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EPA

Project Summary

Spill Alert Device for Earth Dam Failure Warning

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A spill alert device based on the monitoring of acoustic emissions (AE) has been developed, field-tested, and placed into an operational mode at several sites This apparatus can be useful in predicting and anticipating the failure of earthen structures such as dams, waste storage lagoons, and spoil piles With sufficient advance warning, repair of such structures becomes possible, thus avoiding possible catastrophic discharges of their contents into the environment

This report describes the fundamental mechanisms that cause soils to generate AE when placed under strain and the techniques and equipment necessary to monitor such emissions Results of laboratory testing are shown to demonstrate a relationship between soil types and characteristics and the AE that result when such soils are subjected to applied stresses Evidence is presented to show that AE increase as a soil approaches failure due to imposed stresses Conversion of the laboratory apparatus to a portable system suitable for field use is documented This equipment had an estimated cost of under $2,000 in December 1978

Results are presented for field tests of AE monitoring of 19 field sites These results reveal potential weaknesses in some earthen dikes and stockpiles, highway fill stockpiles, and embankments and identify sites of potential failure so that corrective measures can be undertaken

This project was a 1977 recipient of one of the Industrial Research Magazine's IR-100 Awards A number of companies are now marketing AE devices for earth structure monitoring

This Project Summary was developed by EPA s Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back)

Introduction

The problem of failures of earthen dams and dikes retaining walls lagoon embankments, etc is ageless and has continued to be a source of catastrophic losses of life, property and contained materials through the years In addition to large well-documented disasters (e g the Grand Teton and Taccoa Falls dam failures) many smaller less publicized failures also occur in privately owned dams storage piles etc Such failures often have serious impacts on downstream water quality and aquatic life when the hazardous (or foreign) materials in these ponds and lagoons are discharged in an uncontrolled manner

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It has long been known that certain structures emit internally generated sounds when placed under stress conditions In some cases these sounds are audible (e g crying of tin and cracking of wood) while in others the sounds are not in the audible range and can only be detected by sophisticated equipment Historically AE monitoring began in the mining industry to detect instabilities and to predict when failures (rock bursts) might occur Extensive research has now been carried out by numerous investigators on the AE phenomena exhibited in metals, metallic structures (e g , pressure vessels) ceramics rocks various mines plastics soils and earthen and other structures under various conditions In most such programs piezoelectric sensors are used to detect the emissions The very small electrical responses are then amplified, filtered, counted, and recorded

An understanding of the AE emitted by soils and an ability to relate them to the characteristics of the structure allows the information to be used in protecting structures such as dams, embankments, etc , from unexpected and catastrophic failures Thus, a major goal of the current project was the 'translation or conversion of nonaudible AE from soil structures to some measurable or recordable format that could be used as a nondestructive test of the safety of such containment structures

Laboratory Studies

The laboratory work studying the behavior of AE in soil was focused on several granular soils (they are the most emittive) and on different types of fine grained soils (they are the most troublesome) The attempt in all cases was to systematically vary one parameter at a time and, thereby, observe its influence on the subsequent response The response that was generally monitored was both stress/strain and stress/AE Since strain and AE are both cumulative phenomena, they should be capable of being compared, a feature that was indeed present and was brought out in the following studies

Granular Soils

Four types of sands were evaluated in this phase of the work The choices provided a broad range of variation in particle shape and uniformity, however, the size range was rather limited, i e , from 0 20 to 0 45 mm effective size

In the first series of tests, hydrostatic pressure was applied to the specimen to produce isostatic conditions Cumulative AE counts were recorded with time after each pressure increment was applied Other than for the final level of AE counts, the time for the AE to cease (i e , to attain equilibrium of particle reorientation) varied primarily with particle shape Samples containing rounder particles ceased emitting much before those with angular particles

Using the same soil samples and experimental test set up as with the isostatic test results just covered, a series of triaxial shear creep tests was performed The deviator stress (or principal stress difference) versus strain and the deviator stress (or principal stress difference) versus AE behavior for the four soils were determined Almost identical behavioral patterns of stress/strain and stress/AE curves at all levels of confining pressure were observed This behavior indicates a basic correlation between strain and AE, the determination of which was the fundamental goal noted in the introduction to this section

On Particle Shape - The more angular the soil particles contained within the total sample the most emittive is the sample under stress

On Coefficient of Uniformity - As coefficient of uniformity increases, that is, as the soil becomes well-graded, so does the level of cumulative AE This is a strong conclusion for the triaxial test behavior and is in almost perfect agreement with the isostatic test results However, the more angular soils also happen to have the highest coefficient of uniformity The actual cause of greater emissions may therefore be a combined effect

On Effective Size - Little in the way of a firm conclusion can be stated since the range of effective size evaluated, 0 20 to 0 45 mm is quite limited

Fine Grained Soils

Various aspects of fine grained soils were evaluated on a number of silts and clays Each is explained separately in the following paragraphs

On Confining Pressure - The effect of confining pressure on the AE behavior of cohesive soils was evaluated for two of the four soils The close parallel in the behavior of stress/strain and stress/AE curves was easily noted Also, the fact that the overall AE count levels are slightly higher for the clayey silt with its silt-sized particle component than for the kaolinite clay is in agreement with the AE amplitude study described in the report The analogous behavior of strain and AE indicates that the two parameters are related and that either or both can be used in conjunction with stress to characterize or monitor a given soil

On Water Content - The samples were compacted at different water contents and tested in unconfined compression There was a decrease in strength and AE with increasing water content The extremely low number of emissions recorded at higher water contents emphasizes the susceptibility of the technique to experimental error and external noise interference as water content approaches the liquid limit (i e loss of measurable shear strength) of the soil being monitored The low AE activity as the soil loses its shear strength because of moisture inundation could possibly cause problems in some monitoring situations

On Plasticity Index The four cohesive soils tested in this study had plasticity indices of 10 19, 19 and 512 percent Each soil was compacted to achieve a void ratio of 0 89 and tested in consolidated-drained triaxial creep at 34 kN/m^2 (5 psi) confining pressure The most emittive soil is the clayey silt which has the lowest plasticity index and the most silt sized material The kaolinite clay and silty clay have the same plasticity indices and similar AE response curves Thus a strong correspondence exists between AE response and plasticity in fine grained soils

On Sample Structure - All testing conducted up to this point has been on remolded samples prepared in the laboratory under closely controlled thus nearly ideal conditions Since one of the case histories to be examined later provided the opportunity for obtaining undisturbed soil samples, the soil (a silty clay) was tested in the as received condition The AE level was low, due in part to the cohesive character of the predominantly clay soil and its relatively high water content However the AE response closely resembles the stress/strain behavior as has been the case for the remolded soil samples examined previously

On Stress History - The Kaiser effect is well-established in AE literature in which AE levels are low until a material is stressed beyond that which it has experienced in the past Thus many materials retain a record of their stress history which is evidenced by the AE response

In this phase of the study, stress history testing was undertaken for AE monitoring by fixing an accelerometer to the upper load platen of a standard consolidation odeometer Tests were conducted in the prescribed manner with deformation time and AE/time data sets being generated for each pressure increment The soil tested was a sandy silty clay known locally as a preconsolidated marl of low plasticity The standard deflection plot was roughly reflected in the curve of AE counts i e during periods of low deflection rates the AE count rates were low and, during periods of high deflection rates the AE count rates were high The time for 50 percent consolidation t_{50} for each pressure increment was used to obtain an AE count at 50 percent consolidation The AE data were normalized by dividing the accumulated emission count at t_{50} for each pressure increment by the total emission count registered during all pressure increments A graph of the response consists of two nearly straight lines intersecting at about 810 kN/m^2 (8 0 tsf) which coincides with the beginning of the straight line portion of the virgin compression curve Most important is that the AE levels are generally lower at stress levels below the preconsolidation pressure than they are at stress levels that exceed the preconsolidation pressure Thus stress history seems to be identifiable using the AE monitoring technique

Field Test Program

Unlike the low attenuation and easier detection of AE in some natural and man-made structures, the high attenuation of AE in soils requires that some mechanism be used to transmit the acoustic emissions generated within the mass of soil to the surface and then to convert the transduced electrical signal to some quantifiable format To overcome the problem of attenuation wave guides are used to transmit the emissions to the surface these guides may simply be lengths of steel rod existing metal piping reinforcing bars, etc Ideally, the wave guides should be placed in the soil structure during construction but they may also be driven into place when needed In general, the design of the wave guides does not have a great effect on the character of the AE except that increasing the length of the guide does lower the frequency of the first observable resonance

Other than requiring much longer wave guides and incorporating minor changes in the field unit to make it portable and weather resistant the monitoring unit used for field testing is similar to that used in the laboratory The system basically consists of an accelerometer, amplifier electronic counting system and cables In December 1978 the approximate cost of such a system was slightly under $2,000 The project report includes a more detailed description (with photographs) of suitable equipment for both laboratory and field use and specifies procedures for installing and operating an AE system in the field

At the completion of the project work period in June 1979 the apparatus had been or was being installed at 19 field sites A listing of and a few details concerning these sites are presented in Table 1 Complete data were not available for a few sites at the time the report was prepared One particularly fruitful site is described in detail below, more detail on the others can be obtained from the full report

Site #14 consisted of a 4 6-m (15-ft) high stockpile of soil fill in southwest Philadelphia to be used for future highway construction The contractor agreed to bring the embankment to failure by

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	NY	Chemical waste containment	8	4 mi	Poor	Very good	12 rods	0 40
11	CA	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
15	PA	Seepage beneath earth dam	12	1 200 ft	Good	Poor	5 rods	20 480
16	TX	Gypsum dam	150	2 mi	Poor	Poor	(d)	(b)
17	KY	Sludge and wastewater lagoons	13 29	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

sequentially undermining the toe of the slope. Once preliminary arrangements were made the soil was sampled, tested, and found to be a well-graded silty sand with a trace of clay (SW-ML). Its natural water content was 12 percent, and its unit weight was approximately 1.92 g/cm^3 (120 pcf).

An 18-m (60-ft) length of the embankment was excavated in a series of separate cuts beginning at the toe and extending into the slope. To minimize background noise the front end loader used for the excavation actually left the site after each cut until AE ceased completely, that is until full stability was reattained. Five separate cuts were required to bring the slope to failure and the process extended over a 21-day period. Figure 1 is a schematic diagram of the approximate outline of the five cuts. Acoustic emission readings were taken from four 13 mm (1/2 in.) diameter wave guides driven vertically from the top of the slope down through the embankment to within 1 m of the relatively firm foundation. For the first four cuts the resulting response curves of count rate versus time are given in Figure 2. The data shown are from the wave guide in the most actively deforming region of the embankment. From these curves the following observations can be made.

The general response from the first four cuts indicated a high AE rate initially then an approximately exponential decaying rate with time until stability was reached. Overall AE rates generally increased with each successive cut. An exception occurs during Cuts 2 and 3, where it is seen that some AE levels are greater after Cut 2; however, AE is detected for a much longer time after Cut 3.

The emission rate from the fifth and last cut initially followed the general trend, but, 30 min after the cut was made the AE rate began to increase rapidly (see Figure 3). When the count rate reached its maximum (about 7700 counts/min) a large secton of soil pulled away from the intact mass and slid down the remaining slope. Thereafter the count rate began to subside and eventually came to equilibrium. The post-failure count rate curve appears to be consistent with the original curve.

Not shown on these figures is the effect of rain on the AE count rate. Approximately 8200 min (5.7 days) after Cut 3 was made, a heavy rainfall caused the count rate to rapidly increase to 200 counts/min. Thirteen hundred minutes (0.9 days) later, the count rate returned to its former level of 2 to 5 counts/min. Rain again interrupted the testing program after Cut 4 was made. Approximately 3000 minutes (2.1 days) after the cut was made rainfall occurred and the count rate increased to 350 counts/min. An

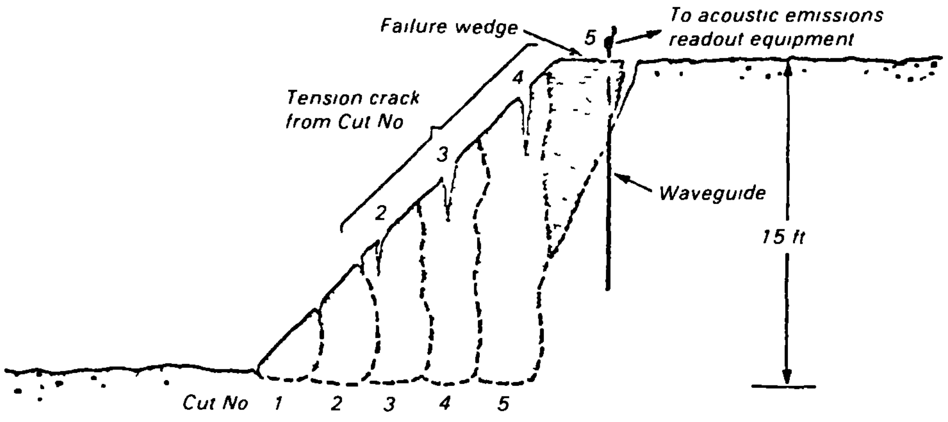

Figure 1 *Schematic diagram of embankment purposely brought to failure by successive excavation at toe of slope*

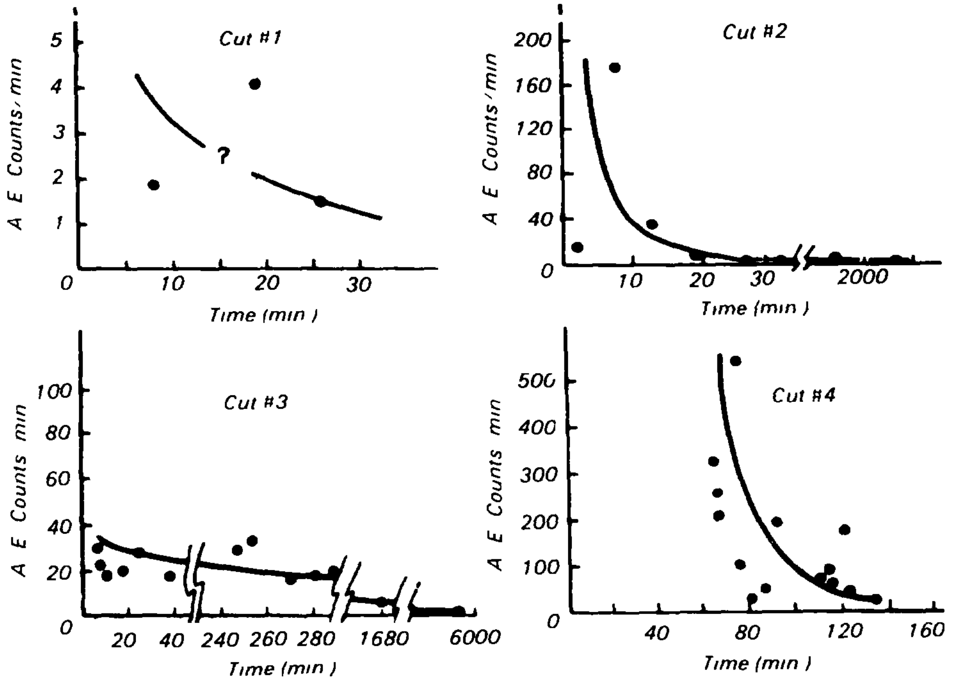

Figure 2 Acoustic emission rate versus time response for Cuts 1 2 3 and 4 of embankment shown in Figure 1

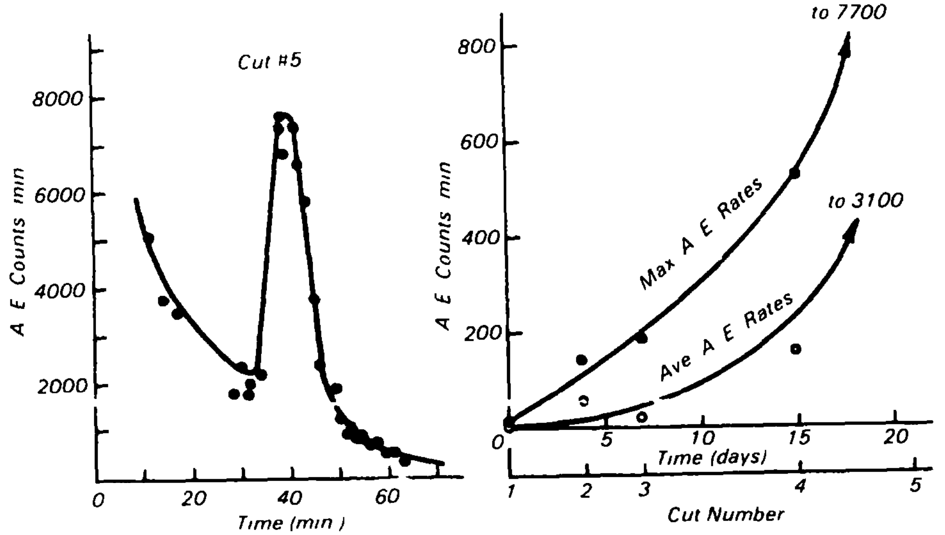

Figure 3 Acoustic emission rate versus time response for Cut 5 of embankment shown in Figure 1 and summary AE rate response from all five cuts

additional 2400 min (1 7 days) were required for the count rate to decrease to ' zero The longer time period necessary for readjustment of the slope to equilibrium conditions after the rain of Cut 4 may be due to the gradual decrease in the slope s factor of safety From this information, it can be concluded that the two rainfalls had an adverse effect on the slope s stability at least on a temporary basis

Additional data can be obtained from this particular site by plotting the AE count rates of each cut as in Figure 3 Shown on this figure are curves for both the maximum count rate and the average count rate during the 1-hr period after monitoring began The response curves are somewhat linear for the first four cuts but increase rapidly thereafter This type of behavior substantiates the generally acknowledged fact that loss of stability in slopes is not a linear process, but one in which instability progresses at an increasing rate as failure is approached

This field test was the most controlled of all those listed in Table 1, and hence allowed the most information to be obtained It shows quite conclusively the stability predictive capability of the AE method The AE results from other field sites have also affirmed the potential usefulness of the technique (details in report)

Recommendations

The AE spill alert device has been subjected to extensive laboratory and field testing It now should be subjected to equally arduous tests in the hands of potential users such as hazardous site owners, engineering firms, and others involved in spill prevention and impoundment design and construction work Extensive field testing in different situations and under various conditions (including controlled failure) must now be carried out to fine-tune the apparatus and its use and broaden the data base needed for predictions

Conclusions

The AE generated by and in an earthen structure such as a dam, embankment or storage pile can be correlated with the strain the structure is experiencing

By monitoring AE over time, changes in the stability of the structures can be predicted and where necessary corrective action can be taken to prevent catastrophic failure or in the most extreme case, initiate evacuation of the downstream area

By monitoring the AE of a dam or dike over time the current and expected safety of such structures can be predicted The character of the soil in the structure and the amount of moisture in the soil can influence the level of AE and make it necessary to use such data with care Much laboratory work has been performed to determine the AE characteristics of the various soil types (sands silts and clays) under different conditions

A wide range of other potential uses and applications exists for AE monitoring Such applications can supplement other engineering techniques, identify problem areas and help to avoid failures, which could expose workers inhabitants and aquatic species to potentially hazardous conditions

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The complete report entitled 'Spill Alert Device for Earth Dam Failure Warning,' (Order No PB 84-138 189, Cost $14 50 subject to change) will be available only from

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