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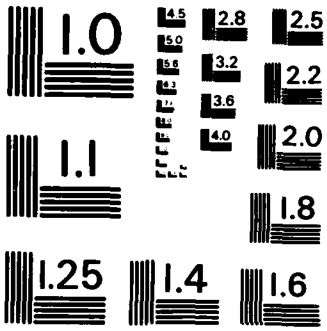

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IN-SITU STRESS DETERMINATION IN SOIL AND ROCK USING THE ACOUSTIC EMISSION METHOD

FINAL REPORT

BY

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SEPTEMBER 21, 1984

U. S. ARMY RESEARCH OFFICE

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The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Soil, Rock, Varied Soil Types, Varied Rock Types, Kaiser Effect, Acoustic Pressuremeter, Acoustic Rock Jack, Acoustic Emission, Stress History Preconsolidation, Horizontal (Lateral) Prestress, Existing Stress State, Residual Stress, Lab Testing, Field Testing, Oedometer, Bore Holes, Goodman (OVER)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A project was undertaken to determine how well acoustic emission (AE) techniques could be used to determine the existing stress state in rock and soil masses. It was found in rock that the Kaiser Effect (No AE until previous stress level exceeded) was obeyed for short times (delay times) after stress application, but was not obeyed for delay times longer than about 100-1000 hours. In soil, the Kaiser effect was obeyed, but the effect of delay times was not investigated. These results apply to a very wide variety of rock and soil types. (OVER)

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19. (cont'd)

Rock Jack, Menard Pressuremeter.

20. (cont'd)

A Goodman rock jack was retrofitted with an AE transducer assembly and field tested in large discrete rock masses at a rock quarry and in bore holes in six different sites with varying rock types. This "acoustic-rock jack" functioned very well above and below the water table. The existing horizontal stresses, predicted from breaks in the AE versus applied stress curves, were of the same order (on the higher end) as those determined by more conventional methods of determining the existing stress state.

A Menard pressuremeter was retrofitted with an AE transducer assembly, and used in bore holes in the field in various soil types. Preliminary field work has shown this "acoustic pressuremeter" to work well to depths of 10 feet (only used above the water table so far). The existing horizontal (lateral) stresses predicted from the AE pressurementer results were in the higher portion of the expected values.

Statement of Problem

Knowledge of existing stresses in a rock or soil mass is very important from both a scientific and technical viewpoint. For design purposes, it is most important that the engineer knows the existing state of stresses in the material so that a structure will be neither over nor under designed. There are many field methods which attempt to determine the existing stress state in a rock or soil mass. However they all suffer from the fact that there is no independent method to assess the validity of the results obtained. Also many of these are quite time consuming and expensive, and thus are only used when designing very critical structures. It would certainly be an advantage to have available a reliable and low cost method which could be used in more general design situations.

To this end, the authors have performed work over the past two and one-half years developing an "acoustic rock jack" for use in rock and an "acoustic pressuremeter" for use in soil. In both cases an acoustic emission (AE) transducer assembly was retrofitted on, and used together with, more "standard" subsurface mechanical testing devices to determine the stress state. The work entailed pertinent laboratory experiments, instrumentation development, and ultimately field deployment. The work will be summarized in the next section of the report.

Results

The details of our work are presented in six publications in refereed journals and two Ph.D. theses. All six journal articles have either been published or have been accepted for publication. As of this writing one Ph.D. thesis has been successfully defended and the other is anticipated to be completed by June, 1985. Therefore, this final report shall only present a brief summary of what are considered the major results. Further details can be found in the appropriate journal articles or theses which are cited at the end of this report.

The project was divided into four segments - rock and soil, with a laboratory and field phase for each material. One graduate student was responsible for the rock phase and another graduate student responsible for the soil phase. Doctors Koerner and Lord were involved with guidance and advice during both phases.

Laboratory Testing of Rock (7)

This phase involved six different rock types (two schists, shale, marble, limestone, granite) being tested in unconfined compression and double punch tension to evaluate the existence of the "Kaiser Effect." This well established concept in metals is defined as "the absence of detectable acoustic emission until previously applied stress levels are exceeded" (ASTM E610-77). Delay times between loads were 0.01, 0.1, 1, 10, 100, 1000 and 10,000 hours, thus requiring at least 6 specimens of each rock type. Each rock type was stressed at 1/4, 1/2, 3/4 and full ratios of its standard unconfined compression strength. Although the results depended somewhat on the rock type and stress level employed, the bottom line is that the Kaiser effect is not obtained at the longer delay times (say after 1000 hours). In terms of a felicity ratio $\left(= \frac{\text{stress at which AE occurs}}{\text{previous maximum stress}}\right)$, the value drops from 1 at short delay times to as low as 0.25 at 10,000 hours. Thus it appears the "effective" residual stress (which must be exceeded to get deformation) which "locks-in" the structures, relaxes with time (of the order of a thousand hours) and allows a very low felicity ratio.

Field Testing of Rock (3,7)

This work involved both a quarry phase and a field phase. In the quarry phase (3) an existing hole cored for blasting in a large piece of rock (~5 feet in dimensions) was stressed with the acoustic rock jack and applied stress (σ), deformation (ε) and AE were concurrently measured. The Kaiser effect (for very short delay times) was observed. Also on the first application of stress, breaks in the AE vs. σ response indicated a possible existing residual stress (parallel to the load direction) in the range 500-2000 psi. These are in the range of existing stresses determined by other methods in similar rocks although a bit on the high side.

In the field borehole phase (7) boreholes were drilled (in six rock types at different sites in the Delaware Valley area) and the acoustic rock jack lowered in (to depths of 10 feet) and σ, ε and AE data taken. There were breaks in most of the AE vs σ curves indicating existing stresses again in the 500-2000 psi range. The acoustic rock jack worked well above and below the water table.

In neither the quarry or field phase were there any consistent breaks in the ε vs σ curves, most often they were relatively straight lines. Thus AE appears to be a much more sensitive indicator than ε to detect any structural changes taking place in the rock mass.

Laboratory Testing of Soil (2,5)

A standard soil oedometer was retrofitted for AE detection. The soil sample (remolded) was placed in the specimen container and stressed to known values. The stress was then released and AE and deformation monitoring was performed to see if the prior load could be detected and to what accuracy. A wide variety of granular and cohesive soils were investigated over a large range of moisture contents. For all soils, the prestress was predicted to at least ±10%, and in most cases to ±5%. Deformation and AE monitoring produced about the same degree of accuracy in prestress prediction. The effect of delay time was not investigated here, as it was for rock. Thus for essentially zero delay times, the Kaiser effect is always observed in soils.

Field Testing of Soils (8)

A Menard pressuremeter (a downwhole expanding rubber probe where pressure versus volume information of the deforming soil can be obtained) was retrofitted with an AE transducer assembly. The system was first successfully tried in a large tank of soil in the laboratory, followed by field work within soil borings. The acoustic pressuremeter performed well in the field. The work, at this point, has not progressed as far as the acoustic rock jack field work, but very promising results have come from the first three test sites where work has been performed. Figure 1 (Curve #1) shows the results of AE during the first pressurization of the acoustic pressuremeter in a borehole. A break occurs in the % AE (of total AE during test) versus pressure at about 1.7 TSF. Assuming this value to be the lateral prestress in the

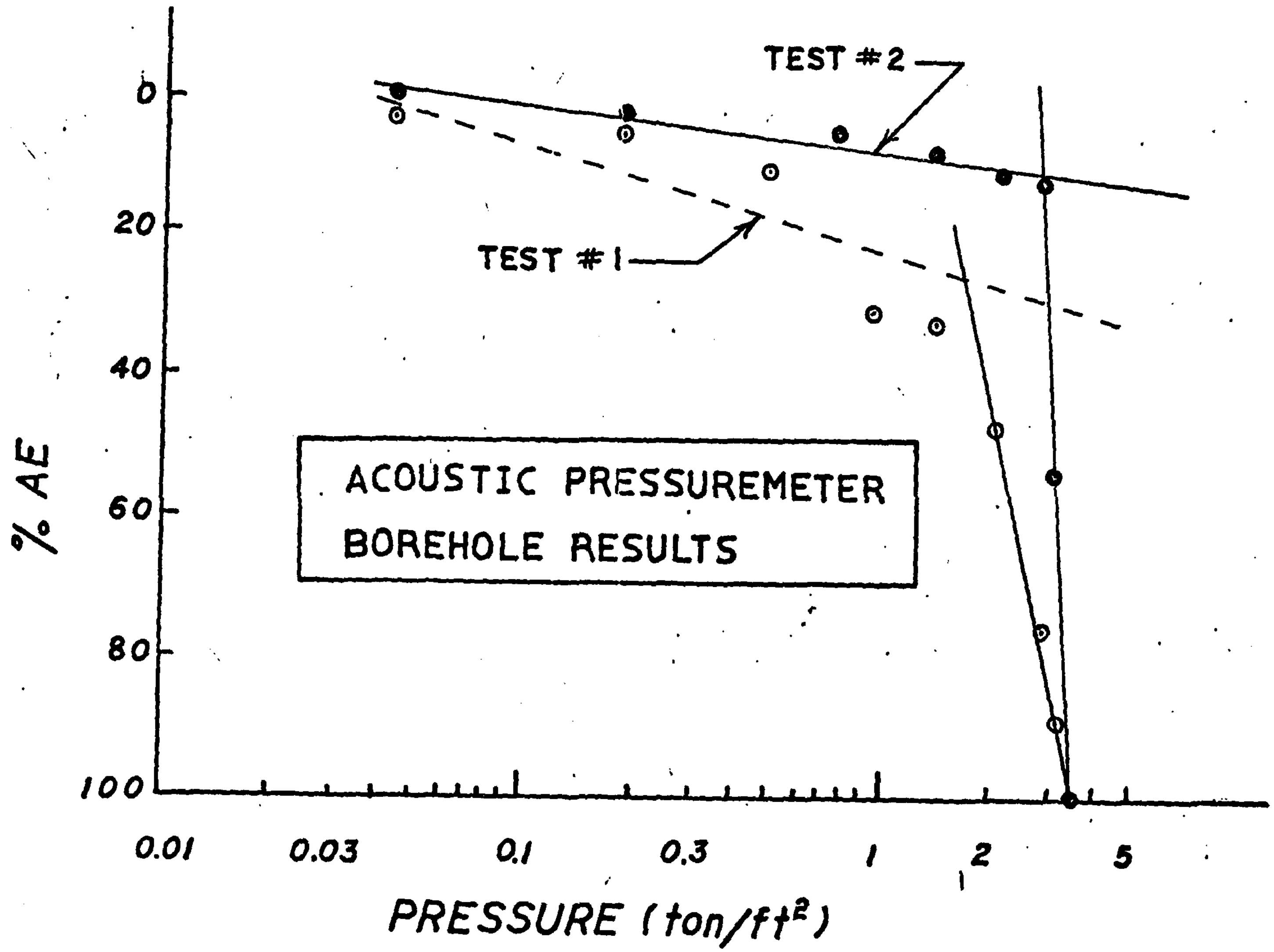

Figure 1 - Results of Acoustic Pressuremeter Tests in Boreholes. Test #1 - First Pressurization of Pressuremeter in Boreholes; Test #2 - Second Pressurization of Different Borehole after First Pressurization to 2.52 TSF

soil, a nearby hole was pressurized (prestressed) to a value higher than this, namely 2.52 TSF. The pressuremeter was unloaded and then AE vs pressure data was taken to see if this "prestress" could be picked up with AE. Figure 1 (Curve #2) shows the results of AE versus stress obtained during this second pressurization. Indeed a break in the curve of AE versus stress occurs at about 2.65 TSF, which is very close to the "known prestress" of 2.52 TSF. It thus appears that an effective Kaiser effect applies to pressuremeter operation. The "raw" pressuremeter data (i.e., pressure vs volume change) do not show these breaks. These acoustic pressuremeter data however should be considered quite preliminary.

Conclusions Reached

The following conclusions were reached as a result of the work performed in the project. Regarding the rock phase of the project:

- The Kaiser effect is not obtained in most rock types for delay times (time after application of stress) larger than about 1000 hours. This applies to both compression and tension loading and for stress values of 25, 50, 75 and 100% of yield stress.

- The Kaiser effect is observed in large rock masses in the field at least for very short delay times.

- A rock jack can be retrofitted with an AE transducer assembly and made to operate both above and below the water table.

- Use of the acoustic rock jack in the field yielded breaks in the curve of AE vs σ which could strongly indicate lateral prestress in the range of 400-2000 psi. These values, although a bit high, are not unrealistic for rock masses in the area.

- The use of the acoustic rock jack for the measurement of lateral prestress is relatively inexpensive compared to presently used methods. It is also much quicker and needs less manpower to operate. The only preparation needed is a good borehole.

Regarding the soil phase of the project:

- The Kaiser effect is well obeyed, for very short delay times, for all types of soil. Prestress can be determined easily to ±10% and generally to ±5%.

- A Menard pressuremeter has been retrofitted with an AE transducer assembly and used successfully in field boreholes above the water table.

- Breaks in the curves of AE vs σ occur in the preliminary borehole data available (as of this writing). The lateral prestresses predicted from these breaks are somewhat high but not completely unreasonable.

<u>List of Publications Generated During the Project</u>

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

2. A. E. Lord, Jr. and R. M. Koerner, "Acoustic Emissions in Geological Materials," J. Acoustic Emission, 2, 195-219 (1983).

3. 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. Geotech. Engin., 110, 346-358 (1984).

4. R. M. Koerner, A. E. Lord, Jr. and W. L. Deutsch, "Acoustic Emission Determination of Preconsolidation in Cohesive Soils in the Laboratory," ASCE J. Geotech. Engineering (accepted for publication).

5. J. J. McElroy, Jr., R. M. Koerner and A. E. Lord, Jr., "An Acoustic Rock Jack to Determine In-Situ Rock Prestress," Intern J. Rock Mechanics, Mining Science and Geomechanics Abstracts (accepted for publication).

6. R. M. Koerner and A. E. Lord, Jr., "Recent Advances in Field Measurements using Acoustic Emission Methods," <u>Proc. 11th International Conf. on Soil Mech. and Found. Eng.</u>, San Francisco, Aug. 12-16, 1985 (accepted for publication)

7. John J. McElroy, "The Determination of In-Situ Stresses in Rock via Acoustic Emission Measurements," Ph.D. Thesis, Civil Engineering Dept., Drexel University, Sept. 1984.

8. William L. Deutsch, Jr., "The Determination of Prestress in Soils via Acoustic Emission Measurements," Ph.D. Degree Candidate, Civil Engineering Dept., Drexel University.

List of Personnel Involved in the Project
(all from Drexel University)

Dr. Robert M. Koerner, Professor of Civil Engineering

Dr. Arthur E. Lord, Jr., Professor of Physics

Mr. (now Dr.) John J. McElroy, Graduate Student, Civil Engineering Dept. - Ph.D. Sept. '84

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Sincerely,

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