ACOUSTIC EMISSION IN SOILS AND LONG TERM EPA FUNDING

A. E. Lord, Jr. (Emeritus Professor)
Drexel University, Philadelphia, PA USA

ABSTRACT

I shall try to review the work with Bob Koerner during our EPA-sponsored research on acoustic emissions in soils. This covered the period from 1972-1985. Personal editorial comments will be included.

BACKGROUND

Bob Koerner and I both started at Drexel in September of 1968. We both rode the Media Local commuter train home, and after seeing each other a few (or many) times and realizing we both were at Drexel, we started talking. This was sometime in 1970, I guess. Bob was interested in soil mechanics research and my background was in vibrations in solids. Maybe we could do some mutually-interesting research? I am not sure how the subject of acoustic emission (AE) came up, as neither Bob nor I had any experience in or knowledge of it. (The idea of AE might have come from Bob Hay in Metallurgical Engineering, whom we both knew, and I have a faint recollection that Bob H. was involved somehow with AE at this time).

START OF WORK

Somehow I asked Frank Davis my Physics Department Head (and incidentally the Weather Man on Channel 10 in Philadelphia) about the acquisition (for little or no cost) of some low frequency vibration measurement. The ultrasonic equipment I had would only work at frequencies above 1 MHz, which would be much too high for a material as lossy (high attenuation) as soils. Frank directed us to some friends of his at the GE Re-entry and Environmental Systems Division at 31st and Chestnut (The building is now an apartment complex). Sid Matthews and Dick Spotts of GE kindly lent us an accelerometer and a charge amplifier and give us advice into their use. We did some preliminary work on AE in soils in 1971 and submitted our results to ASCE Journal of the Soil Mechanics and Foundation Division. The manuscript was accepted and appeared as a Technical Note in the January 1971 issue(1). Figure 1 shows our first experimental setup and Figure 2 our first results. Bob drew the figures for all our articles (I was always impressed by his drafting ability. He would many times say “I have to go home and draw figures tonight". I eventually learned to draw passable figures, but not as good as Bob.) As far as we knew these were the first AE results in soil published - although there were some results of AE in rock already in the literature.

FUNDING

About this time Bob and I wrote a proposal to EPA using AE monitoring to assess earth structure stability. The proposal was sent to EPA Washington, DC who in turn sent it to Dr. John Brugger of EPA, Edison, NJ. John was interested in the proposed work and called us and we arranged a meeting at Drexel to talk about the proposed work. We hit it off immediately and we received funding in late 1972.(2) John continued to be a great supporter of our work through EPA funding. He supported us very well for well over twenty years and certainly this level of support helped Bob and I get tenured and promoted to full professor. We became fast friends and scientific colleagues of John and his untimely death in the early 90's shocked us both very much. Christmas cards and occasional telephone calls are exchanged with his widow Marion who lives in Prescott, Arizona. We miss John Brugger very much - he was a prince of a fellow.

BULK OF WORK

Our next work used a wider range of dry soils(3) (sand/clayey silt mixtures) and a wave guide connected to the soil (see Figure 3). Figure 4 shows some typical results here. The higher the sand content the higher the AE's (Table 1).

By 1974, there was enough interest in our work that we were asked by a technical editor to give a few short reviews of our AE work to date in soils to be published in the Journal of the Acoustical Society of America.(4,5)

Our first ideas of an earth dam AE monitoring scenario was presented at a Hazardous Materials Spill Conference in August 1974 in San Francisco.(6) At that time we had three earth dams instrumented, two in Pennsylvania and one in Nebraska. Figure 5 gives a schematic of the instrumentation. This dam is a 67-ft high, homogeneous earth dam. Table 2 gives some preliminary AE readings from this site. It should be mentioned that the counter we were using at the time was a very large and heavy (~30 lbs) Nixie tube variety. It was very difficult to take in the field. After a year or two with EPA funding we purchased a much smaller, and much lighter counter. Incidentally shortly after starting this work, all the Nixie tubes were stolen from this counter in my lab. I knew the student who stole them - but I never could prove it.

Due to the high attenuation of AE (i.e., elastic waves) in soil a low loss media must be used to convey the AE's to the surface for monitoring (see Figure 5).

Isolated steel rods will conduct AE's very well, but what happens when the steel "wave guide" is surrounded by soil. To this end we did preliminary work with a 4-ft. long, 0.5-in. diam. steel rod surrounded by silty sand soil at various densities and water contents. The results are shown in Table 3. The resonant frequency of the rod/soil system is not affected much by the nature of the surrounding soil, but the amplitude of the resonance is very strongly affected. The low amplitude would mean significant attenuation of the AE's as they travel up to the monitoring electronics. A much more detailed study of the surrounding soil affects was undertaken in reference 7. Figure 5 shows the attenuation of elastic waves in various materials as a function of frequency. It is obvious from the Figure that soil structures are much too lossy to be monitored without the use of low loss waveguide material. Figure 7 shows the experimental setup to determine the effect of soil covering on wave guide behavior. Table 4 gives the results of the study in a concise form. Note that transverse waves are attenuated very strongly by the soil covering. Typical losses due to soil covering for axial waves (i.e., essentially longitudinal waves) are some 1-5 dB/m. Using the results of this paper a calculation is made of the range of soil that can be monitored via AE measurements with and without the use of waveguides.

A settling pile was instrumented(8) and the field situation, load, settlement and AE results are shown in Figures 8, 9 and 10.

Figure 11 shows the frequency content of AE's from a lab experiment for a typical soil.(9) These results have certainly been effected by the resonant effects of the waveguide and the very high attenuation of AE's in the soil at frequencies above the monitoring frequencies and the high frequency cutoff the experimental measurement technique (about 20 kHz).

Figure 12 shows the results of a controlled slope failure.(10) A portion of the base of the large soil box could be lowered, resulting in a slope failure. It is seen that the number of emissions was strongly dependent on the moisture content of the soil. Another controlled laboratory experiment is described in reference 11. This was a bearing capacity experiment and the experimental situation and results are shown in Figures 13 and 14.

As an aside, we worked on some AE detector development(12). Figure 15 shows a longitudinal wave detector. We also developed a shear wave detector. These were lab studies and the detectors were not used in the field.

The first indication (although somewhat crude) that prestress in a soil could be observed via AE measurements(13) was seen in 1976. Figure 16 shows this result of AE and strain versus pressure in a consolidation odometer.

A number of field sites were monitored. A list of twenty-five of these can be found in reference 14 (see Table 5). The most significant (in our estimation) of these field tests is described in reference 14, 15 and 16.

This case history which the authors feel best demonstrates the utility of AE monitoring, 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 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%, 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. In order to minimize background noise, the front end loader used for the excavation actually left the site after each cut until the AEs ceased completely, i.e., full stability was achieved. Five separate cuts were required to bring the slope to failure, and the process extended over a 21-day period. Figure 17 shows a schematic diagram of the approximate outline of the five cuts. AE readings were taken from four 13 mm (1/2 in) diameter waveguides driven vertically from the top of the slope down through the embankment to within 1 m of the relatively firm foundation. The resulting response curves for the first 4 cuts of count rate vs. time are given in Figure 18. The data was retrieved from one waveguide in the most actively deforming region of the embankment. From these curves the following observations can be noted.

The general response from the first four cuts indicated a high acoustic emission rate initially. Then an approximately exponential decaying rate occurred with time until stability was reached. Overall AE rates generally increased with each successive cut. The exception being cuts 2 and 3; where it is seen that some AE levels are greater after cut 2, however they exist for a much larger time after cut 3.

The emission rate from the fifth, and last cut followed along this general trend, but 30 min. after the cut was made, the AE rate began to increase rapidly, see Figure 18. When the count rate reached it maximum (about 7,700 counts/min) a large section 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 8,200 min (5.7 days) after cut No. 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 was back to its former level of 2 counts/min to 5 counts/min. Rain again interrupted the testing program after cut No. 4 was made. Approximately 3000 min (2.1 days) after the cut was made rainfall occurred and the count rate increased to 350 counts/min. An additional 2,400 min (1.7 days) was required for the count rate to decrease to zero. The longer time period necessary for readjustment of the slope back to equilibrium after the rain of cut No. 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 18f. Shown on this figure are curves for both the maximum count rate and the average count rate during the 1-hour period after monitoring began. The response curves are somewhat linear for the first four cuts, and thereafter increase rapidly. 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 a increasing rate as failure is approached. Thus, instead of 30 minutes warning before failure as seen on the left side of Figure 18, there is actually much more as seen on the right side of Figure 18.

A theory was developed to estimate the magnitude of AE's in soils. The result was

$$a_{max} = \sqrt{\frac{\pi f^2 e^2 V R c}{2 \Delta t r^2}} \tag{1}$$

where

a_{max} = the maximum acceleration of the generated AE at position r.
f = frequency of the AE
e = strain in the volume of released elastic energy at the source
V = volume of strained region
R = radiation efficiency (fraction of total stored elastic energy that is released as elastic waves at the source volume)
c = elastic wave velocity
Δt = time of release of stored elastic energy
r = distance from source to monitoring area

A number of articles dealt with the determination of prestress in soils(18,19,20,21). Some typical consolidation laboratory results in granular soils are shown in Figure 19 and a summary of results is given in Table 6. Table 7 gives corresponding results in cohesive results. Field tests have also been conducted(22,23). The

"Acoustic pressuremeter device" is shown in Figure 20. Results of volume vs. pressure are shown in Figure 21 and AE vs. pressure in Figure 22. The field study results are tabulated in Table 8. Acoustic rock jack and soil pressuremeter were discussed in the "prestigious" (my editorial comment) Eleventh International Conference on Soil Mechanics and Foundation Engineering(24) in San Francisco in 1985. I believe this was Bob's first time giving a paper at this conference. From what Bob said of the importance of this conference I felt very proud to be part of the article.

In 1977 our "Spill Alert Device" received an IR-100 award from Industrial Research magazine. The magazine considered our device as one of the years 100 most promising industrial research developments.

COMMENTS

As this is a symposium about Bob Koerner I thought I should end this article with a few personal comments.

I was very active in the initial idea phase and laboratory phase of the AE program, but in all truth, as the program really got going, Bob got all the great graduate students (all CE's) and was the prime mover in the field studies. This general approach also applied to our second project of the nondestructive testing for buried objects, also funded by EPA through John Brugger.

In the later years at Drexel our work together lessened. The last big project of Bob's that I had major input into was the stress cracking project in polyethylene geomembranes (together with Grace Hsuan).

I really enjoyed working with Bob and getting to know his wonderful family and all the neat graduate students who worked for us through the years.

ACKNOWLEDGEMENT

I'd like to dedicate this article to the memory of John Brugger of EPA a dear friend and great supporter of our work. Without you John, we couldn't have got off to such a running, fun start at Drexel.

Dr. John E. Brugger - U.S. EPA
(1923 - 1992)

REFERENCES

(1) R. M. Koerner and A. E. Lord, Jr., “Acoustic Emissions in Medium Plasticity Clayey Silt,” Proc. ASCE J. Soil Mech. and Found. Div. 98, 161-165, 1972.

(2) EPA - Spill Alert Device for Impounded Hazardous Materials, to R. M. Koerner and A. E. Lord, Jr. with Drexel University, $100,000 for one year, 1972.

(3) A. E. Lord, Jr. and R. M. Koerner, “Acoustic Emission Response of Dry Soils,” J. Test. and Eval. 2, 159-162, 1974.

(4) R. M. Koerner and A. E. Lord, Jr., “Acoustic Emissions in Stressed Soil Samples,” J. Acoust. Soc. Am. 56, 1924-1927, 1974.

(5) A. E. Lord, Jr. and R. M. Koerner, “Acoustic Emissions in Soils and Their Use in Assessing Earth Dam Stability,” J. Acoust. Soc. Am. 57, 516-619, 1975.

(6) R. M. Koerner and A. E. Lord, Jr., “Earth Dam Warning System to Prevent Hazardous Material Spills,” Proc. Conf. on Control of Hazardous Material Spills, AICh.Eng and US EPA, August 15-28, 1974, San Francisco, CA.

(7) A. E. Lord, Jr., C. L. Fisk and R. M. Koerner, “Utilization of Steel Roads as AE Waveguides,” Jnl. of Geotech. Eng. Div., ASCE U108, 300-305, 1982.

(8) R. M. Koerner, A. E. Lord, Jr. and W. M. McCabe, “Acoustic Emission Monitoring in Concrete and Foundation Soils,” Proc. of Conf. on Analysis and Design of Foundations for Tall Buildings, Lehigh Univ., PA, August 4-8, 1975, pp. 637-653, ed. by H. Y. Fang.

(9) A. E. Lord, Jr., R. M. Koerner and J. W. Curran, “Fundamental Studies of Acoustic Emission in Soils,” Proc. of First Conf. on Acoustic Emission/Microseismic Activity Geological Structures and Materials, Penn State Univ., University Park, PA, June 9-11, 1975, pp. 135-148, ed. by H. R. Hardy, Jr.

(10) R. M. Koerner, A. E. Lord, Jr. and W. M. McCabe, “Acoustic Emission Studies in Soil Masses in the Laboratory and Field,” Proc. of First Conf. on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, Penn State Univ., University Park, PA, June 9-11, 1975, pp. 244-256, ed. by H. R. Hardy, Jr.

(11) A. E. Lord, Jr., R. M. Koerner and W. M. McCabe, “Acoustic Emission Behavior of Sand as Used in Foundation Bearing Capacity,” Proc. of National Fall Conf. of Am. Soc. Nondestr. Testing, Oct. 13-16, 1975, pp. 103-108.

(12) A. E. Lord, Jr., J. W. Curran and R. M. Koerner, “New Transducer System for Determining Dynamic Mechanical Properties and Attenuation in Soil,” J. Acoust. Soc. Am. 60, 517-520, 1976.

(13) R. M. Koerner, A. E. Lord, Jr. and W. M. McCabe, “Acoustic Emission Behavior of Cohesive Soils,” Proc. ASCE, Jnl. of Geotech. Eng. 103, 837-850, 1977.

(14) A. E. Lord, Jr. and R. M. Koerner, “Acoustic Emission in Geological Materials,” J. Acoust. Emission 2, 195-219, 1983.

(15) R. M. Koerner, A. E. Lord, Jr. and W. M. McCabe, “Acoustic Emission Monitoring of Soil Stability,” Proc. ASCE, Geotech Eng. Div. 104, 571-582, 1978.

(16) R. M. Koerner, A. E. Lord, Jr., “Acoustic Emission (Microseismic) Monitoring of Earth Dams,” Proc. Conf. on Evaluation of Dam Safety, Pacific Grove, CA, Nov. 28-Dec. 3, 1976, 274-291.

(17) A. E. Lord, Jr. and R. M. Koerner, “Estimated Magnitude of Acoustic Emissions in Soil,” Proc. ASCE, Geotech Eng. Div. 105, 1249-1253 (1979).

(18) R. M. Koerner, A. E. Lord, Jr., G. M. Boyce and W. M. McCabe, “Acoustic Determination of Stress History in Soil and Rock,” Proc. of Conf. on Updating Subsurface Sampling of Soils and Rocks and Their In-Situ Testing, Miramar Hotel, Santa Barbara, California, Jan. 3-8, 1982, ed. by S. K. Saxena, Engineering Foundation, pp. 199-211.

(19) R. M. Koerner, A. E. Lord, Jr. and W. L. Deutsch, “Acoustic Emission Detection of Stress History in Granular Soils in the Laboratory,” ASCE, Jnl. of Geotech. Engin. 110, 346-358, 1982.

(20) A E. Lord, Jr. and R. M. Koerner, “An Acoustic Pressuremeter to Determine In-Situ Soil Properties,” J. Acoust. Emission , 2, 187-190, 1983.

(21) R. M. Koerner, A. E. Lord, Jr. and W. L. Deutsch, “Determination of Prestress in Cohesive Soils Using AE,” Proc. Jnl. of Geotech. Engin., 110, 1537-1548, 1983.

(22) J. J. McElroy, R. M. Koerner and A. E. Lord, Jr., “An Acoustic Jack to Assess In-Situ Rock Behavior,” Intl. J. Rock Mech. Min. Sci., 22, 21-29 (1985).

(23) W. L. Deutsch, R. M. Koerner and A. E. Lord, “Determination of Prestress in In-Situ Soils Using Acoustic Emissions,” Proc. Jnl. Geotech. Engin., 115, 228-245 (1989).

(24) R. M. Koerner and A. E. Lord, Jr., “Recent Field Advances Using Acoustic Emission,” Proc. 11th Intl. Conf. on Soil Mech. and Found. Eng., San Francisco 12-16 August 1985, pp. 875-878.