

# Piezoelectric Gages for Dynamic Soil Stress Measurement

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A study was made of the suitability of piezoelectric gages for the measurement of dynamic stresses in soil. A number of variations of thickness-diameter ratio was investigated, as well as several simple methods of sensor encasement. The gages were tested statically and dynamically under fluid pressure and embedded in both confined and constrained specimens of sand.

The disk-shaped piezoelectric sensor from which the gages were constructed was found to have high electrical sensitivity, high stiffness, and to be suitable for miniaturization. It is, however, sensitive to moisture, electromagnetic radiation, temperature, and distortions produced by shearing stresses, bending moments and lateral pressures.

Measurements made with the gages embedded in sand showed that (a) the static and dynamic gage sensitivities are the same; (b) the gage response is influenced by soil density, confining pressure and placement techniques; and (c) the gage output is a nonlinear function of applied stress when the soil stress-strain relationship becomes appreciably nonlinear. It was clear from the study that an elaborate stress gage design is required to isolate the sensing element from all undesirable influences. A more refined gage is currently under development.

•THE MEASUREMENT of stress in soil has long been recognized as a difficult experimental problem. All of the important gage concepts that have been devised and used in the past for measuring stress have involved a transducer whose signal is related to the gage stiffness. The gage functions by using its "built-in" stiffness to resist soil pressure. It is the reaction of the gage to this pressure that is measured, whether the reaction is in the form of a diaphragm deflection, the force required to prevent deflection, or distortion of a crystal as in the case of piezoelectric ceramics. Because the stress-strain characteristics of a particular soil are neither linear nor unique, it is not possible to devise a gage in which the ratio of soil stiffness to gage stiffness can be held constant. Hence, the gage output will not, in general, be a constant function of the soil stress. This is an inherent difficulty in measuring stress in soil.

This paper reports on the results of an investigation of the problem involved in measuring dynamic stresses in soil with miniature gages suitable for embedment in small soil specimens. Ordinary gages are unsuitable for this application because they either are too large, do not have the required shape, or have inadequate high-frequency response. Furthermore, the accuracy of stress measurement with most of these gages has not been clearly established.

## PREVIOUS WORK

Considerable attention has been given to the measurement of stresses in soil. The most important conclusions derived from these studies are:

1. Gages respond differently in different soils.
2. Since the soil stiffness cannot generally be matched by the gage, its stiffness should be high compared to that of the soil.
3. A thickness-diameter ratio of  $\frac{1}{10}$  or less is desired because the gage error increases as this ratio increases.
4. Gage placement techniques exert a considerable influence on the accuracy of stress measurements.
5. Accuracies of measurement to within  $\pm 5$  percent have been reported, but these appear to have been based upon indirect rather than direct comparison with known stresses.
6. A gage registers stresses higher than those actually existing if its stiffness exceeds that of the soil. This overregistration increases with the ratio of gage stiffness to soil stiffness but apparently reaches a maximum as this ratio becomes very large.
7. The overregistration increases with the ratio of sensitive area to total gage cross-sectional area because of stress concentrations on the perimeter of the gage.
8. In general, all the problems of stress measurement arise because stress gages have stress-strain characteristics different from those of the soil.

## GENERAL DESCRIPTION OF GAGES

The gages considered in this study utilized piezoelectric ceramic transducers as sensing elements with a number of variations in the thickness-to-diameter ratio and methods of encasing the gage. The use of a piezoelectric sensing element is not new, but previous piezoelectric gages (7, 13) were not suitable for this application.

The advantages of the piezoelectric transducer are (a) its short response time (microseconds) that makes it especially suitable for shock-type loading, (b) the small crystal size possible, (c) high electrical sensitivity and (d) high stiffness (about the same as aluminum for the gages used in this study). But aside from the inherent difficulties of stress measurement with any type of gage, the use of these transducers introduced other experimental problems. These are, principally, extreme sensitivity to electromagnetic radiation, temperature, and moisture. The piezoelectric ceramics are also sensitive to any impressed distortions resulting from the way in which the stress from the soil is applied to the gage. They are, therefore, sensitive to mounting and method of placement and to the manner in which the sensing element is isolated from the soil. For example, shearing stresses on the face of the transducer, as well as bending moments, produce appreciable signals. The piezoelectric transducer acts as an electrical charge generating device. Because of the resistance-capacitance characteristic of the electrical circuitry (Fig. 1), extremely high circuit resistance is required to measure stresses of greater than a few seconds duration. This required resistance is difficult to obtain.

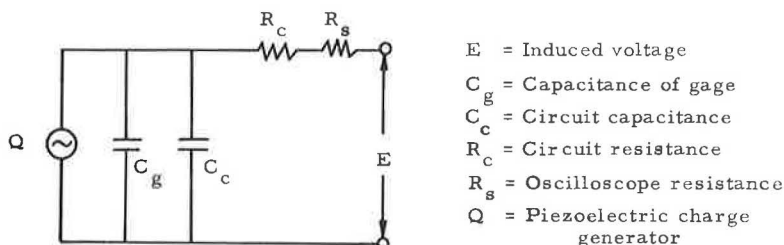


Figure 1. Schematic of piezoelectric circuit.

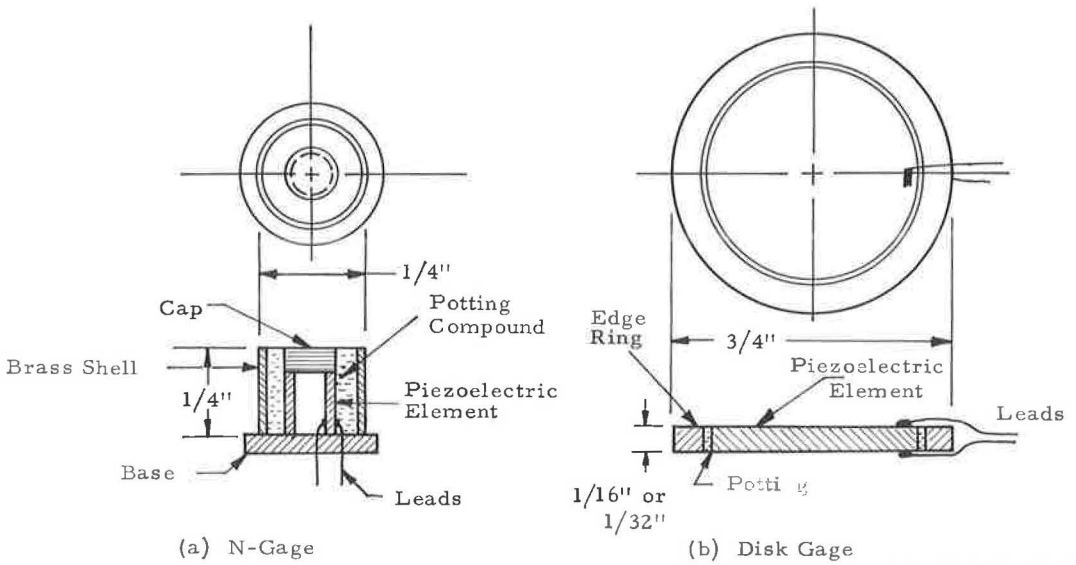


Figure 2. Stress gage configurations.

The gages studied had thickness-diameter,  $T/D$ , ratios varying from 1.0 to 0.08 with a maximum gage diameter of 1.0 in. The two basic configurations investigated are shown in Figure 2. Figure 2a shows a cylinder of barium titanate mounted in a small metal cup. This N-gage was designed and constructed by Nagumo of the IIT Research Institute for use in measuring air shock pressures. The other gages, constructed from disk-shaped piezoelectric elements (Fig. 2b), made with and without a metal edge ring to isolate the element from the effects of lateral pressure and with and without a teflon face covering to isolate the effects of friction on the face of the gage. In some cases the unmounted ceramic crystals were coated with moistureproof materials, such as epoxy.

## APPARATUS

Several types of tests were used in the gage evaluation: (a) triaxial, or constrained static and dynamic tests; (b) consolidation or confined compression tests; and (c) hydrostatic pressure tests. The soil used was 20 to 40 mesh air-dry Ottawa sand.

The dynamic triaxial tests were performed with a specially designed double pendulum apparatus (Fig. 3). The specimen was horizontally mounted on one pendulum and impacted by a second pendulum. The sand specimens used with this apparatus were 4 in. long and 3 in. in diameter and were enclosed in thin rubber membranes. Stress gages were embedded at several positions within each specimen. The confining pressure was controlled by applying the proper vacuum to the pores through an opening in the reaction pendulum. Initial specimen density was determined by the method of preparation.

The pendulums were constructed of 8-in. long, 3-in. diameter solid steel bars weighing approximately 17 lb each. An accelerometer was mounted on the outside end of each pendulum. In operation, the pendulums were first lined up at the bottom of their swing with the specimen between them. The impact pendulum was pulled back to a predetermined height and then released to impact the specimen. A switch was contacted just prior to impact to trigger the oscilloscopes that recorded the signals from the accelerometers and the embedded stress gages. The accelerations of the two pendulums were recorded throughout the duration of impact. Since the masses of the pendulums were accurately known, the average stress over the ends of the specimen

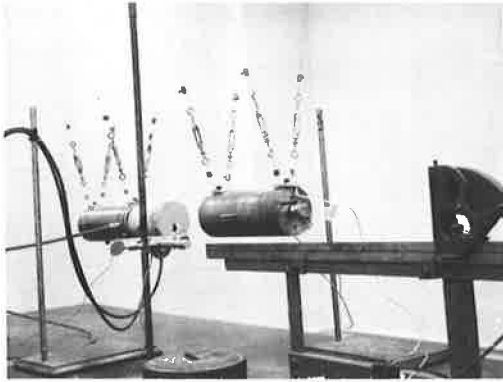


Figure 3. Pendulum apparatus.

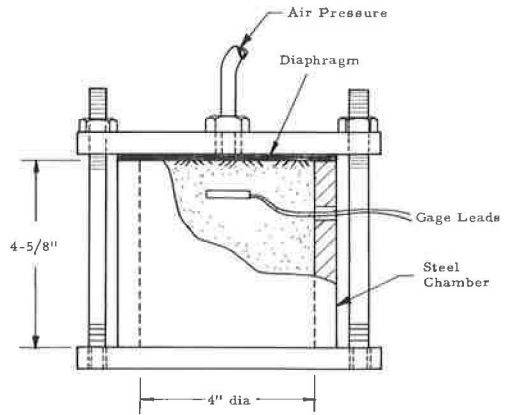


Figure 4. Schematic of confined compression device for gage calibration.

could be computed from the product of the pendulum mass per unit cross-sectional area and its acceleration. The fact that the stress cannot be assumed to be truly uniform over the cross-section is a limitation of this method of calibration.

The confined compression device (Fig. 4) consists of a rigid steel chamber 4 in. in diameter and  $4\frac{5}{8}$  in. deep covered with a rubber diaphragm and a rigid cap. The gage was embedded approximately 1 in. from the top of the sand surface to minimize wall friction effects and the surface was loaded by applying air pressure through the diaphragm.

For the hydrostatic pressure tests the gage was placed in a closed chamber and pressure was applied and released at controlled rates using either air or water. In this apparatus the pressure could be prevented from acting on the edges of the gages.

### CALIBRATION OF N-GAGES

The calibration of the N-gages obtained with air pressure was usually quite linear (Fig. 5), but they were not entirely reproducible. Successive calibrations usually varied less than 5 percent, but over a period of time random variations averaging 13 percent were observed. Perhaps 5 percent of these variations could have derived from the recording system.

Typical records with the pendulum apparatus are shown in Figure 6. The traces are approximately of the general shape expected, but they exhibit a roughness, apparently due to the movement of individual grains of sand. This might be expected because the diameter of the sensing element was only about 6 times the average grain diameter of the sand.

The gages were placed in both the center of the pendulum specimen and approximately  $\frac{1}{2}$  in. from the impact end. The initial specimen density and the confining pressure were varied and records were obtained using the maximum gage output voltage and the average maximum stress at the ends of the specimen during impact.

Calibration results for low, high and medium density specimens are given in Figures 7, 8 and 9, respectively. The impact sequence and corresponding impact velocity,  $v_0$ , and confining pressures,  $\sigma_3$ , are indicated. The following conclusions were drawn from these results:

1. The sensitivity (defined as ratio of gage output to applied stress) increased significantly with repeated impacts at the same  $v_0$  and  $\sigma_3$  (see impacts 3, 4, 5, Figs. 7 and 8; and impacts 1, 2, 3, 4, Fig. 9). This effect cannot be explained on the basis of specimen density, but it could have been caused by placement or rearrangement of the sand particles around the gage to form a more stable configuration.

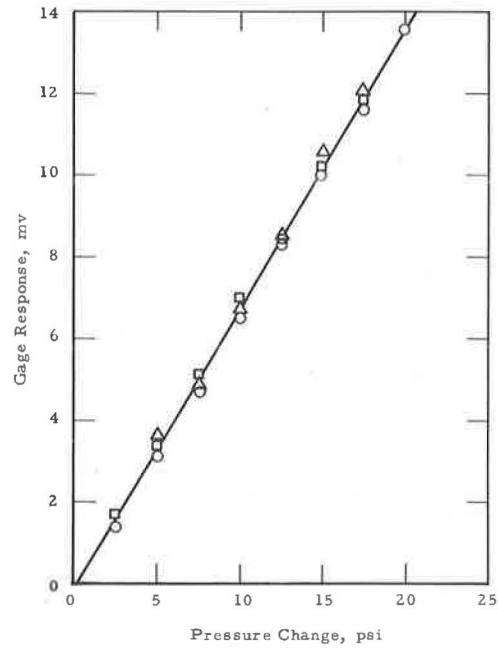


Figure 5. Air calibration results for gage N-11.

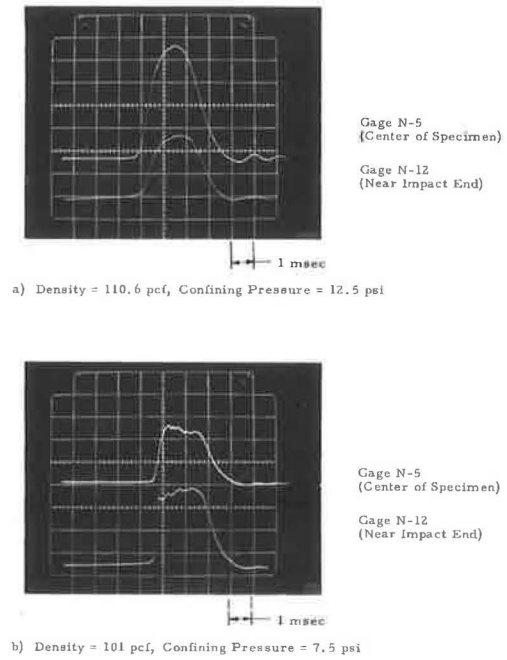


Figure 6. Typical embedded N-gage stress records.

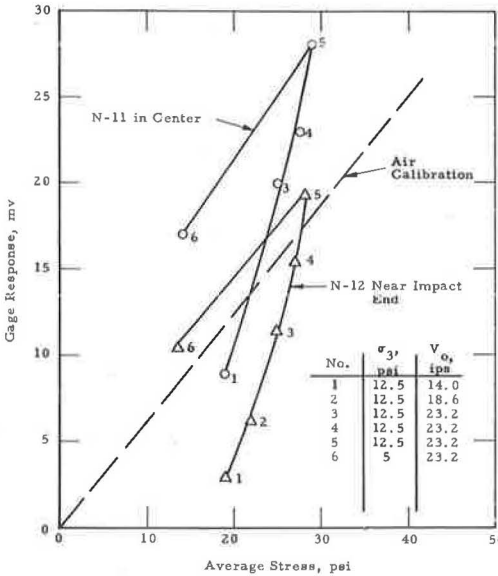


Figure 7. Embedded calibration of N-gages in low density specimen ( $\gamma_0 = 101.5$  pcf).

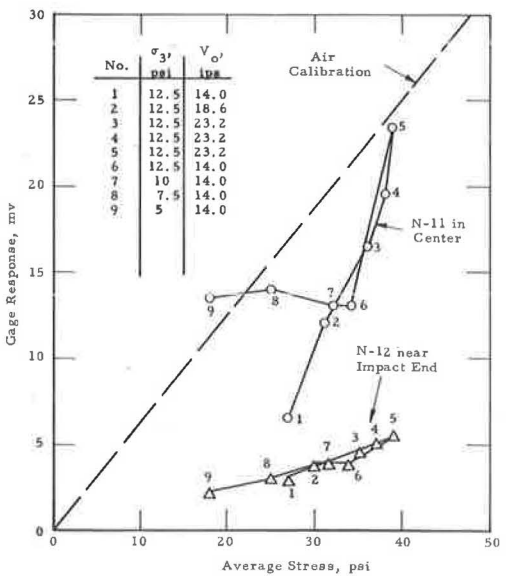


Figure 8. Embedded calibration of N-gages in high density specimen ( $\gamma_0 = 111.0$  pcf).

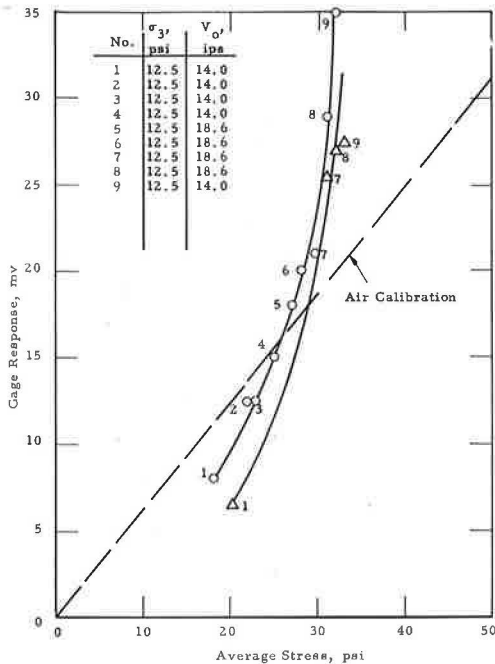


Figure 9. Embedded calibrations of N-12 in center of medium density specimen ( $V_o = 103.6$  pcf) showing reproducibility.

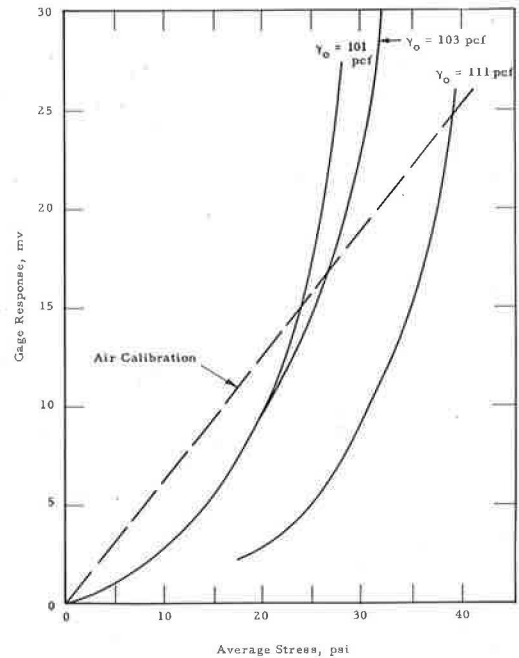


Figure 10. Effect of density on embedded calibration of N-gage in center of specimen at 12.5 psi confining pressure.

2. The sensitivity increased significantly with a decrease in confining pressure (see impacts 6, 7, 8, 9, Fig. 8). This could be predicted because the stiffness of the specimen decreases with a decrease in  $\sigma_3$ . Because the effect of successive impact also is included, it is not possible to say which is the greater effect.

3. Both N-11 and N-12 have similar embedded calibration curves; however, the output of the gage in the center of the specimen is much greater than that near the impact end. Because both gages have approximately equal sensitivities in air, the presence of the rigid boundary at the end may prevent arching over one side of the gage. The difference in output of the gages in the two positions was much greater for the high density than for the low density specimen.

4. The sensitivity of both gages for the first few impacts was less than that for a corresponding air pressure, i.e., underregistration occurred. For a gage in which the over-all stiffness is greater than that of the specimen, this behavior would not be expected. It appears that, although the gage case acts as a stiff unit and picks up load from the soil, because of the way the sensing element is mounted in the case the soil stress arches across the sensing element. Under successive impact this arch breaks down through rearrangement of the sand, thus increasing the gage signal.

5. For the first several impacts, the trace of the gage in the center of the specimen returned to a point above the initial zero, indicating a residual compressive stress. For the last several impacts, the trace ended below its original zero, indicating a tension, relative to  $\sigma_3$ . This appears to be an interaction phenomenon caused by a difference in soil stiffness between stress increase and decrease.

6. The calibration records with the gage in the center of the specimen for the three densities at a constant confining pressure are compared in Figure 10. The gage sensitivity increased with a decrease in density as would be expected because soil stiffness increases with density.

7. In general, the embedded gage sensitivities did not appear to be unique functions of any of the important variables. The observed behavior probably was greatly influenced by details of the particular gage design, in addition to the shape.

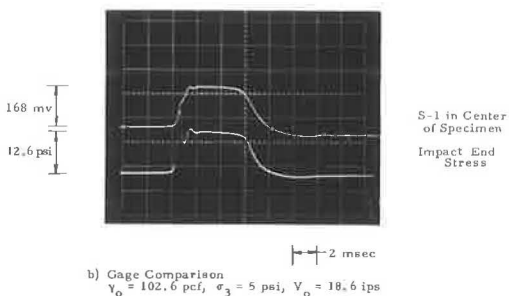
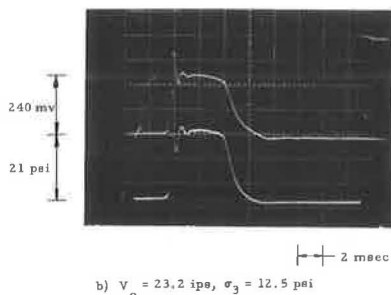
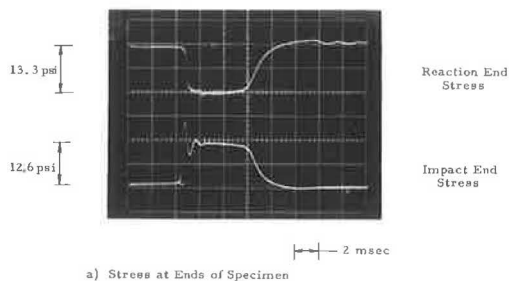
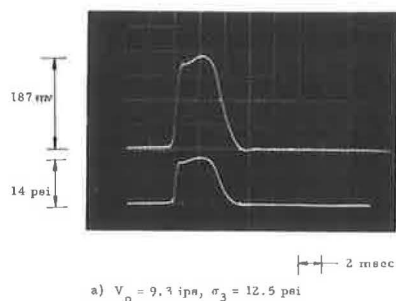


Figure 11. Comparison of embedded disk gage records with applied stress for low density specimen.

Figure 12. Typical records from pendulum tests with disk gage in center of specimen.

### INITIAL STUDIES OF DISK GAGES

To improve stress measurements, disk-shaped gages were considered. The first of these gages were simply piezoelectric disks with silvered surfaces and leads attached, i.e., Figure 2b without the edge ring.

The fluid pressure calibrations showed that the signals generated by the piezoelectric material were significantly affected by method of support or clamping, edge pressures, temperature change, moisture and electromagnetic radiation. Any change in clamping or support conditions affected the distortions under pressure of the ceramic crystal. The gage response was an order of magnitude less with the pressure acting all around the disk than it was with pressure acting only on the faces. For one typical gage the temperature sensitivity was  $4.5 \text{ mv}/^{\circ}\text{F}$  compared to a pressure sensitivity of  $0.5 \text{ mv}/\text{psi}$ . Intrusion of moisture caused a decrease in circuit resistance, thereby decreasing the time constant.

The response of the embedded plain disk gages was also evaluated with the pendulum apparatus. A variety of piezoelectric disks was used, ranging in diameter from  $\frac{1}{2}$  to 1 in. and in T/D ratios from 0.026 to 0.12. Figure 11 compares the specimen impact end stress records with the response records of one of these gages (S-1 with a diameter of 1 in. and T/D ratio of 0.12) placed about  $\frac{1}{2}$  in. from the impact end. The pairs of traces are geometrically identical, therefore, the gage reproduces the shape correctly. Figure 12 compares the response records for the same gage located in the center of the specimen. The shape of the gage record lies between the shapes of the two end stress records.

The calibration curves corresponding to these two gage locations are compared in Figure 13. Both are reasonably linear and indicated the same sensitivity. The



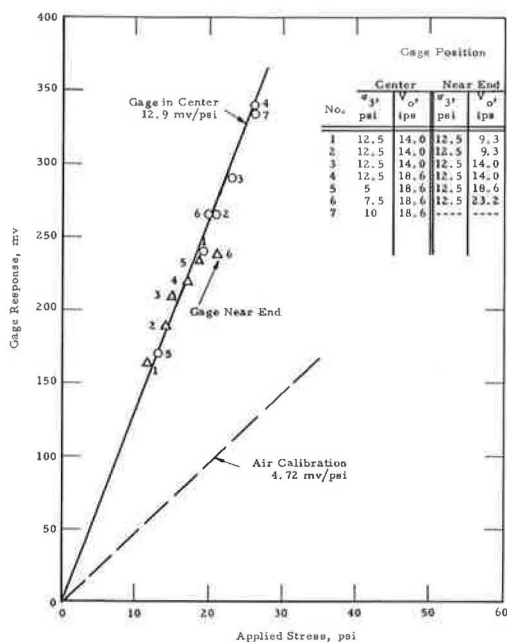


Figure 13. Calibration results for disk gage S-1 in low density specimen ( $\gamma_0 = 102.6$  pcf).

sensitivity was essentially constant for successive impacts. The stress increased at constant  $v_0$  and  $\sigma_3$ , due to a greater deceleration of the pendulum on impacting a stiffer specimen. The sensitivity, however, was about 2.7 times greater than the air calibration value, i.e., overregistration was 170 percent. This high overregistration was largely due to a combination of shearing stress on the face of the gage and reduction of edge pressure resulting from lateral expansion of the soil.

The calibration curves were not always linear and reproducible. The average values varied from test to test and, especially for the high density specimens, the data points were grouped about different values for each  $\sigma_3$  (Fig. 14). The gage trace did not always return to the initial zero (Fig. 12b). There was generally a positive residual stress indicated for the first impact and a negative residual for the fourth impact, which took place after the confining pressure had been reduced from 12.5 to 7.5 psi. These changes in calibration, indicated by arrows in Figure 14, are caused by a change in the specimen stiffness under each loading cycle.

Two sets of gages were used to evaluate the effect of T/D ratio and density on gage response. The gages were all unmounted piezoelectric disks  $\frac{1}{2}$  in. in diameter. One set had a thickness of  $\frac{1}{16}$  in. and the other a thickness of  $\frac{1}{32}$  in.; T/D ratios were 0.125 and 0.062, respectively.

The average variation of the sensitivity of embedded gages in the high density specimens was  $\pm 20$  percent and in the low density specimens was  $\pm 16.4$  percent. The varia-

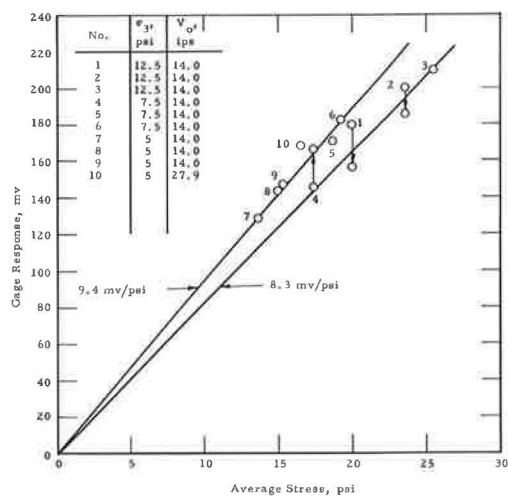


Figure 14. Typical calibration results for disk gage S-21 in high density specimen ( $\gamma_0 = 111.7$  pcf).

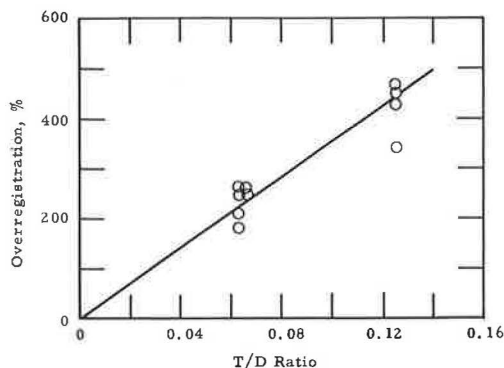


Figure 15. Overregistration of unmounted disk gages for two T/D ratios.



tion for any one particular test may be taken as roughly half this total variation. Two gages showed an increase in sensitivity with increase in density and three showed a decrease. If density were the most significant factor influencing gage response, all gages would show a decrease.

The average overregistration for the two sets of gages (Fig. 15) appears to be directly proportional to the T/D ratio and ranges from 180 percent to 470 percent. As indicated previously, most of this overregistration was caused by friction on the face of the gage and reduction of pressure on the edge of the gage.

### DISK GAGE WITH EDGE RING

The initial studies with the disk gages clearly indicated that the unmounted piezoelectric disks are extremely sensitive to edge pressures. To eliminate this, several gages were ringed with steel, aluminum or plastic with a thin band of rubber latex separating the metal or plastic from the piezoelectric material (Fig. 2).

The embedded calibrations for these gages showed some significant improvements. In general, the trace returned to its initial zero reference; when it did not, the deviation was much less than it had been for the gages without edge rings. The embedded calibration curves were similar in shape for both types of gages (Fig. 14). Gage sensitivities are shown as a function of density in Figure 16. Sensitivity appeared to be independent of density for these gages, but the same variation in average values was found. The metal rings reduced the overregistration by about 100 percent. Part of this reduction may have been due to the decrease in ratio of sensitive area to total face area, but most of it is believed to be attributable to the elimination of edge effects. The plastic rings were not effective, probably because they were not stiff enough to resist the lateral soil pressure.

During the evaluation of the disk gages with edge rings, suitable instrumentation (Kistler Charge Amplifier Model 566, Kistler Instrument Co., N. Tonowanda, N. Y.) became available to permit static measurements with the piezoelectric materials. This capability made possible a more detailed and critical examination of the embedded gage response. A series of static and dynamic tests were performed using gages  $\frac{1}{16}$  in. thick with steel edge rings.

Triaxial soil specimens were used for the first embedded static tests. The specimens were prepared on the reaction pendulum as for the dynamic tests. Load was applied to the specimen with a standard unconfined compression machine. Following the static loading cycle the reaction pendulum was mounted and a series of dynamic tests was performed for comparison.

Typical calibration curves are shown in Figures 17 and 18. In the lower stress range where the stress-strain characteristics of the soil were linear, the gage response was approximately linear. As the soil stiffness decreased under greater stress, the gage sensitivity increased. This increase was observed in some cases to be as much as 100 percent as the failure stresses were approached. The unloading portion of the calibration curves was usually linear or bent slightly downward and, except when the maximum stresses were much lower than failure, there was considerable hysteresis.

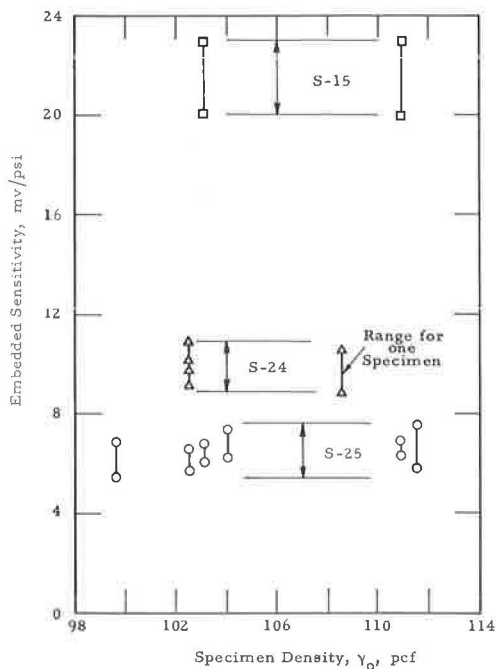


Figure 16. Embedded calibration of disk gages with edge ring as a function of density.

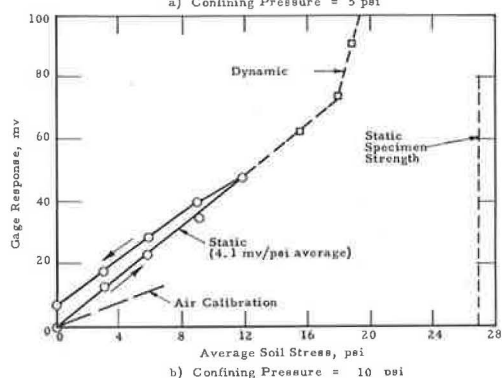
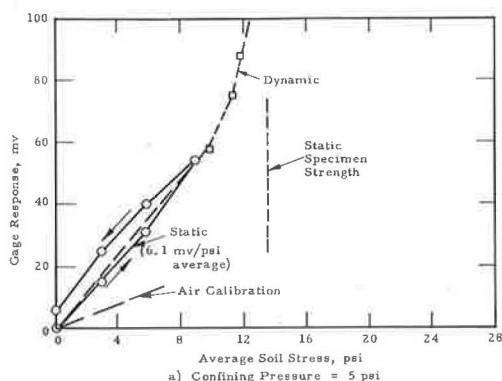


Figure 17. Typical triaxial calibration curves for disk gages with edge ring (maximum stress = below specimen strength,  $\gamma_0 = 108$  pcf).

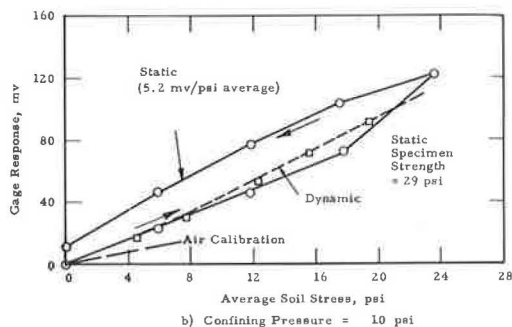
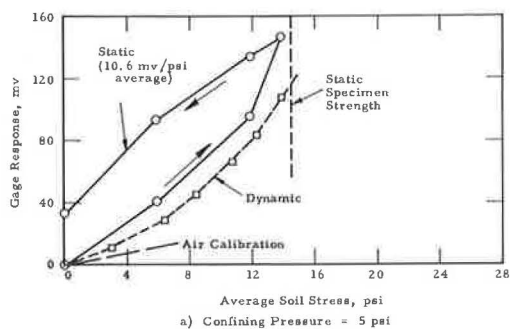


Figure 18. Typical triaxial calibration curves for disk gages with edge ring (maximum stress = specimen strength,  $\gamma_0 = 110$  pcf).

The overregistration for the initial linear portion averaged 100 percent. Some residual charge usually remained after the load was completely removed. This phenomenon was caused partly by electronic drift and partly by soil-gage interaction.

The curves for the dynamic stress coincided approximately with the load portion of the curves for the static tests. Thus, the static and dynamic sensitivities were approximately the same.

A number of the disk gages was embedded in the 3 in. diameter triaxial specimens that were subjected to a series of repeated loadings at stress levels equal to about 50 percent of the specimen strengths. The variation under the repeated load for each placement averaged 20 percent. The variation for four placements of seven gages ranged from 32 to 108 percent and averaged 73 percent ( $\pm 36$  percent). When the results were separated on the basis of confining pressure the range reduced to  $\pm 26$  percent.

#### DISK GAGE WITH EDGE RING AND TEFLON COVER

Some overregistration was caused by shearing stresses on the face of the gage associated with lateral expansion of the soil specimen. To evaluate this effect, thinflexible teflon sheets were placed over the face of each gage and separated from the gage by a thin coating of silicone grease. Typical results from a series of static and dynamic tests performed with these gages in triaxial specimens of sand are shown in Figure 19.

In general, the amount of hysteresis was less with the teflon cover, and the residual charge did not remain after the soil was unloaded. The static and dynamic results were

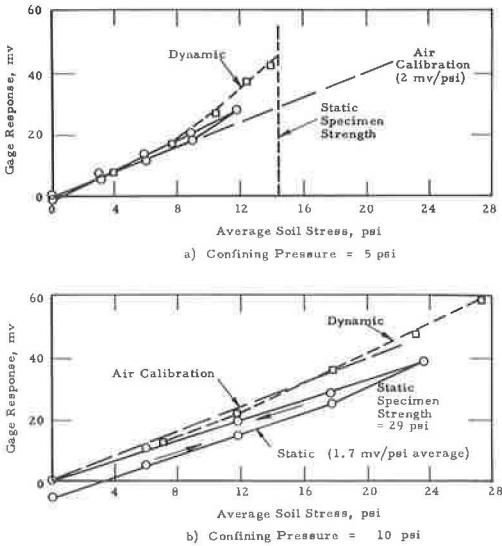


Figure 19. Typical triaxial calibration curves for disk gages with edge ring and teflon cover (maximum stress = specimen strength,  $\gamma_0 = 110$  pcf).

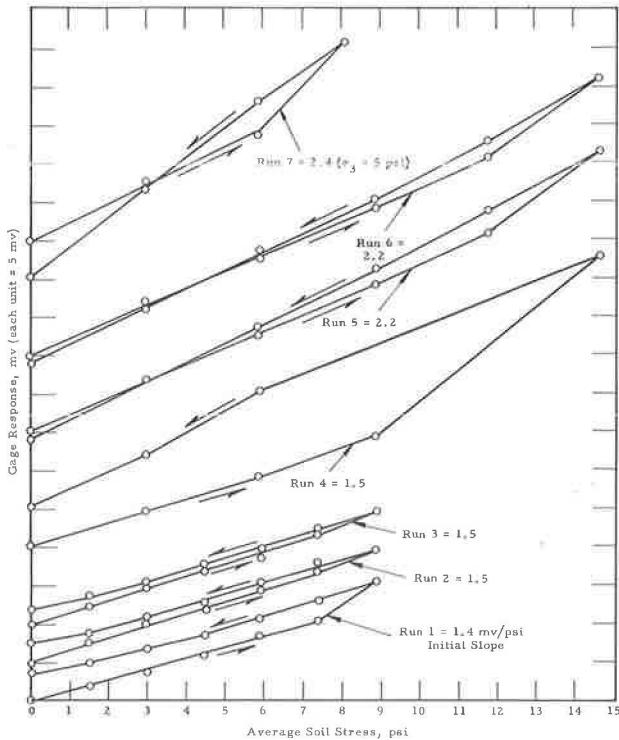


Figure 21. Triaxial calibration curves for gage S-25RT under repeated loading ( $\gamma_0 = 100$  pcf,  $\sigma_3 = 12.5$  psi).

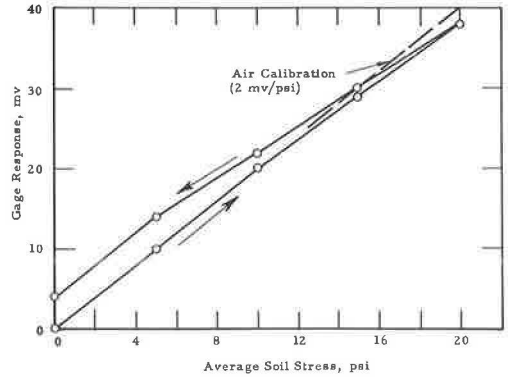


Figure 20. Typical confined calibration curves for disk gages with edge ring and teflon cover.

approximately the same, although the dynamic curve generally bent upward at a lower stress than did the static curve. For a wide range of calibration values the ratio of static to dynamic calibration remained about 1.0 with a variation on the order of  $\pm 10$  percent. Sensitivity distinctly tended to decrease with an increase in confining pressure. Gage sensitivity was reduced by approximately 100 percent with the teflon, thus greatly reducing the overregistration.

To further evaluate the factors influencing overregistration, several of these gages were calibrated in the confined compression device (Fig. 4). The resulting calibration curves (Fig. 20) were generally linear on load and unload. The major portion of hysteresis and residual charge may be caused by instrumentation drift.

Previous tests had indicated that gage sensitivities would increase with each consecutive loading cycle. A series of tests was performed to determine this effect under static loading. The test procedure consisted of seven to nine loading cycles. In cycles 1 through 3 the maximum applied stress was approximately

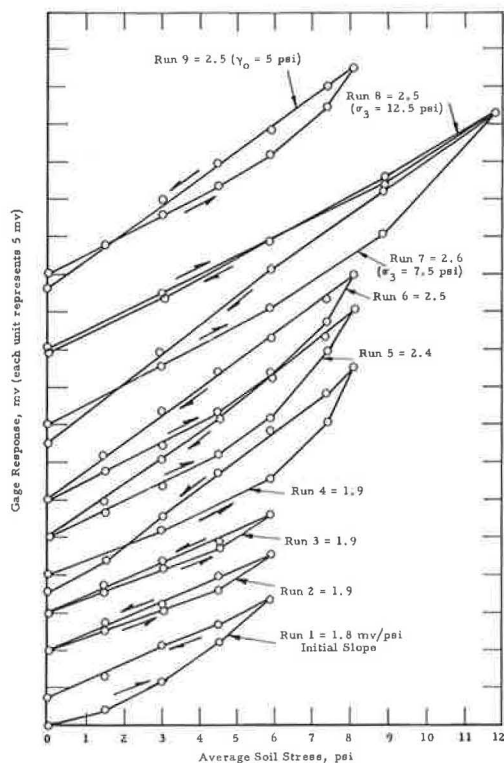


Figure 22. Triaxial calibration curves for gage S-25RT under repeated loading ( $\gamma_0 = 100$  pcf,  $\sigma_3 = 5$  psi).

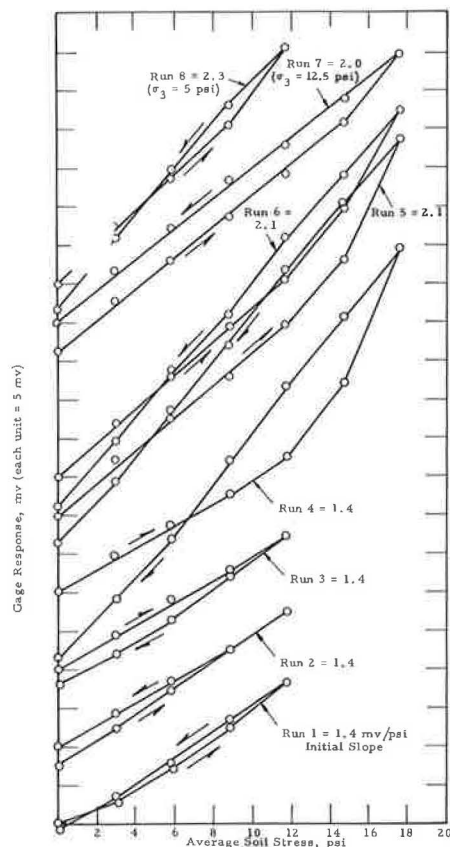


Figure 23. Triaxial calibration curves for gage S-25RT under repeated loading ( $\gamma_0 = 110$  pcf,  $\sigma_3 = 7.5$  psi).

three-fourths the specimen strength for the existing confining pressure and density. For cycles 4 through 6 the applied stress was increased to failure. The confining pressure was held constant during the first six cycles. In cycles 7 through 9 the specimen was loaded to failure at three different confining pressures.

Results of three such tests are given in Figures 21, 22 and 23. In each example the gage response for the first three cycles was approximately linear and constant. In most cases, however, the slope of the first cycle was different from that of the next two. In general, if all variables, including the peak cycle stress, remained unchanged, the gage response remained unchanged for consecutive loading. As the applied stress was increased toward failure, the gage sensitivity increased, and on unloading and for successive identical cycles remained at this higher value. Increases in confining pressure between cycles reduced the sensitivity on the next cycle and decreases in the confining pressure increased the sensitivity. These changes in sensitivity are summarized in Figure 24.

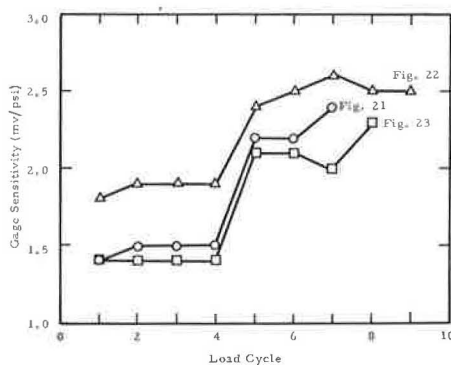


Figure 24. Change of gage sensitivity with repeated loading.

## SUMMARY

The cylindrically-shaped N-gage could not satisfactorily measure stress in sand. The embedded gage sensitivity, the calibration factor, varied significantly with specimen confining pressure, sand density, stress level, and repeated loading. The gage was also quite sensitive to placement conditions. As a result the gage could not be calibrated so that its output could be used to reasonably predict the true stress in sand specimens.

The factors contributing to the gage's deficiencies were (a) the stress sensing element was not sufficiently larger than the grain size of the sand, (b) the thickness-diameter ratio was too large, and (c) the location of the electrical leads created placement difficulties. Some of these problems might be less significant in compacted clay specimens.

A disk gage was designed to eliminate the undesirable features of the N-gage. The sensitive area was increased, the thickness-diameter ratio was decreased and the leads were attached to the side of the gage to simplify placement. The sensitivity of the resulting gage was much less influenced by such factors as confining pressure, density, and placement, but these effects were still significant.

An evaluation of overregistration, i.e., ratio of gage sensitivity when embedded to gage sensitivity under uniform hydrostatic pressure, was made using the results from the hydrostatic pressure tests. This evaluation could only be qualitative because of the large variation in values for the embedded calibration. It was observed that for stress levels much lower than specimen failure there was an average of 30 percent overregistration for the embedded gage protected with an edge ring and a teflon covering. Without teflon, the overregistration was about 100 percent, and without either teflon or edge ring the overregistration was about 200 percent. The significant overregistration in the latter two cases was a characteristic of the gage construction because the piezoelectric ceramic was sensitive to friction across its face and pressure on the edges. It is apparent, then, that the largest observed overregistrations can be eliminated by suitable gage design.

The gage calibration curves were linear for stresses well below specimen failure, but the sensitivity increased as the failure stress was approached. The gage response was linear, in general, only when the soil stress-strain relationship was linear. Thus, a change in the soil stiffness had an appreciable effect on the gage response whether it was caused by a change in confining pressure, density or by the normal stress level. This was true even when the gage stiffness itself was very high compared with that of the soil. As a consequence of this effect, the gage calibration curves showed appreciable hysteresis for stresses close to specimen failure. Also as a result the gage performance was much better in confined than in constrained specimens. It is evident that although the gage stiffness was greater by a factor of 200 or more than the soil stiffness, a change in soil stiffness still affected the gage response.

Gage placement was another significant factor affecting gage response and accounting for a significant variation in the response even when all other conditions were constant. Variations due to placement of up to  $\pm 50$  percent were observed.

The static and dynamic sensitivities of the disk gages were identical, but showed a  $\pm 10$  percent variation when used in specimens having a wide range of confining pressures and densities.

The measurement of stress in soil with embedded gages remains an inherently difficult problem because of the complex nature of the soil stress-strain relationships on which the gage response depends. Gages utilizing the piezoelectric sensing element, however, potentially provide one of the most suitable methods for accomplishing this task. Such gages provide high sensitivity, are simple to construct, and can be made essentially rigid with respect to the soil. Their extremely short response time makes them especially suitable for dynamic measurements. For slowly varying or static stress applications, sensitivity to temperature changes and the instrumentation requirements for maintaining sufficient circuit time constant, present limitations on their use. The reproducibility of the very simple disk gages constructed for the study was not satisfactory for general application. However, the performance was much better than that of miniature diaphragm gages also investigated.

It was clear from this investigation that a more elaborate stress gage design is required to isolate the sensing element from the undesirable influences. The gages used in the study were clearly affected by a complex set of circumstances as a result of their particular design features. This makes generalization of the conclusions to other gage designs subject to some question. The study has indicated the problems involved in stress measurement with piezoelectric sensors. As a result of this information a more elaborate stress gage has been designed which appears to give better performance than the simple versions. Extensive evaluation of the new gage is currently under way.

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