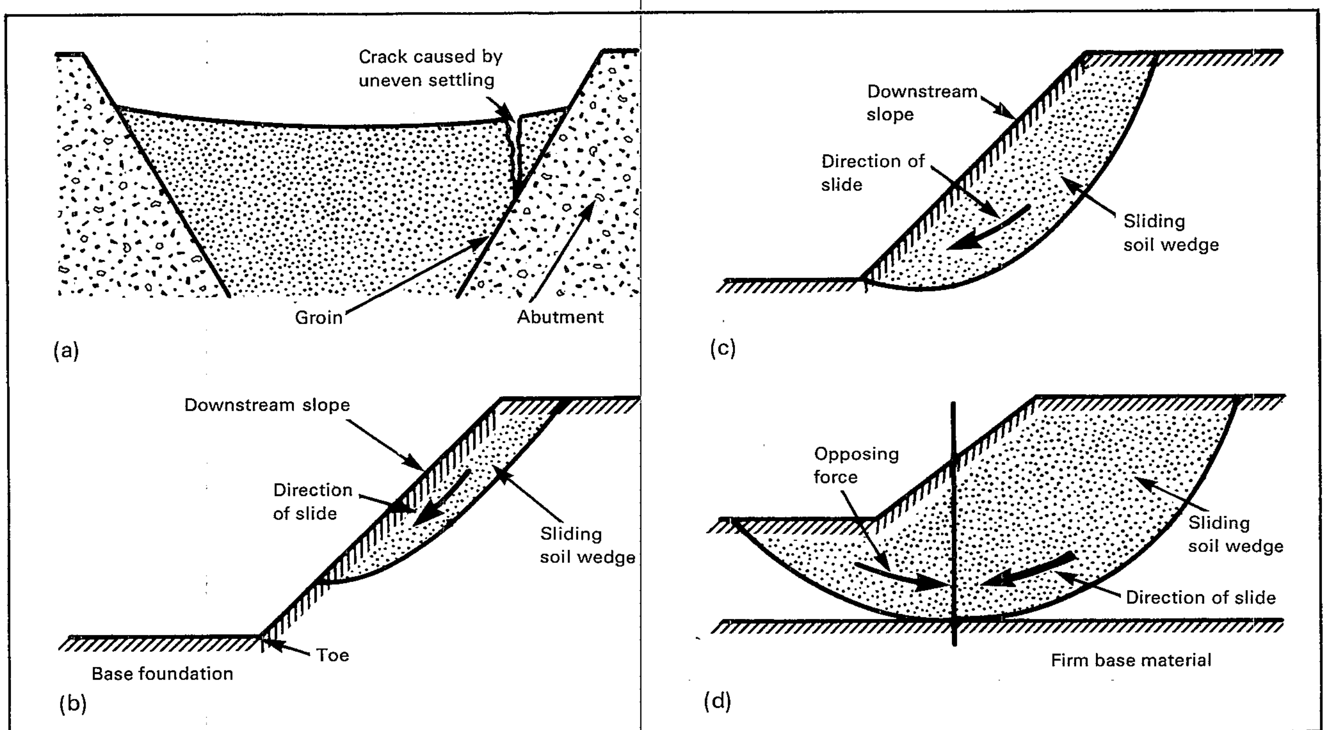


Figure 2.

Some Modes of Dam Failure: (a) Groin Failure, (b) Slope Failure Above Toe, (c) Slope Failure Through Toe, and (d) Base Failure (Deep-Seated Rupture Surface Below Toe)

Slope stability may be analyzed based on measured strength properties of the soil. The usual procedure is to postulate a failure surface, often taken to be the arc of a circle. The total shear force tending to slide the soil along the failure surface is calculated. Then the resisting force in the soil along the surface is computed, usually under the worst expected conditions, for example, maximum pore water pressure or a seismic event. The ratio of resisting force to the driving force is termed the factor of safety. The surface having the lowest factor of safety is considered the most dangerous rupture surface.

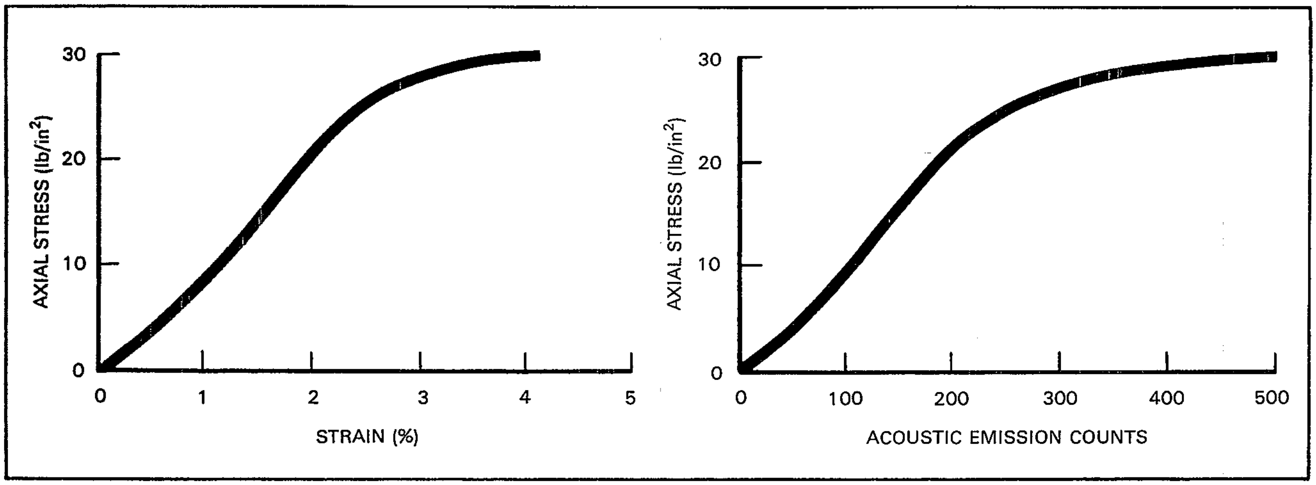


Figure 3.

Unconfined Compression Test Results for Undisturbed Sample of Silty Clay at 56-Percent Water Content

Monitoring Soil Stability

Conventional Methods. Soil engineers and earth scientists use a number of conventional devices to determine the deformation and strain of a mass of soil, including:

- Piezometers (devices to measure the pore water pressure)
- Soil strain gages (linear potentiometers measuring distance between reference anchor plates)
- Slope inclinometers (pendulum-actuated transducers lowered down flexible near-vertical tubes)
- Grids of stakes (monitored by standard surveying methods)
- Settlement plates within the soil mass (to determine foundation settlement)

Each of these devices is expensive to install, or requires considerable expertise to monitor and interpret, or both. Piezometers and settlement plates must be installed during construction or drill holes must be provided. Piezometers must be installed in large numbers to provide a clear picture of the pore water distribution.

Surface instruments require extensive surveys to obtain data or require maintenance when monitoring over a long period of time. Moreover, the data must be interpreted by experts. Nevertheless, major dams are often so instrumented because proper instrumentation can provide warning of potential failure. It has long been recognized that warning signals—for example, strain discontinuities, pore-pressure buildup, leakage, or an increase in deformation rate—almost always precede embankment failure, except when the failure is caused by an unanticipated catastrophic event such as overtopping or an earthquake. But, to observe the signals, someone must be watching, and until recently there has been no economically viable method of instrumenting the multitude of small waste dams that exist across the country.

Acoustic Emissions. Because of the difficulty of implementing each of the foregoing methods for long-term monitoring of dam stability, EPA's Office of Research and Development sponsored studies to develop an alternative monitoring technique. Acoustic emission was a promising area. Acoustic emission is the sound generated internally by the strain resulting within a material when a stress is applied. The emission is the result of the transient elastic energy that is released when materials undergo deformation, fracture, or both.

To apply the acoustic emission technique to monitoring dam soil stability, Drexel University researchers have studied the acoustic emissions produced by soils under stress. They found that curves of applied stress vs. cumulative noise counts look very much like curves of applied stress vs. resulting soil strain, as illustrated in Figure 3. These results contributed to the conclusion that acoustic emissions do, in fact, display a one-to-one correspondence with soil movement and instability. This conclusion holds for granular, sandy soils as well as for cohesive, clayey soils, even though the emission levels and mechanisms involved vary with soil type. Considerable data have been obtained on emissions within soils.

3. Acoustic Emission Technology

Acoustic emissions are generated by stress waves within materials during dynamic processes. The particular dynamic process may be the result of an externally applied stress, or it may be the result of some other unstable situation. At present there is no proven theory for the actual mechanism of acoustic emission in any material, even though such emissions are quite common. Some examples are the cracking of wood when it is over-stressed, the "crying" of tin as it is bent, the cracking of ice, and the crunching of snow. A stress (force) is applied, something gives (a strain is produced), and energy is released that appears partly as sound energy.

A large volume of information on emissions from soils of various types has been obtained by laboratory studies using the triaxial shear test apparatus (a standard laboratory tool for evaluating the shear strength of soil) with a transducer (accelerometer) embedded in the center of the soil sample being tested. Some results obtained from such tests and by other means are discussed in the subsections that follow.

Sources of Emissions in Soils

It has long been realized that when individual soil particles move with respect to one another they produce a small, but nevertheless detectable, noise. This noise, which is designated acoustic emission, is generated within soils by the mobilization of the same mechanisms, such as friction and cohesion, that are responsible for the shear strength of soils. The application of stress produces potential energy. As friction and cohesion are overcome, some of this potential energy is converted to other forms, including acoustic energy.

The primary shear strength mechanisms in granular soils (Figure 1) include sliding friction, rolling friction, and structural resistance (overcome by particle degradation). Friction between the individual particles is the predominant mechanism in granular soils. Studies have shown that conditions producing the greatest number of interparticle and, therefore, frictional contacts, that is, well-graded uniform soil conditions, also produce the greatest amount of acoustic emission activity. Cohesion of particles also is a mechanism of the strength of clay soils, but cohesion does not provide as many emissions as does friction.

Tension crack in highway stockpile, induced during testing

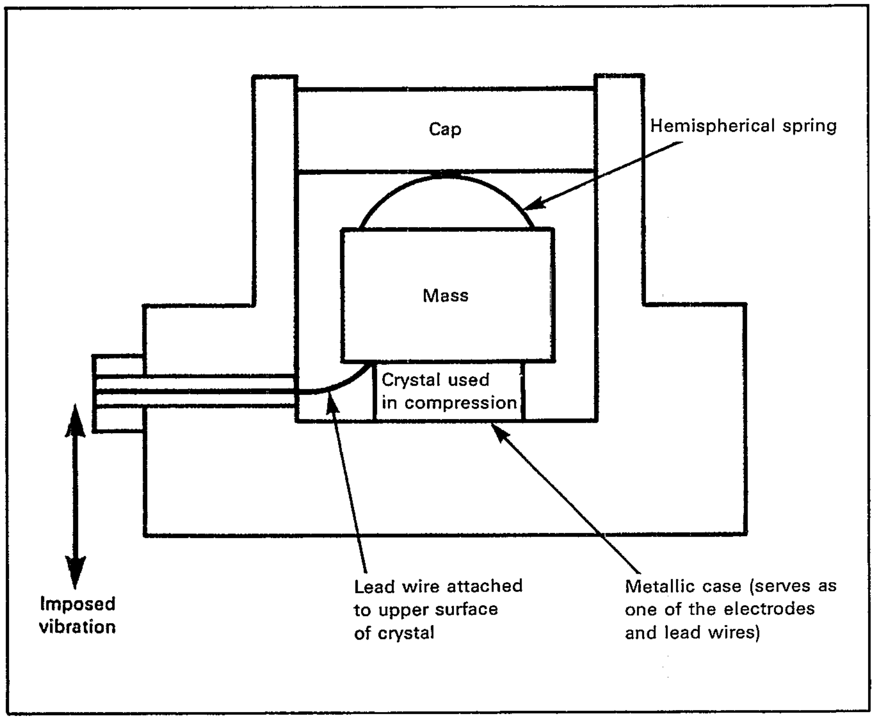


Figure 6.

Typical Piezoelectric Accelerometer Construction

Laboratory Studies

The resistance to shear deformation depends on different mechanisms in different types of soil. Because the mobilization of these mechanisms is the source of acoustic emissions, it is important to know the different signal strengths of the different soils.

Figure 7 shows the results of tests with three soils—two sands and one clay—tested in triaxial shear. The load was increased in several increments until the soil sample failed. After each load increment was applied, both the rate and the amplitude of the emissions decreased with time as relative stability was approached. At each load increment, the average signal strength was represented by summing the peak voltages for all signals obtained and dividing by the number of signals.

The following important observations were made:

- Both sands tested showed the same general response.
- The amplitude of the emissions for the sands increased with stress up to failure, and the rate of increase was greatest as failure stress was approached.
- The average signal amplitude for sands is 100 times greater near failure than at 20 percent of failure stress.
- The clay response is markedly different. Significant signals are not emitted from clay until a higher percent failure stress is reached.
- Signal levels in clay are from ½ to ¹⁄₄₀₀ the level of signals from the sands at corresponding stress levels.
- Initially the signal level for the clay increases, as with sands, but then it levels off and decreases as the maximum stress is approached.

The decrease in signal level in clay as failure is approached is believed to result from reorientation of the platelike clay particles. At first they are randomly oriented, and emissions increase with increasing stress. But then the particles become aligned with the direction of maximum shear stress, and emissions decrease.

There are other important features of cohesive soils (clays and clayey silts):

- Emissions decrease with increasing water content, and are reduced to very low levels as the liquid limit (water content beyond which a mass of soil cannot sustain a shear force) is approached.
- A strong correspondence exists between acoustic emission response and plasticity (ability to be reshaped without developing surface cracks). Cohesive soils with the highest plasticity index give least response.
- As is the case for granular soils, stress vs. cumulative emissions curves corresponds closely to stress vs. strain curves (Figure 3). Thus, acoustic emissions are an indicator of deformation.
- Most cohesive soils, and certainly all granular soils, can be monitored successfully using the acoustic emission technique. Possible exceptions are highly plastic clays with high water content (poor candidates for dam construction materials).

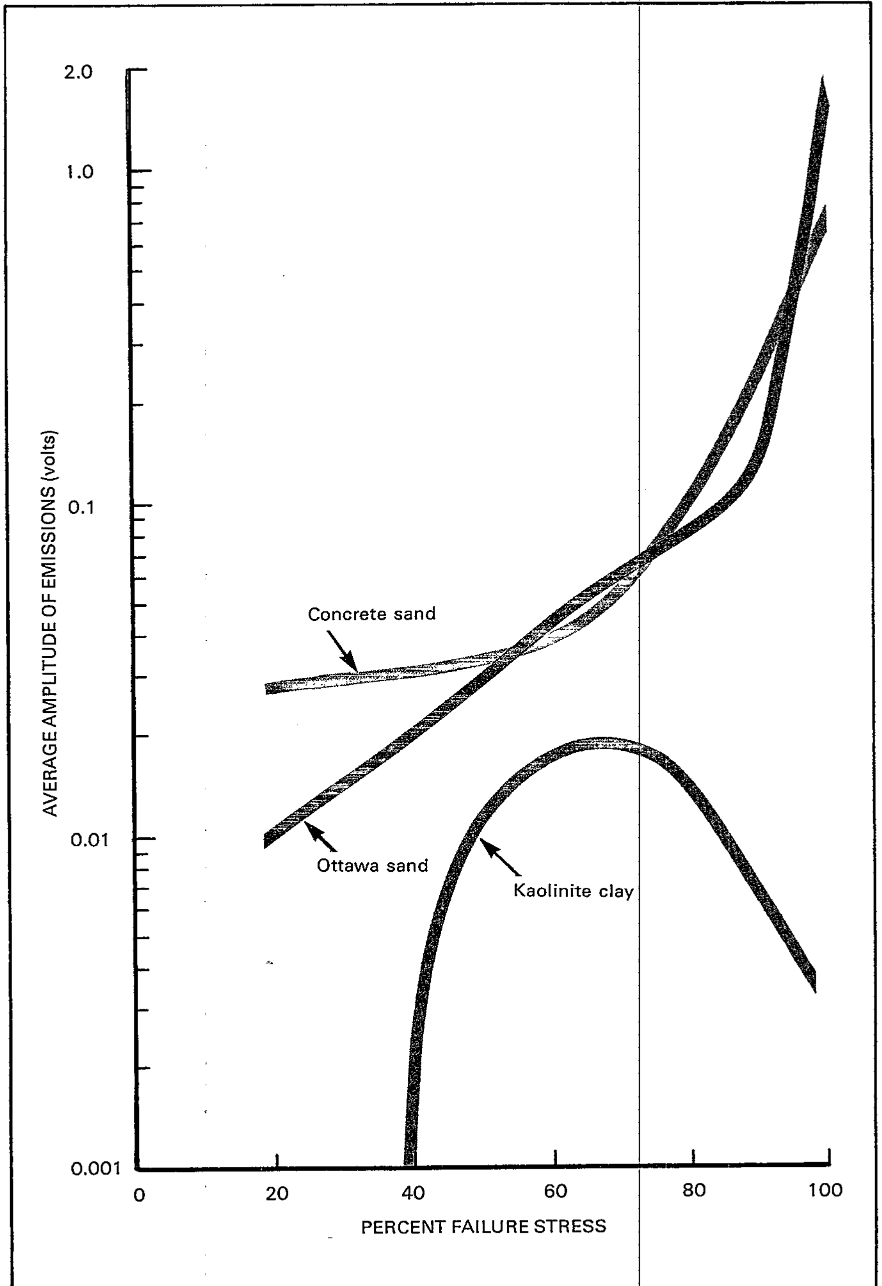


Figure 7.

Average Amplitude of Acoustic Emissions (Measured as Peak Signal Voltage Output) for Various Soils as a Function of Percentage Failure Stress in Triaxial Creep at 5-lb/in^2 Confining Pressure

Field Studies

In addition to laboratory tests on soils, 18 field installations (listed in Table 1) have been monitored. The table shows the considerable range in size of dam, stability of foundation, and quality of embankment. Although the dams being monitored are of several types, most do hold back wastes of one sort or another.

Site 14, an earthen stockpile 15 feet (4.6 meters) high, is of particular interest because it was brought to failure as a planned experiment while being monitored by acoustic emission techniques. Five successive cuts were made in the bank, as shown in Figure 8, before a large wedge of soil separated; this result was considered to be bank failure.

Each response from the first four cuts indicated a high acoustic emission response initially, then an approximately exponential decay with time until relative stability was reached. In general, the more precarious and unstable the situation became with each successive cut, the greater the acoustic emissions count rate experienced.

Approximately 30 minutes after the fifth and last cut was made, the acoustic emission rate rapidly began to increase. When this count rate reached its maximum, about 7,700 counts per minute, a large section of soil pulled away from the intact mass and slid down the remaining slope. Thereafter, the count began to subside and eventually returned to a low level.

Table 1.

Overview of Sites Being Monitored Using the Acoustic Emission Method

Site No. and location	Purpose	Height (ft)	Length	Embankment design and construction	Foundation stability	Acoustic emission waveguides[a]	Range of acoustic emission count rate (counts/min)
1. PA	Flood control	30	2,600 ft	Excellent	Excellent	20 rods*	0
2. PA	Recreation	66	2,500 ft	Excellent	Excellent	12 rods*	0
3. NE	Flood control	67	900 ft	Excellent	Compressible	12 re-bars+	0-200
4. MD..........	Ore stockpile	40	300 ft	Good	Poor	2 pipes* 1 pipe+ 1 re-bar+	0-20
5. PA	Surcharge load	6	120 ft	Good	Poor	1 pile* 3 rods*	2-750
6. NE	Flood control	68	600 ft	Excellent	Compressible	6 rods*	([b])
7. PQ	Tailings dam	95	900 ft	Good	Good	3 rods* 3 pipes+	([b])
8. DE	Dredging spoil containment	15-40	6 mi	Poor	Good	11 rods*	2-10
9. PA	Water supply	120	600 ft	Excellent	Excellent	12 re-bars*	0-5
10. NJ	Chemical waste containment	8	4 mi	Poor	Very poor	12 rods*	0-40
11. VA	Chemical waste containment	4-15	500 ft	Poor	Unknown	4 rods*	0-3
12. NY	Petroleum waste containment	8-20	450 ft	Poor	Unknown	6 rods*	2-100
13. PA	Stockpile for highway fill	15	20 ft	Poor	Good	1 rod*	10-190
14. PA	Stockpile for highway fill	15	60 ft	Poor	Good	4 rods*	2-7,700[c]
15. PA	Seepage beneath earth dam	12	1,200 ft	Good	Poor	8 rods*	20-480
16. TX	Gypsum dam	150	2 mi	Poor	Poor	([d])	([b])
17. KY	Sludge and wastewater lagoons	13-28	2 mi	Good	Average	8 rods*	0-4
18. DE	Water reservoir	25	1,000 ft	Good	Good	1 casing* 3 rods*	0-40

[a]Asterisk (*) = vertical; plus (+) = horizontal.

[b]Monitoring in process.

[c]High count occasioned by intentional destabilization.

[d]Installation in progress.

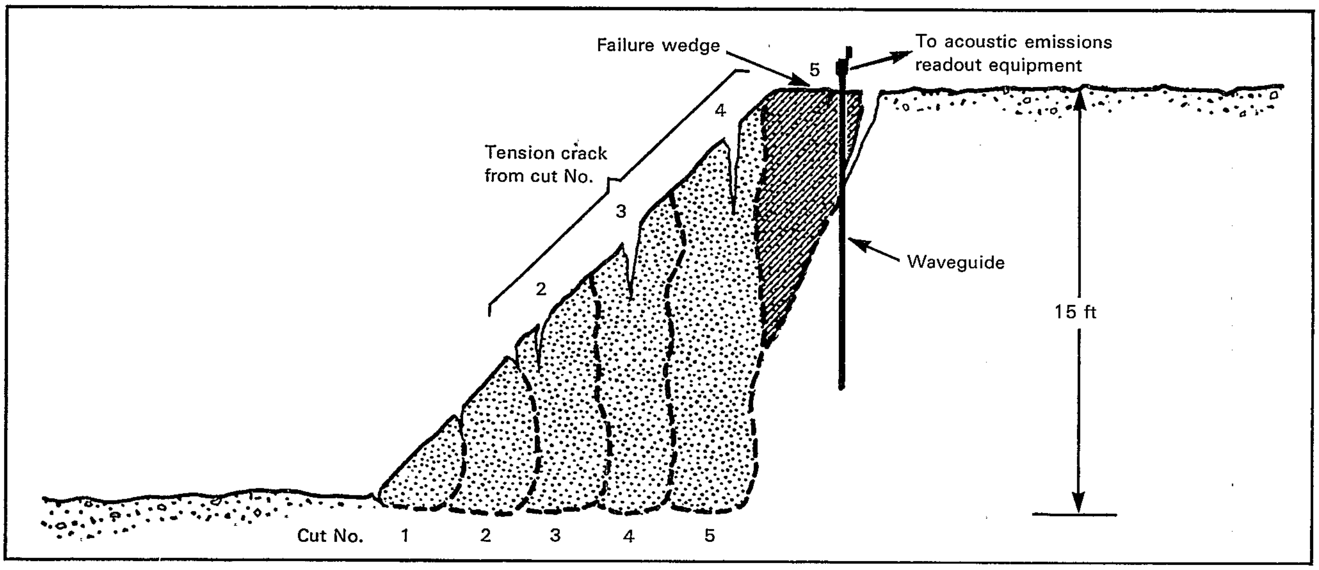


Figure 8.

Earth Stockpile Intentionally Brought to Failure

Highway stockpile (Site 14) deliberately brought to destruction during testing

The effect of rain on the acoustic emission count rate was seen clearly during this experiment. Heavy rainfall occurred twice, following the third and the fourth cuts. Both times the count rate increased substantially and required about a day to return to the former level. It took longer for readjustment of the slope back to equilibrium after the rain of cut No. 4, possibly because of the gradual decrease in the slope's factor of safety. Irrespective of the relative magnitudes involved, it can be concluded that the two rainfalls did have an adverse effect on the slope's stability, at least temporarily, and that the destabilizing effect of the additional water in the soil was detected by acoustic emissions.

The experience gained from field testing verifies that unstable soil produces large quantities of acoustic emissions. Conversely, when the soil is stable, emission rates are low or nonexistent.

A full correlation between some index of dam instability and the emission count rate is not yet available; further experience with field installations should provide needed data. Nevertheless, a qualitative guide has been developed for assessing the danger of dam failure based on acoustic emission readings.

5. Prospects and Costs

Acoustic emission waveguides have been installed at a number of sites (see Table 1) with locations as far west as Nebraska, north to upper Quebec Province, and south to Texas. The size of the embankments or dams varies greatly, with heights from 6 feet (1.8 meters) to 150 feet (45.7 meters), and lengths from 20 feet (6.1 meters) to 6 miles (10 km).

Acoustic monitoring systems have been installed privately by several corporations in the United States that have waste chemical lagoons, and a large chemical manufacturer in England is in the process of procuring the components. At least three American companies will now supply ready-for-use systems.

How well has the system performed? Some results are indicated in the following:

- Failure of a suspect reservoir wall was easily predicted before the wall collapsed inward during drawdown of the impounded water.
- The sliding of an embankment was predicted hours before the actual collapse.
- A dangerously unstable industrial dike, containing a large quantity of dissolved toxic heavy metals (lead, cadmium) as a sludge, was reinforced in time to prevent breaching.
- An abandoned lagoon at a chemical waste disposal facility was detected as in danger of failure during a storm. Prompt action in shoring up the wall and adding more earth prevented collapse.

Table 3.

Acoustic Emission Equipment

Supplier and address	Equipment	Model	Approximate cost[a]
Columbia Research Laboratories, Inc. .... McDade Boulevard and Bullens Lane Woodlyn PA 19094	Accelerometer	No. 476, nominal resonance = 7.5 kHz	$175 (less then 6), $155 (6 to 10)
	Amplifier	Vibration meter, Model VM-103	$395
Hewlett-Packard Co. .... King of Prussia Industrial Park King of Prussia PA 19406	Electronic counting system	Measuring system, 5300A	$500
		Timer/counter, 5304A	$385
		Battery pack, 5310	$275
B&K Instruments, Inc. .... 5111 W. 164th Street Cleveland OH 44142	Cable connectors	Coaxial Microdot Cable A0-0037 (with JP-0012 connectors)	$2/ft
		Microdot to Microdot connector, JJ-0032	$3

[a]1978 prices.

Not only has the system proven effective, it is also inexpensive and nearly maintenance free when used periodically. Some suppliers whose components have been used in work to date are listed in Table 3, with the components and addresses of the suppliers.

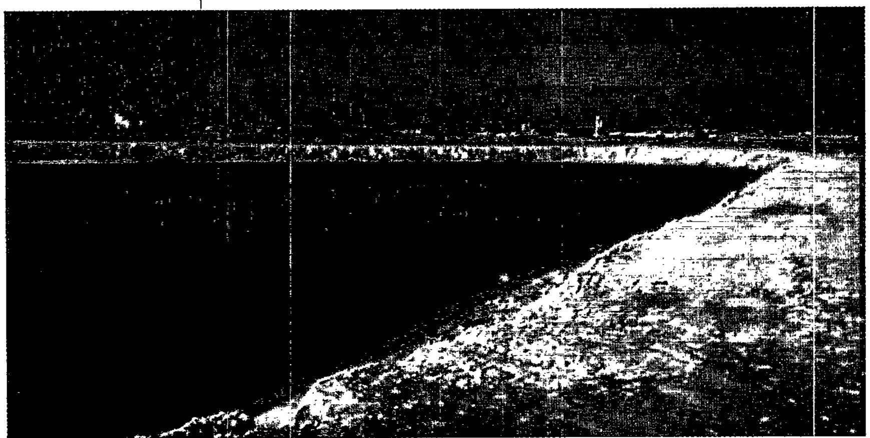
Manufacturers having packaged systems available for acoustic emission monitoring of earth structures are:

Acoustic Emission Technology Corporation
1828A Tribute Road
Sacramento CA 95815

Dunegan/Endevco
Rancho Viejo Road
San Juan Capistrano CA 92675

Geotechnical Instruments, Ltd.
Geotechnical House
Hatton, Warwick CV357JL
England

Weston Geophysical Engineers, Inc.
Post Office Box 550
Westboro MA 01581



Typical waste pond retained by an earthen dam

Packaged systems intended to be used in the portable periodic sampling mode, handling a single channel of information, are available in the $2,000 to $4,000 price range. A microcomputer-based system for continuous operation with eight-channel output, programmable alarm level, and camera for hard copy is available at about $10,000. More sophisticated warning systems use a minicomputer and can scan an unlimited number of channels continuously. The cost of such systems is on the order of $25,000.

Manufacturers should be contacted for details concerning their systems. Each of the companies will provide advice and assistance in the installation of an acoustic emission monitoring system.

This report was prepared for the U.S. Environmental Protection Agency by the Centec Corporation, Reston VA. Dr. John E. Brugger of the EPA Industrial Environmental Research Laboratory's Oil and Hazardous Materials Spills Branch provided assistance and reviewed the report. Photographs were provided by the Centec Corporation, Drexel University, and Mason & Hanger-Silas Mason Co., Inc., of Edison NJ.

Additional information or reference material may be requested from EPA or from Drexel University. The Drexel University contact is:

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EPA's Oil and Hazardous Materials Spills Branch can provide information on acoustic emission monitoring and other programs dealing with spill prevention. Comments or questions should be addressed to:

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